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**PHYSIOLOGICAL FOUNDATION FOR CLINICAL
VALIDATION OF AEROMEDICAL EVACUATION PATIENTS**

**William P. Butler, MD, MTM&H
(Colonel (ret), USAF, MC, CFS)**

711 HPW/RHBA

**Lawrence W. Steinkraus, MD, MPH
(Colonel (ret), USAF, MC, SFS)**

Mayo Clinic

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**AIR FORCE RESEARCH LABORATORY
711TH HUMAN PERFORMANCE WING,
AIRMAN SYSTEMS DIRECTORATE,
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE**

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TERESA L. MILLWATER, DNP, DR-II
711 HPW/RHBAM

//signature//

DAVID BURCH, DR-III, PhD
Core Research Lead Area
Biomedical Impact of Flight Branch
Airman Biosciences Division

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TABLE OF CONTENTS

LIST OF FIGURES	iii
LIST OF TABLES.....	iv
1.0 EXECUTIVE SUMMARY	1
2.0 INTRODUCTION/BACKGROUND	3
3.0 THE TVFS's CLINICAL VALIDATION ALGORITHM.....	7
4.0 FLIGHT STRESSOR PHYSIOLOGY AND COUNTERMEASURES	11
4.1 Introduction to GHOSTBaN	11
4.2 Acceleration/Deceleration.....	11
4.2.1. Description.....	11
4.2.2. Countermeasures.....	13
4.3 Drop in Humidity	14
4.3.1. Description.....	14
4.3.2. Countermeasures.....	15
4.4 Hypothermia/Hyperthermia	16
4.4.1. Description.....	16
4.4.2 Countermeasures	18
4.5 High Levels of Noise.....	19
4.5.1 Description.....	19
4.5.2. Countermeasures.....	21
4.6 Vibration.....	22
4.6.1. Description.....	22
4.6.2. Countermeasures.....	25
4.7 Hypobaria.....	27
4.7.1. Boyle's Law Effects.....	27
4.7.2. Venous Gas Emboli Effects.....	60
4.7.3. Altered Tissue Dynamics Effects.....	62
4.8 Hypoxia	67
4.8.1. Description.....	67
4.8.2. Countermeasures.....	70
5.0 TISSUE OXYGEN DELIVERY (DO ₂ PARADIGM) PHYSIOLOGY	75
5.1 Introduction	75
5.2. Derivation of and Factors Affecting DO ₂	75
5.3 Calculation of DO ₂	79

5.4	Application of DO ₂ --- Case Report	80
5.5	Evidence Supporting the DO ₂ Paradigm	81
6.0	THE BRADFORD-HILL CRITERIA	90
7.0	FUTURE	93
8.0	CONCLUSION	97
	ACKNOWLEDGEMENTS	98
9.0	REFERENCES	99
	APPENDIX A --- TVFS TOOLKIT	130
	APPENDIX B --- TVFS PROGRAMMED LEARNING: CASE STUDIES	177
	LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS	256

LIST OF FIGURES

Figure 1. Checks & Balances --- How the Four Physicians Interact to Evacuate a Patient	4
Figure 2. The TVFS's Clinical Validation Algorithm	7
Figure 3. The Three-Dimensional View of Flight (aircraft and human)	12
Figure 4. Graphic Depiction of Blood Volume Movement on Take-off and Landing	13
Figure 5. Atmospheric Humidity and Temperature Response to Altitude	14
Figure 6. Sound Level Distribution Across Frequency Bands for the C-130 and KC-135	20
Figure 7. Noise Attenuation Afforded by Ear Plugs and/or Ear Muffs	21
Figure 8. Frequency Range for "Least" Human Vibration Tolerance	23
Figure 9. Damping Effect of Cushions on Vibration	26
Figure 10. Pressure-Volume-Diameter Relationships with Increasing Altitude	28
Figure 11. Graphic Depiction of the Mt Fuji Sign	32
Figure 12. Chest X-Ray & CT Scan of Barotraumatic Pneumothorax	36
Figure 13. Estimated Pneumothorax Size Employing the Rhea-Collins Method	37
Figure 14. Section of Dog Lung Following Alveolar Overinflation/Overpressurization	42
Figure 15. TVFS Prescribing Algorithm for Patients with Pneumomediastinum	45
Figure 16. Pressure-Volume Relationships with Pneumopericardium	46
Figure 17. Normal Abdominal Pressure-Volume Response to Altitude	48
Figure 18. Abdominal Compartment Syndrome in the Burn Patient	49
Figure 19. Natural History of Postoperative Pneumoperitoneum Resorption	50
Figure 20. Percent of Casualties with Eye Injuries, Over Time	53
Figure 21. Estimated Rise in IOP with Each 1,000 Feet of Cabin Altitude	54
Figure 22. Altitude Exposures Found in Large Case Series of Low Altitude DCS	61
Figure 23. Hypobarica Impact on the Starling Intravascular-Extravascular Equilibrium	64
Figure 24. Balloon Analogy for Altitude-Mediated Tissue Edema (Starling Physiology)	66
Figure 25. Oximetry Readings of Two Patients, on the Ground and at Altitude	68
Figure 26. Oxyhemoglobin Dissociation Curve	68
Figure 27. Effect of FiO ₂ and PEEP in Oleic Acid ARDS Swine Model at 8,000 Feet	70
Figure 28. Pulmonary Shunt Ratio-Percent-Severity Depiction	73
Figure 29. How Inflight Stressors Influence AE Patient DO ₂	76
Figure 30. "Two Pore" Leaky Capillary Model, Associated with Major Trauma	78
Figure 31. Tools Developed for Calculating DO ₂	79

Figure 32. Annual Incidence of CAR Missions and Prescriptions	81
Figure 33. Graphic Depiction of CAR Rates versus Postflight Complication Rates	84
Figure 34. Dose-Response Relationship Between DO ₂ and Postflight Procedures	88
Figure 35. USAF's Transport Isolation System and Portable Bio-Containment Module	94
Figure 36. Modular AE in the Danish Air Force (2014)	95

LIST OF TABLES

Table 1. Part 1. Prescribing Considerations for the TVFS	9
Table 1. Part 2. Prescribing Considerations for the TVFS	10
Table 2. AE Aircraft Airflow Characteristics	17
Table 3. Physiological Effects of Various Vibration Frequencies	24
Table 4. Trapped Air Resorption Gradients	29
Table 5. Tissue-Trapped-Air Resorption Times	30
Table 6. Trapped Air Volume at Sea Level	34
Table 7. Trapped Air Pressure-Volume-Diameter Relationships	35
Table 8. Tension Pneumothorax Characteristics, Awake versus On Ventilator	38
Table 9. TVFS Prescribing Approach for Patients with Pneumothorax	41
Table 10. TVFS Prescribing Approach for Patients with Intra-Abdominal Air	52
Table 11. TVFS Prescribing Approach for Patients with Pneumatosis Oculi	56
Table 12. Commercial Cabin Altitudes at a Cruising Altitude of 35,000 Feet	58
Table 13. CCATT CPG - ARDSNet Lung Protective Ventilator Strategy	71
Table 14. Table for Determining Sea Level Oxygen Equivalency at Altitude	72
Table 15. PaO ₂ /FiO ₂ versus SpO ₂ /FiO ₂ Pulmonary Shunt Ratio Correlation	74
Table 16. Classes of Hemorrhagic Shock	80
Table 17. Indirect Evidence Supporting DO ₂ Paradigm --- Inflight	82
Table 18. Indirect Evidence Supporting DO ₂ Paradigm --- Postflight	82
Table 19. Postflight Outcomes from the Matched Case-Control Study. (Fouts, 2017)	85
Table 20. Postflight Outcomes from the Dual Case-Control Study. (Butler, 2018)	86
Table 21. Postflight Outcomes from the Pilot DO ₂ Study. (Butler, 2020b)	87
Table 22. The Bradford Hill Criteria of Causality as Applied to the DO ₂ Paradigm	92

1.0 EXECUTIVE SUMMARY

This monograph is an in-depth discussion focused on the physiological foundations for clinically validating a patient for aeromedical evacuation (AE). It is designed to serve as a guide and resource for the Theater Validating Flight Surgeon (TVFS) upon whom rests the final validation authority for manifesting a patient on an AE flight.

The monograph is divided into five parts. The first part, the Introduction/Background, describes how AE has changed over the past several decades. It delves into the “first hit” (aka initial injury/illness) and “second hit” (aka added physiological insult) model as it applies to postflight patient morbidity and mortality. This leads into a brief history of inflight patient mortality. The checks and balances devised to preempt this catastrophic outcome are then discussed. That is followed by a brief overview of the tissue oxygen delivery (DO_2) paradigm and its utility, along with a case example.

The second part, The TVFS’s Clinical Validation Algorithm, presents an algorithm for clinical validation. A step-by-step guide is proffered to facilitate its use. Additionally, a rather extensive table of stressors-prescriptions-indications is presented.

The third part, Flight Stressor Physiology and Countermeasures, is dedicated to an extensive discussion of inflight physiological stressors. Each stressor is described and countermeasures to its physiological effects are tendered. Acceleration/deceleration is about hemodynamic vascular flow effects and how patient positioning and modification of take-off and landing flight parameters can be ameliorative. Reduced inflight humidity is characterized and counters offered. Inflight thermal instability is considered and ways to fend off hyperthermia and, especially, hypothermia are presented. Next reviewed is ubiquitous noise and how ear plugs and ear muffs can block it. Vibration is then at issue along with its effects and the potential ways to dampen it. Lastly analyzed, but of greatest import, are hypobaria and hypoxia. The hypobaric pressure-volume effects and mitigation strategies are reported for pneumocephalus, pneumothorax, pneumomediastinum, pneumoperitoneum, pneumatosis oculi, and equipment. Venous gas emboli, both evolved and infused, are deliberated. And, altered tissue dynamics are painstakingly pondered. Hypoxia and supplemental oxygen rounds out the discussion and introduces the concept of DO_2 .

The fourth part, Tissue Oxygen Delivery (DO_2 Paradigm) Physiology, is all about DO_2 and the DO_2 paradigm. The impact of various stressors on DO_2 , including vibration, hypoxia, and hypobaria, are contextually reiterated. How DO_2 is crucial to the health and well-being of patients and how this is true especially with “stabilized,” or clinically volatile AE patients is emphasized. The technique for calculating DO_2 and its application to individual patients are described. That application, referred to as the DO_2 paradigm, consists of manipulating DO_2 influential factors, specifically the oxygen fraction of inspired air (FiO_2), the hemoglobin level, and the cabin altitude. In other words, the TVFS prescribes supplemental oxygen, transfusion, and cabin altitude restriction (CAR), respectively. Both indirect and direct research studies confirming the salutary effect of the DO_2 paradigm are shared.

The fifth part, the Bradford Hill Criteria for Causality, takes the DO_2 paradigm and submits it to the Bradford Hill Criteria for epidemiologic causality. In other words, it considers the cause-effect statement: the DO_2 paradigm, as prescribed by the TVFS, results in reduced postflight patient morbidity. Each of the nine criteria is examined. Some are met with limited vigor and one is weak. However, the remaining six criteria are strongly met. This test soundly supports prescribing for the AE patient within the DO_2 paradigm’s conceptual framework.

The sixth and final part, Future, peers “what’s next” for AE. Tackled here are the KC-46, casualty evacuation with remotely piloted vehicles, autonomous patient care systems, mobile AE treatment modules, hyperbaric oxygen pretreatment, biostasis, and even genetic modulation.

Finally, the monograph offers up an extensive bibliography of references for the TVFS. In addition, an appendiceal toolkit of tables and graphics is provided to assist the TVFS in constructing the validation prescription (Appendix A). And, from a training viewpoint, a graduated program of learning case series (20 cases) is also included as an appendix (Appendix B).

2.0 INTRODUCTION/BACKGROUND

Medical evacuation of injured soldiers from harm's way has been part of the battlefield for generations, dating back to Dominique Larrey at the Battle of Metz (1793) and Jonathan Letterman at the Battle of Antietam (1862). (**Haller, 1992; Gabriel, 2013**) Air transport of casualties may go back as far as 1870 and the Franco-Prussian War when 160 French casualties were evacuated from Paris aboard 66 balloons. Fixed wing AE of casualties is relatively recent having been invented in the 20th century. In 1909, Captain George Gosman and Lieutenant A.L. Rhodes made the first attempt to build an airplane capable of casualty carrying. (**Reiter, 1993**) In 1912, French aviatrix and visionary Marie Marvingt saw the future and became a life-long advocate of AE; she eventually lived to see her vision realized. (**Lam, 2003**) In the mid-1930s, Surgeon General Erich Hippke elaborated the AE concept for the Luftwaffe, gaining experience with Condor Legion evacuations during the Spanish Civil War. (**Harsch, 2006**) And, then, during World War II, General David Grant proposed a plan for a workable aeromedical evacuation system. When the Army Air Corps became the Department of the Air Force in 1947, AE became one of its core competencies. (**Reiter, 1993**)

Today, there are two modes of aeromedical evacuation: rotary wing and fixed wing. Generally, rotary wing is used for battlefield clearing or short distance intra-theater aeromedical evacuation; this is commonly referred to as MEDEVAC. In contrast, fixed wing is used for long distance intra-theater (aka tactical) or inter-theater (aka strategic) aeromedical evacuation; this is commonly referred to as AIREVAC (AE). (**Borden Institute, 2004**)

Long distance tactical and strategic AE are well proven tools in casualty care. These tools are especially important today as AE is no longer a venue limited to stable patients. Patients, up until the latter part of the 20th century, were not evacuated from forward medical facilities in a non-stable condition, often meaning days/weeks of care prior to AE. With the advent of the Critical Care Air Transport Teams (CCATTs), "stabilized," or clinically volatile, patients are regularly transported. (**Norton, 2012**) Today, a soldier can be injured in the Middle East and returned to the United States for definitive care and rehabilitation within 72-96 hours. (**Gawande, 2004**)

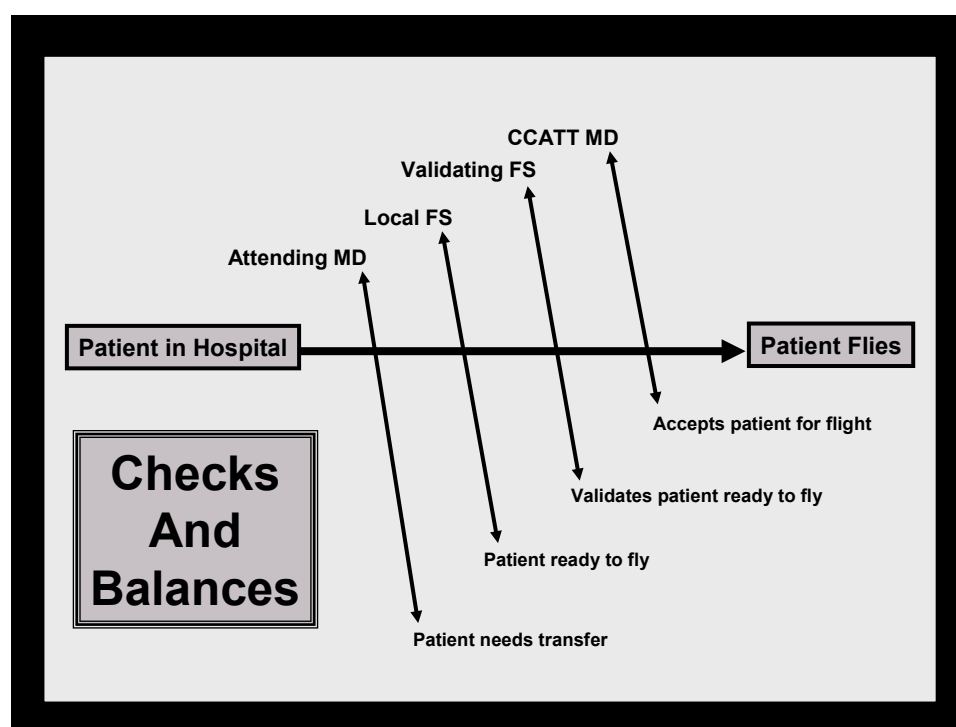
Just as AE care has advanced, so has on-the-ground clinical care. Lethality rates are among the lowest ever, ranging from 9.6% to 10.2%. (U.S. Casualty Status, published February 12, 2015; Department of Defense; <http://defense.gov/news/casualty.pdf>; accessed February 17, 2015; website no longer operable) (**Gawande, 2004; Goldberg, 2010**) Behind this striking success is far forward placement of the highest level medical care ever, backed with the best battlefield technological support ever. (**Butler, 2020a**) This sort of success means that AE is moving some of the sickest patients in history.

Taking a critically ill patient to a cabin altitude of 8,000 feet aboard a military cargo transport offers up a number of inflight physiological stressors --- acceleration/deceleration forces, excess noise, thermal instability, reduced humidity, unrelenting vibration, hypoxia, and hypobaria. These stressors pose a *second hit* risk. The *first hit* being the initial injury/illness; the *second hit* being an added physiological insult. (**Goodman, 2010; Goodman, 2011**) The result, a potential for added patient morbidity and/or mortality.

Prior to manifesting "stabilized" AE patients, inflight mortality reflected the "stability" of patients. Although ground-care lethality rates during World War II were around 30%, there were only 46 inflight deaths among 1.2 million evacuated (0.004%). (**Gawande, 2004; Schaeffer, 1948; Link, 1955; McFarland, 1958**) Ground-care lethality for the Korean War was

25%; there were 6 inflight deaths, a mid-air collision, among 311,673 evacuated (0.002%). (Gawande, 2004; Futrell, 1983) In Vietnam, ground-care lethality was 24%; there were at least 14 inflight deaths, all moribund, with 406,022 evacuated (0.003%). (Gawande, 2004; White, 1968; White, 1971). And, with Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF), ground-care lethality hovered around 10%, while inflight mortality was < 0.02% (1⁺ death in 177,770). (Gawande, 2004; Ingalls, 2014; Butler, 2020a)

To evacuate these very ill, clinically volatile, patients with minimal inflight mortality is a testament to both the clinical skills of CCATTs, but also the clinical judgment of the TVFS. This physician's job is not to care for the patient inflight (that is the job of the CCATT and AE crew), rather it is to tailor the flight to the patient. To do this, the TVFS coordinates with the attending physician, the clearing flight surgeon, and the CCATT physician. The attending physician decides that the patient must be evacuated. Reasons include need for beds, higher level care, specialty support, and/or rehabilitation. The patient's clinical situation is then reviewed by the local clearing flight surgeon, the focus being the patient's ability to tolerate the inflight stressors. At the same time, the patient's condition demanding it, the CCATT physician is brought into the mix. If these three physicians deem the patient a candidate for evacuation, the TVFS is approached via the Transportation Command's Regulating and Command and Control Evacuation System (TRAC²ES) with its Patient Movement Request. The TVFS, usually a geographically-separated senior Aerospace Medicine specialist, studies the request and assesses the patient's readiness for flight, often speaking with the other physicians. (Hurd, 2006) See Figure 1.



Note: MD (medical doctor), FS (flight surgeon), CCATT (Critical Air Transport Team).

Figure 1. Checks & Balances --- How the Four Physicians Interact to Evacuate a Patient

In this way, no one physician decides the patient's AE fate. That said, however, it is the TVFS who guides the process and with whom the final authority for validation (aka approval) rests. Indeed, it is the TVFS who must actively mitigate/minimize the patient's vulnerability to flight-related risks prior to validating the patient "fit to fly." To do so, the TVFS employs both clinical and aircraft prescriptions. Clinical prescriptions include interventions such as supplemental oxygen, head first loading, and assignment of CCATTs, while aircraft prescriptions take in long, slow landings, no stops, and cabin altitude restrictions.

Little has been written about the TVFS's clinical practice until recently. In fact, the last comprehensive discussion took place over 30 years ago. Then, AE consisted of stable patient movement; evacuation of "stabilized" patients was unheard of. (**Johnson, 1977a; Johnson 1977b**) With the advent of CCATTs and "stabilized" patient transfer, TVFS's clinical practice of patient validation became a dynamic and challenging process. (**Butler, 2016; Fouts, 2017; Butler, 2017; Butler, 2018; Butler, 2020a**) To that end, in late 2006/early 2007, the notion of tissue DO₂, a foundational concept in intensive care, was introduced into pre-hospital patient care and AE. (**Grissom, 2006; Pollan, 2006; Butler, 2007b**) In fact, Pollan and Fisher followed by Butler created DO₂ tables, facilitating the validation process. (**Pollan, 2006; Butler, 2007b**) Although the tables had great utility, they were not necessarily user-friendly. This led to the development of a spreadsheet-based DO₂ graphic user interface. (**Butler, 2020a; Butler, 2020b**) Employing DO₂ in AE clinical decision-making (aka the DO₂ paradigm) brought intensive care principles into the validation process and helped standardize the TVFS's prescribing of supplemental oxygen, transfusion, and cabin altitude restriction. In short, it made for a coherent and logical clinical approach when considering "stabilized" patient evacuation.

Prior to this sort of thinking and these tools, flying such patients was a perilous adventure, both for the patient as well as those tasked with transporting the patient. One particularly well-documented example described a patient whose vehicle struck a land mine. The patient suffered a right femur fracture, comminuted left tibia-fibula fractures, a grade IV splenic laceration, and multiple small bowel lacerations. Over the ensuing 3 days, the patient underwent splenectomy, small bowel resection and repair, as well as orthopedic surgeries. At the same time, he developed acute respiratory distress syndrome (ARDS), requiring ventilator support, and acute oliguric renal failure, requiring evacuation for more specialized support. At the time of transport, 7 days post-injury, the patient's blood pressure was 73/38, heart rate 146, FiO₂ 100%, positive end-expiratory pressure (PEEP) 10 centimeter (cm) H₂O, and arterial partial pressure of oxygen (PaO₂) 52. The patient was enplaned with an FiO₂ 70% and a cabin altitude restriction of 3,800 feet. During transport, the patient desaturated, became progressively hypotensive with persistent bradycardia, and, despite all interventions, eventually died 45 minutes into the flight. (**Turkan, 2006**) Retrospective estimates of DO₂ just prior to enplaning and during flight were well below the critical DO₂ (DO_{2crit}) threshold of < 7.3 milliliters oxygen per minute per kilogram (ml O₂/min/kg). (**Lieberman, 2000**)

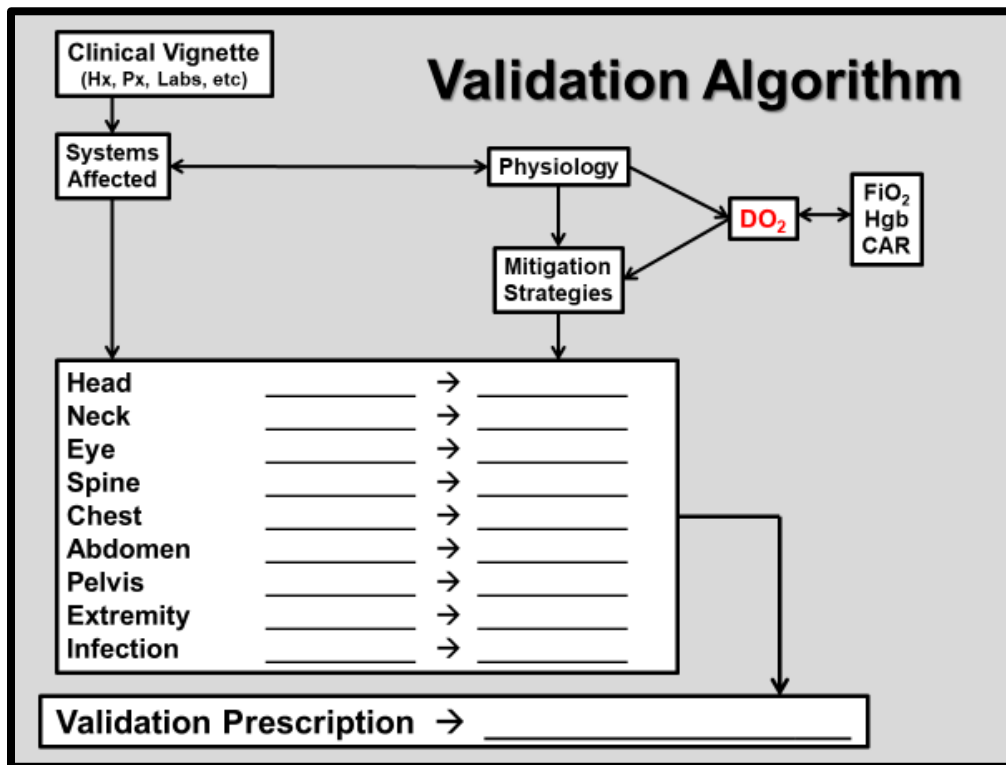
Such untoward outcomes must be avoided. Moreover, postflight morbidity from potential *second hits* must also be avoided. This means that the TVFS must counter the various flight stressors and modulate the patient's physiology to better withstand the AE flight. A systematic and repeatable algorithm is essential. Such an algorithm will be presented in **Section 3.0 - The TVFS's Validation Algorithm**. In **Section 4.0 – Flight Stressor Physiology and Countermeasures**, specific inflight physiologies and various interventions will be discussed, while in **Section 5.0 - Tissue Oxygen Delivery (DO₂ Paradigm) Physiology** will detail the

calculation of DO₂ along with its defining factors, pointing out those readily modifiable factors within easy reach of the TVFS. Throughout Sections 4.0 and 5.0, animal and human evidence for *second hit* morbidity will be presented, as will be evidence for the salutary clinical impact of the DO₂ paradigm. In **Section 6.0** - The Bradford-Hill Criteria, this evidence will be examined within a trusted epidemiological causal model. In **Section 7.0** - The Future and **Section 8.0** - Conclusion will posit potential futures for AE and the TVFS along with an overall summary of present-day AE and TVFS, respectively. And, lastly, **Appendix A** proffers a toolkit of helpful instruments for the TVFS and **Appendix B** presents a graduated program of learning case series (20 cases).

3.0 THE TVFS's CLINICAL VALIDATION ALGORITHM

To manifest a patient aboard an AE flight, a logistic requirement must be created. This is a two-pronged process consisting of an administrative validation and clinical validation. The administrative validation, performed by a medical service corps officer, looks at the nonclinical aspects of transport, such as passports, overfly diplomatic clearances, and destination resources. On the other hand, the clinical validation, by the TVFS, seeks to posture the patient for a physiologically safe flight. (Hurd, 2006)

It is important that the clinical validation be a systematic and coherent search for the patient's potential inflight physiological vulnerabilities and an application of appropriate countermeasures to minimize the clinical impact of those vulnerabilities. One such methodology is presented. See **Figure 2**.



Note: Hx (history), Px (physical), DO₂ (tissue oxygen delivery), FiO₂ (oxygen fraction of inspired air), Hgb (hemoglobin level [g/dl]), CAR (cabin altitude restriction).

Figure 2. The TVFS's Clinical Validation Algorithm

With this approach, the clinical picture (aka vignette) is explored for system vulnerabilities. An example would be an eye injury with globe disruption and global air retention. Next, these system vulnerabilities are considered in light of the inflight physiological stressors. Continuing the example, going to a standard cabin altitude of 8,000 feet will result in about a 34% volume expansion of any retained air. Depending on the ground volume of the global air, the effect of such an expansion could range from nothing to occlusive retinal vessel

pressure to optic nerve pressure-based ischemia to global content extrusion. This physiology must be countered. Here, the TVFS might well offer up a CAR. Other strategies might include bilateral eye patching and head of bed elevation --- both minimizing globe content activity --- not to mention ground equivalent supplemental oxygen --- to avoid retinal and nerve hypoxia. At the same time, DO₂ must be considered. Of the factors easily modulated by the TVFS, a CAR has already been imposed and FiO₂ has been set to mirror ground level, leaving hemoglobin level which must be confirmed adequate. Thus, the validation prescription for this exemplar eye injury would contain CAR, ground equivalent supplemental oxygen, eye patching, and head of bed elevation.

Needless to say, there is a wide gamut of prescriptions available to the TVFS. They can be directed at mitigating inflight physiological stressors (e.g., earmuffs for noise), countering specific system issues (e.g., bringing aboard an extra cardiac monitor for detecting a potential cardiac event), or general inflight problems (e.g., prophylaxis for deep vein thrombosis). They can include patient prescriptions (e.g., supplemental oxygen) or aircraft prescriptions (e.g., cabin altitude restriction). (Butler, 2016; Butler, 2017; Butler, 2020a) Of course, there is no all-inclusive listing; however, a list of prescriptions *vis a vis* inflight stressors and clinical settings should prove useful. See **Table 1** for details.

Occasionally, operational pace will result in many casualties often coupled with small or even large mass casualty events. Clinical exigencies can threaten to overwhelm the TVFS. One methodology for avoiding that was developed and validated by the authors (WPB and LWS), referred to as the “Worksheet.” It was an ExcelTM spreadsheet with columns for specific validating information and rows dedicated to specific patients. The *worksheet* proved highly effective. (Butler, 2017) See **APPENDIX A --- TVFS’s Worksheet**.

Table 1. Part 1. Prescribing Considerations for the TVFS

Prescribing Considerations for the TVFS in Aeromedical Evacuation --- Part 1			
Inflight Stressors	Physiological Effects	Clinical Effects	Countermeasures
Gravity	acceleration-deceleration	hemodynamic flow	head-first load, feet-first load, head of bed elevation, prohibit traction weights, consider Stryker™ or vacuum spine board, long steady take-off, gentle climb out, long slow landing
Humidity	reduced humidity	dehydration	rehydration (oral, intravenous), humidified breathing gases
Temperature	thermal instability	hypothermia, hyperthermia	<u>Hypo</u> : upped aircraft heat, blankets (reflective, heated), warmed IV fluids, warmed ventilator air; <u>Hyper</u> : upped aircraft cooling, upped airflow, cool misting (ground)
Noise	temporary threshold shift	temporary hearing loss	earplugs, earmuffs
Vibration	vibration	increased pain intensified pressure points upped metabolic activity tissue edema	damping with cushions (preferably air bladder* or jelly/gel), seat/litter isolation (hammock-like), centered fuselage loading away from engines, aircraft routing
Barometric Pressure	pressure-volume-diameter changes -- <i>pneumocephalus</i>	trapped gas expansion -- headache, confusion, nausea (tension pneumocephalus)	supplemental O ₂ , head-first load, HOB elevation, avoid Valsalva, long slow take-off & landing, CAR
	-- <i>pneumothorax</i>	-- chest pain, dyspnea (tension pneumothorax)	needle/chest tube, Heimlich valve/suction water seal, lung protective ventilation, supplemental O ₂ , CAR
	-- <i>pneumomediastinum</i>	-- chest pain, dyspnea, neck pain (subq air) ("malignant" pneumomediastinum)	bedrest, avoid Valsalva, supplemental O ₂ , lung protective ventilation, CAR
	-- <i>pneumopericardium</i>	-- chest pain, shifting tympany, muffled heart (pericardial tamponade)	bedrest, avoid Valsalva, supplemental O ₂ , lung protective ventilation, needle/tube drain suction water seal, CAR
	-- <i>pneumoperitoneum</i>	-- distention, tympany, oliguria (abdominal compartment syndrome)	NGT, supine, bedrest, supplemental O ₂ , CAR
	-- <i>pneumotosis oculi</i>	-- peri-orbital/orbital emphysema -- damaged/disrupted globe (impaired vision, expelled globe content) -- retinal reattachment bubble (pathologic IOP, impaired retinal perfusion)	avoid Valsalva/lifting, supplemental O ₂ , humidity, CAR recline w/ HOB elevated, patch & shield, contralateral pinhole patch, supplemental O ₂ , slow take-off/landing, CAR < 20% bubble, recline w/ HOB elevated, CAR (> 10%), slow take-off/landing, 2,000' foot descent w/ sxms; supplemental O ₂ as needed for retina (of questionable resorption benefit) baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg} should be < 50 mmHg
	-- <i>miscellaneous (equipment)</i>	ET (or tracheostomy) cuffs: <i>tracheal pressure necrosis</i> bladder catheter balloon: <i>balloon rupture</i> closed system drains: <i>air and/or drain fluids into wound</i> ostomies: <i>ostomy dislodgement</i> air splints: <i>tourniquet-like effect</i> epidural catheter: <i>back pain</i>	air exchange with ascent/descent; air replacement w/ saline air replacement w/ saline venting drain on ascent/descent "burping" or "pinholing" appliance air exchange with ascent/descent; substitute plaster splint analgesics via AE nursing staff
	venous gas emboli effect	evolved, infused (tissue edema effect)	CAR
	altered tissue dynamics		
	-- <i>inflammatory upregulation</i>	leaky vessels, tissue edema	CAR
	-- <i>Starling dysequilibrium</i>	leaky vessels, tissue edema	CAR
Oxygen	drop in DO₂	ischemia	CAR, transfusion, supplemental O ₂
	hypoxia	ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>injured bone & soft tissue</i>	tissue ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>on supplemental oxygen</i>	hypoxia & ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>immediate postop extubation</i>	transient pulmonary shunt & hypoxia	postpone validation at least 4-6 hours
	drop in DO₂	ischemia	CAR, transfusion, supplemental O ₂

Note: * Denotes the concern for Boyle's Law effects with air bladder cushions (altitude-induced expansion with asymmetry). Hypo (hypothermia), IV (intravenous), Hyper (hyperthermia), O₂ (oxygen), w/ (with), HOB (head of bed), CAR (cabin altitude restriction), NGT (nasogastric tube), IOP (intraocular pressure), mmHg (millimeters of mercury pressure), ET (endotracheal tube), AE (aeromedical evacuation), DO₂ (tissue oxygen delivery), postop (postoperative), CCATT (Critical Care Air Transport Team), GI (gastrointestinal), ENT (Ear, Nose, & Throat = Otolaryngologic), OSL™ (oversize litter), lb (pound), DCS (decompression sickness), RON (remain overnight).

Table 1 – Part 2. Prescribing Considerations for the TVFS

Prescribing Considerations for the TVFS in Aeromedical Evacuation --- Part 2		
Prescriptive Category	Prescription	Clinical Setting
Medical Adjuncts	cardiac monitor; suction; pulse oximeter medical attendant (tech, nurse, doctor) CCATT	Cardiac, Pulmonary, Critical Care Cardiac, Psychiatric Critical Care, Cardiac, Pulmonary
Medical Interventions	protect airway (nasotracheal/orotracheal intubation) nasogastric tube supplemental O ₂ ; positive end-expiratory pressure sedation/physical restraints in flight deep vein thrombosis prophylaxis blood components (transfusion) medications extended ground stabilizing (fluids, vasopressors, blood, tertiary survey) equalization maneuvers (Valsalva, Toynbee, Frenzel, etc)	Critical Care, Immediately Post-Operation Critical Care, Abdominal Surgery (GI, splenectomy) Critical Care, Pulmonary, Trauma, Burns Psychiatric All Settings Trauma, Anemia All Settings Trauma, Critical Care
Middle Ear Adjuncts	Afrin TM and neosynephrine myringotomy	All Settings All Settings All Settings
Patient Paraphernalia	endotracheal (or tracheostomy) tube cuffs - cuff inflation w/ water chest tube - suction or Heimlich valve (no clamping of tubing) Jackson-Pratt TM drain - open on ascent and descent Hemevac TM drain - open on ascent and descent colostomy bag - decompress on ascent ("pinhole", "burp") bladder catheter - balloon inflation w/ water bivalve casts; control air splints cushions (litter, head, heel) blankets	Trauma, Pulmonary Trauma, Pulmonary Orthopedic, ENT, Thoracic, Abdominal Surgery Orthopedic, ENT, Thoracic, Abdominal Surgery Abdominal Surgery All Settings Orthopedic Neurologic, Orthopedic, Critical Care All Settings
Positioning Interventions	head first loading litter at aircraft airflow outlet valves head of bed elevation headrest to elevate and protect head seizure precautions spine precautions cervical spine collar OSL TM litter (regular litter = 250 lb; oversize litter = 400 lb) Stryker TM frame; vacuum spine board	Neurologic, Ophthalmologic Infectious Neurologic, Ophthalmologic, ENT, Pulmonary, Cardiac Neurologic, Ophthalmologic, ENT Neurologic Neurologic Neurologic (cervical spine injury) Orthopedic (pelvic injury), Neurologic (spine injury) Neurologic (spine injury)
Aircraft Manipulations	cabin altitude restriction full use of runway length modify rate of climb and descent (long, slow landings; long steady climbs) cabin airflow patterns aerial refueling no RONS (remain overnight); no stops	Trapped Gas, DO ₂ optimizing, Pulmonary, DCS Neurologic, Pulmonary, Cardiac Neurologic, Pulmonary, Cardiac Infectious Cabin Altitude Restriction, Extended AE Flight Critical Care, Cardiac, Pulmonary

Note: * Denotes the concern for Boyle's Law effects with air bladder cushions (altitude-induced expansion with asymmetry). Hypo (hypothermia), IV (intravenous), Hyper (hyperthermia), O₂ (oxygen), w/ (with), HOB (head of bed), CAR (cabin altitude restriction), NGT (nasogastric tube), IOP (intraocular pressure), mmHg (millimeters of mercury pressure), ET (endotracheal tube), AE (aeromedical evacuation), DO₂ (tissue oxygen delivery), postop (postoperative), CCATT (Critical Care Air Transport Team), GI (gastrointestinal), ENT (Ear, Nose, & Throat = Otolaryngologic), OSLTM (oversize litter), lb (pound), DCS (decompression sickness), RON (remain overnight).

4.0 FLIGHT STRESSOR PHYSIOLOGY AND COUNTERMEASURES

4.1 Introduction to GHOSTBaN

During flight, the healthy human experiences physiological stressors that routinely affect performance and safety. (McFarland, 1953; McFarland, 1958) Likewise, during AE, the ill or injured human (aka patient) faces the same stressors. (AFI 48-307 Vol 1, 2017) They are best remembered with the mnemonic GHOSTBaN. (Dufour, 2003; Butler, 2007a)

G → Gravity (acceleration and deceleration)
H → Humidity (drop in humidity)
O → Oxygen (reduced oxygen partial pressure)
S → “Shakes” (vibration)
T → Thermal Instability (hypothermia/hyperthermia)
Ba → Barometric Pressure (hypobaria)
N → Noise (high levels of noise)

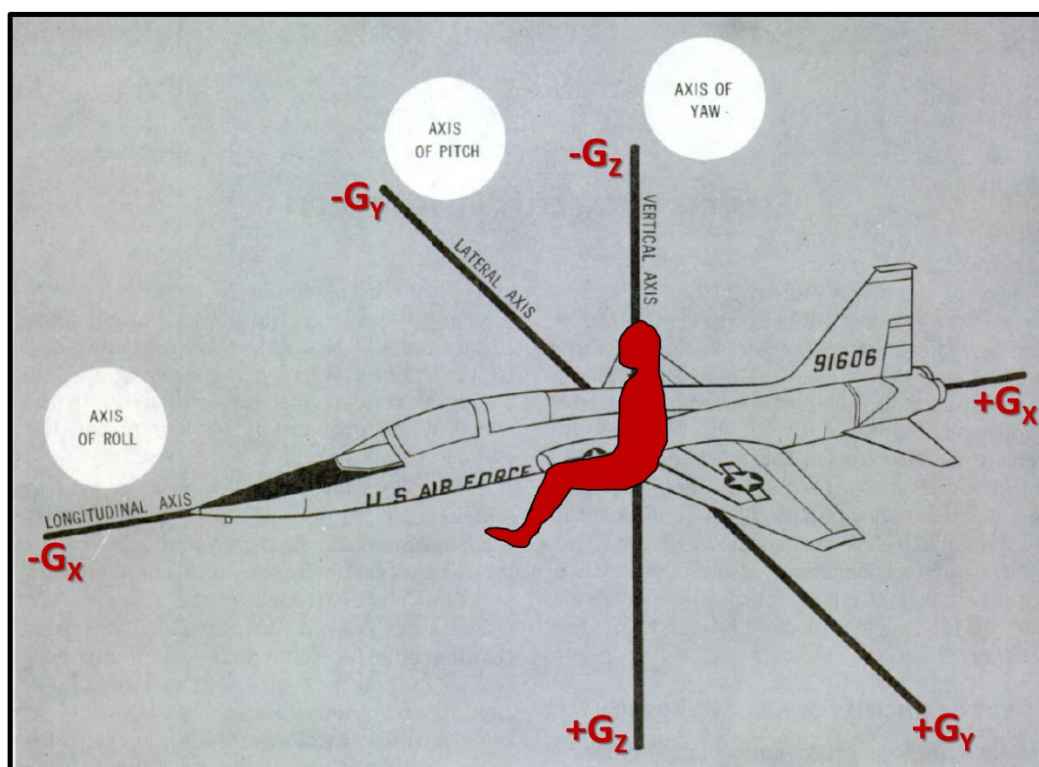
Each stressor has the potential to levy a *second hit* upon evacuated patients. The following sections will discuss the physiology of each stressor apropos to its *second hit* potential along with mitigating TVFS prescriptions (aka countermeasures).

4.2 Acceleration/Deceleration

4.2.1. Description

There is a large body of literature discussing the effect of gravity on high-performance fighter pilots, especially relating to gravity (G)-induced loss of consciousness. In contrast, little has been written on the impact of gravitational forces (aka acceleration/deceleration) upon evacuated patients. In fact, a recent systematic bibliographic review of the literature identified only four relevant articles. (Fouts, 2017)

To better understand the following discussion, it is important to visualize the three-dimensional environment of flight. With the aircraft, the three planes (i.e., roll, pitch, yaw) define motion about the center; whereas, with the human, the three planes (i.e., longitudinal axis (G_X), lateral axis (G_Y), vertical axis (G_Z)) define the resultant forces imposed. Most important physiologically is the vertical, G_Z plane. Force directed cephalad is defined as $-G_Z$; force directed caudal, $+G_Z$. See **Figure 3**.

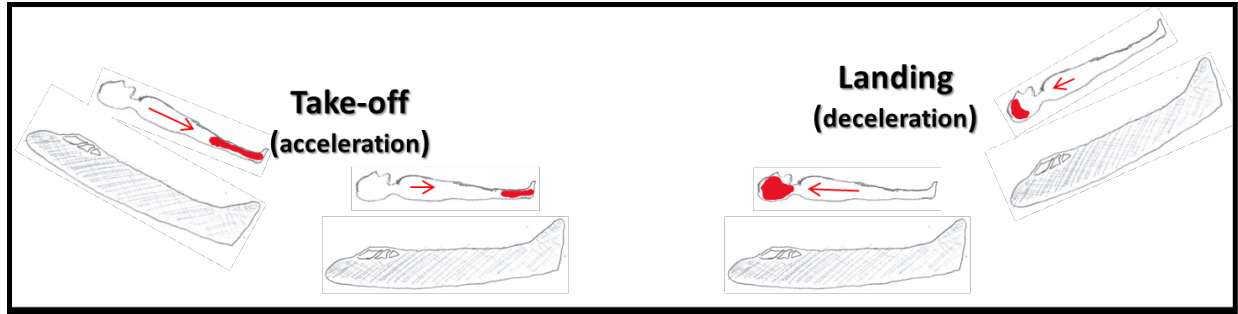


Note: Graphic taken from AFP 161-18 (1968), Figure 4-1, page 4-2. Human figure created by author (WPB). US government product not subject to copyright.

Figure 3. The Three-Dimensional View of Flight (aircraft and human)

As with fighter pilots, a major concern in patients is the gravity-induced movement of blood volume from the brain. Under normal ground-based conditions (1-G), the seated hydrostatic pressure differential between heart and head is about 22 millimeter of mercury pressure (mmHg). This differential is altered with each added “G” of acceleration/deceleration. For instance, with a 3-G take-off, a supine, head-first oriented patient would experience a 3-fold differential, or 66 mmHg. The pressure differential would be directed footward (+G_z). If heart-level systolic blood pressure is 110 mmHg, then head-level pressure would drop by 66 mmHg to around 44 mmHg. (**Green, 2016**)

This G-effect is of great importance with fighter pilots making quick, tight turns; however, in the AE arena it is not so well defined. Donovan et al, in their case series of AE patients with pneumocephalus, observed intracranial pressure (ICP) bumps of < 5 mmHg on take-off and inflight in a feet-first patient with severe brain injury, malignant cerebral edema, and baseline ICP of approximately (~)25-30 mmHg. (**Donovan, 2008**) Likewise, in a detailed observational case series, 6 of 11 patients demonstrated ICP elevations above 20 mmHg (with median durations ranging from 13 seconds to 26 minutes), while 10 of 11 showed a $\pm 50\%$ change over baseline ICP (with median durations ranging from 18 seconds to 2.7 minutes). Interestingly, 2 of 11 had ICP > 20 mmHg and 6 of 11 had the $\pm 50\%$ change on take-off; whereas, with landing, it was 5 of 11 and 10 of 11, respectively. (**Johannigman, 2015a**) See **Figure 4**.



Note: Direction of blood volume movement depicted by the red arrows. Blood volume accumulation depicted by red shading. Graphic created and courtesy of author (WPB).

Figure 4. Graphic Depiction of Blood Volume Movement on Take-off and Landing

Such G-effect has not been limited to the head. In fact, one particularly well-documented instance involved a trans-Atlantic evacuation of a head-first, cardiac transplant patient with a biventricular assist device. During take-off, the pressure differential produced a 33% drop in cardiac output (pushing blood volume into the extremities while dropping venous return to the assist device). With landing, the pressure differential resulted in the opposite, a rise in cardiac output. Notably, the Gulfstream III did not exceed 1.2 G in acceleration/deceleration. (McLean, 2011)

Other potential acceleration/deceleration effects may be anticipated for patients with orthopedic/spine injuries. Indeed, fracture stability can be affected with sudden movements in the G_x , G_y , or G_z planes. The G_x plane in a supine patient with a pelvic fracture and/or spine injury is of especial importance. The standard North Atlantic Treaty Organization (NATO) litter permits up to 4-8 inches center-excursion during rapid take-offs, hard landings, expedited transfers, and ambulance bus (aka ambus) transports (authors' personal observation, WPB and LWS). Clearly, such movements have the potential for added patient morbidity (e.g., pelvic fracture re-bleeding, neural tissue contusion, loss of fracture reduction, pain).

4.2.2. Countermeasures

Even this limited literature suggests a potentially serious acceleration/deceleration impact upon evacuated cardiac and brain injured patients. Consequently, the TVFS must account for and counter it. Countermeasures include aircraft prescriptions and patient prescriptions. Aircraft prescriptions are designed to mitigate the burst of acceleration and deceleration associated with take-off and landing, respectively. Long, steady take-offs with gentle climb-outs to altitude, along with long, slow landings without reverse thrusters do this. Patient prescriptions take aim at patient positioning. Head-first loading of supine litter patients means take-off will unload blood volume from both the heart and brain. On the other hand, it makes for an upped load of blood volume upon landing. (Blumen, 1995; Dufour, 2003; McLean, 2011; Green, 2016) Managing head-first/feet-first loading *vis a vis* take-off/landing smoothness will minimize fluctuations in cardiac output and intracranial pressure. In addition, head of bed elevation to 30-45 degrees will change the plane of gravitational forces from the G_z

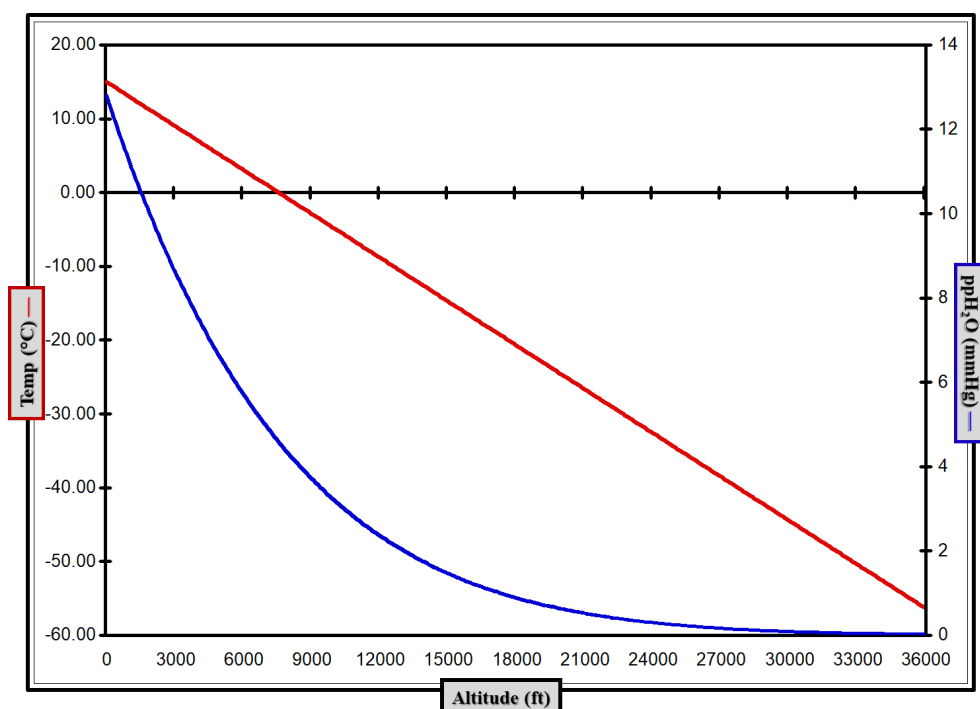
axis to the G_x axis. In the G_x axis, gravitational forces are much better tolerated and hold much less physiological sway. (Green, 2016)

In addition, maintenance of fracture stabilization and immobility is paramount. External fixators and traction frames ensure minimal acceleration/deceleration effect while restrictions, if not prohibitions, on hanging weights ensure little chance for patient, crew, or aircraft injury from errant weights. Similarly, spinal immobilization may well require advanced litter configurations (e.g., Stryker™ frames, vacuum splints) to avert not only G_z impacts, but also G_x excursions. (Erpelding, 1995; Legan, 2000; Bernhard, 2005; Mok, 2013; Weber, 2015) Table 1 lists the various countermeasures.

4.3 Drop in Humidity

4.3.1. Description

Water vapor makes up about 2% of the sea level atmosphere. Going to altitude is associated with a drop in the environmental partial pressure of water vapor (aka vapor pressure), declining from ~15-17 mmHg to approach near zero at around 30,000 feet. Vapor pressure also drops with a fall in atmospheric temperature. See Figure 5. For example, at sea level, vapor



Note: Graphic created by and courtesy of Lt Col Daniel Cole (USAFR, MC, FS). Temp (temperature), C (Centigrade), ppH₂O (partial pressure of water), mmHg (millimeters of mercury pressure), ft (feet).

Figure 5. Atmospheric Humidity and Temperature Response to Altitude

pressure at +20 C is around 15 mmHg, but at -20 C is only 1 mmHg. (West, 2013) Combining these two effects, an aircraft cruising at 30,000 feet with an ambient temperature of about -40 C

is surrounded by air with very little water content. (Nagda, 2001; West, 2013) In order to create a habitable cabin meeting airworthiness standards, the aircraft's environmental control system takes air from the engines (aka "bleed air"), compresses it, conditions it, and streams it into the cabin. However, nothing is done to humidify the air (< 1% relative humidity); one exception is the Boeing 787, designed to add humidity. As a result, humidity, for all intents and purposes, comes from the initial ground level cabin air and human respiration. (Nagda, 2001; Gradwell, 2016b) After about 2 hours, the relative humidity falls to ~5% and, after about 4 hours, < 1-3%. (Hansen, 1987; Nagda, 2001; McLaughlin, 2003; AFI 48-307 Vol 1, 2017)

Such dry air is not necessarily the commercial routine, what with moisture provided by passenger/crew respiration and food preparation and beverage distribution. Indeed, the average commercial inflight relative humidity ranges between 14 and 19%. (Nagda, 2001) This relative humidity coupled with the mild hypoxia-induced hyperventilation from an 8,000 foot cabin offer up a milieu notable for insensible respiratory water losses and the potential for dehydration. In the mountaineering literature, calculations suggested up to 200 ml water loss per hour with moderate exercise at ~18,000 feet, while counter-calculations maintained the loss to be more like 80 ml per hour. In reality, it appeared that a 7-hour climbing day at ~19,600 feet required 3-4 liters of fluid to maintain a urine output at 1.5 liters per day. (West, 2013) Clearly, water loss in the face of low humidity and cabin altitude happens, though, just as clearly, not at the mountaineering level. Indeed, anecdotal observations from CCATT physicians early in Operation Iraqi Freedom and Operation Enduring Freedom support this notion (personal communications). To date, the water loss and degree of dehydration from an AE flight has not been formally gauged; however, serious insensible loss should be anticipated in any flight > 4 hours. (McLaughlin, 2003)

4.3.2. Countermeasures

Generally, the normal human consumes about 2 liters daily with about 2 liters lost, around 1,500 ml urine and 500 ml insensible (i.e., skin and respiration). A patient on an AE flight will experience a disproportionate rise in insensible water loss. Untreated, dehydration follows, often marked by thirst, dry mouth, dry mucous membranes, sore throat, hoarseness, and dry/scratchy eyes. To counter dehydration, the TVFS must ensure that oral fluids are available to non-critical patients and intravenous fluids to critical patients. In addition, ventilator patients must be ventilated with humidified gases. (Blumen, 1995; Dufour, 2003; AFI 48-307 Vol 1, 2017) **Table 1** lists the various countermeasures.

4.4 Hypothermia/Hyperthermia

4.4.1. Description

Most attention is rightfully placed on hypothermia as opposed to hyperthermia. The latter is commonly related to on-ground ambient temperatures (e.g., warm locales such as Egypt) seen during on-loading and off-loading of patients; it seldom poses a problem inflight. The former is the more common issue with inflight patients. Trauma patients, by nature, are generally hypothermic and often suffer with the Lethal Triad of hypothermia, acidosis, and coagulopathy; the Lethal Triad as well as hypothermia itself are associated with increased mortality. **(Gerecht, 2014)** A cold cabin environment can only intensify the patient's hypothermia and must be avoided.

Ambient temperatures fall approximately 2 C for every 1,000 feet elevation, up to an altitude of 36,000 feet. This drop is referred to as the Standard Lapse Rate. At 36,000 feet, the ambient temperature is around -55 Celcius (C) (-67 Fahrenheit (F)). **(West, 2013; Pilot's Handbook, 2016; Gradwell, 2016a)** See **Figure 3**. Cruising at 36,000 feet *sans* an environmental control system, the thin-skinned cabin would be frigid. To prevent this, engine-compressed blistering-hot air is conditioned and circulated within the cabin. Since an aircraft's environmental control system degrades overall engine effectiveness, each aircraft's system is specific to its purpose as is the cabin air circulation patterns. Generally speaking, commercial aircraft systems are more passenger-friendly than those in military aircraft. **(Trudgill, 2016)** Thus, military AE is often thermally challenged.

For the most part, there is little published describing the temperature characteristics of AE-purposed aircraft. Passing mention is made of the outdated C-141 having a cabin temperature, after 60-90 minutes flying, of 59 F (15 C) with an airflow velocity of 0.20-0.26 meters per second (m/sec) (i.e., 0.45-0.58 miles per hour (mph)). **(Schmelz, 2007; Bridges, 2007)** This temperature is far below the human thermo-neutral temperature of ~82 F (~28 C), an ambient temperature where an unclothed person does not require excess thermogenesis beyond normal metabolism. **(Fiege, 1996; Schmelz, 2007)**

In the C-130, within 15-30 minutes of flying, air temperature at the front/top litter position was found significantly warmer than that at the back/bottom litter position (80 F versus 73 F). Likewise, subjects' skin temperatures in the front/top litter were significantly warmer than those in the back/bottom litter (92 F versus 89 F). At the same time, airflow was significantly less at the front/top litter than at the back/bottom litter (0.04 m/sec versus 0.08 m/sec). Interestingly, subjects' thermal perception was significantly correlated with both air temperature and air flow. **(Walsh, 1998)** These findings are compatible with the known C-130 engineering airflow characteristics that is top to bottom/aft to forward. **(AFI 48-307 Vol 1, 2017)** See **Table 2**.

Unfortunately, no readily available temperature data exists for the AE-configured C-17, the workhorse intertheater/strategic AE aircraft, or, for that matter, the KC-135. However, engineering airflow data does exist. See **Table 2A**.

Notably, airflow in the C-17 is aft to forward just as the C-130 and C-21. **(AFI 48-307 Vol 1, 2017)** This characteristic makes these aircraft less than optimal for transport of potentially contagious patients, putting Line aircrew at added risk. With such patients, transport aboard a KC-135, with top to bottom airflow, is wiser. **(AFI 48-307 Vol 1, 2017)** Indeed, recent airflow studies suggest that the KC-10, KC-46, and KC-135 protect the cockpit very well inflight, but not so well during loading and unloading. In addition, only the KC-10 and KC-46

provide a highly safe environment for medical crew rest out of personal protective equipment. See **Table 2B**. (personal communication, Lieutenant Colonel Christopher Cieurzo, Chief, Patient Movement Operations Division, TRANSCOM)

At the same time, micro-release airflow studies in the commercial airframes 777-200 and 767-300 have been performed. Aerosol risk (1 um particles) and fomite risk (3 um particles) were examined. In the face of air exchange characterized by 50% high-efficiency particulate-air-filtered recirculation and 50% fresh bleed air, aerosol residual with and without a mask was around 0.004% and 0.005%, respectively. In other words, well over 99% of aerosol particulates were removed. As for fomite, or deposition, particles, the maximum surface residual ranged from 0.000-0.005% in the 767-300 and 0.000-0.055% in the 777-200. Again, well over 99% of fomite particulates were removed prior to deposition. This air handling performance is 5-6 times better than the modern hospital operating room or isolation room and 15 times better than the standard home. In short, these two commercial aircrafts' environmental control systems significantly reduce the exposure to aerosols generated by passengers, not to mention contagion risk. (Silcott, 2020)

Table 2. AE Aircraft Airflow Characteristics

Table A14.1. Aircraft Airflow.				A
Aircraft Type	Air Flow Direction	Ambient Air Intake and Exchange Rate (minutes)	Post-Mission Time Required to Obtain 99.9% Removal Efficiency*	
C-130	Top to bottom/aft to forward. NOTE 2	4 (Sea level) - 8 (FL35)	1 Hr	
C-17	Aft to forward	16-30	3.5 hrs.	
C-21	Aft to forward	2.2	15 minutes	
KC-135	Top to bottom	4-5 NOTE 3	35 minutes	
KC-10	Top to bottom/forward to aft	7.5	1 hr.	

Airframe Performance Overview					B
Testing Rank	Airframe	Cockpit Safety (IN FLIGHT)	Cockpit Safety (Loading & Unloading)	Medical Staff Rest Capabilities	
1st	KC10	Very High	High	Very High	
2nd	KC46	Very High	Low	Very High	
3rd	C5	High	Low	High	
4th	KC135	Very High	Low	Low	
5th	C17	Medium	Not Tested	Low	
6th	C130J	Low	Low	Very Low	

Note: **A** → Table taken from AFI 48-307 Vol 1, 9 January 2017, page 241. US government product not subject to copyright. **B** → Table courtesy Lieutenant Colonel Christopher Cieurzo, Chief, Patient Movement Operations Division, TRANSCOM. US government product not subject to copyright. Hr(s) (hour[s]), FL350 (Flight Level 350 (35,000 feet)).

4.4.2 Countermeasures

Hyperthermia

With high ambient temperatures during the on-loading and off-loading of patients, overheating can be countered with cool water misting and cool, moist dressings. In addition, oral and/or IV hydration with cool fluids can be prescribed, not to mention increasing respiratory rate settings on ventilated patients. (**Blumen, 1995**) Importantly, high ambient temperatures dissipate rapidly with take-off and must be kept in mind to avoid subsequent evaporative hypothermia.

Hypothermia

Heat is lost in four ways: radiation (body heat moving into the cool cabin environment), conduction (direct loss of heat to cool litter and litter pad), convection (heat loss as cool air flows across the patient), and evaporation (heat lost insensibly from low humidity). Moreover, sedatives, narcotics, and neuromuscular blocking agents, all frequently employed during AE, predispose patients for heat loss. (**Fiege, 1996; Walsh, 1998; Schmelz, 2007**) In fact, a heat loss exceeding 0.5 C results in hypothalamic-mediated vasoconstriction, shivering, and metabolic thermogenesis. (**Feige, 1996**)

To counter heat loss, both passive and active measures must be considered. Passive measures prevent further heat loss, allowing the body's metabolism to generate the requisite heat. Among such measures are insulating blankets and reflective blankets. Active measures generate heat for transfer to the body by internal or external means. External active heating includes heated air from the aircraft's environmental control system, warmed insulating blankets, and exothermic heating pads. Internal active heating includes warmed IV fluids and warm, humidified air via ventilators. (**Blumen, 1995; Fiege, 1996; Walsh, 1998; Dufour, 2003; Schmelz, 2007**)

Probably best is some combination of passive, external active, and internal active heating. With a swine model, placed for 6 hours in an environmental chamber at 50 F with airflow of 0.2 m/sec, Schmelz et al found that the group using the active external warming Chillbuster™ blanket combined with a passive reflective blanket remained warm, while the groups using either the Chillbuster™ warming blanket or wool blanket developed mild hypothermia. (**Schmelz, 2007**) Along the same lines, Bridges et al employed a hemorrhagic shock swine model where resuscitation with Hextend™ at 50 F, mimicking field conditions (120 minutes), was followed with transfusion, mimicking field hospital conditions (180 minutes). One group had only blankets, another group was wrapped with the passive baffled reflective Blizzard Blanket™, and a third group was wrapped with the passive warming baffled reflective Blizzard Blanket™ and transfused with the active internal warming Thermal Angel™, a battery-powered IV warmer. The combination of passive Blizzard Blanket™ and active internal Thermal Angel™ proved best. (**Bridges, 2007**) Recently, Army research has had some success with the active external warming of forced-air blankets. (**Wang, 2020**)

Thus, warmed blankets (active external warming), reflective blankets (passive warming), warmed IVs (active internal warming) make great sense. In addition, warmed ventilator air and aircraft environmental system adjustments to up cabin warmth are indicated. **Table 1** lists the various countermeasures.

4.5 High Levels of Noise

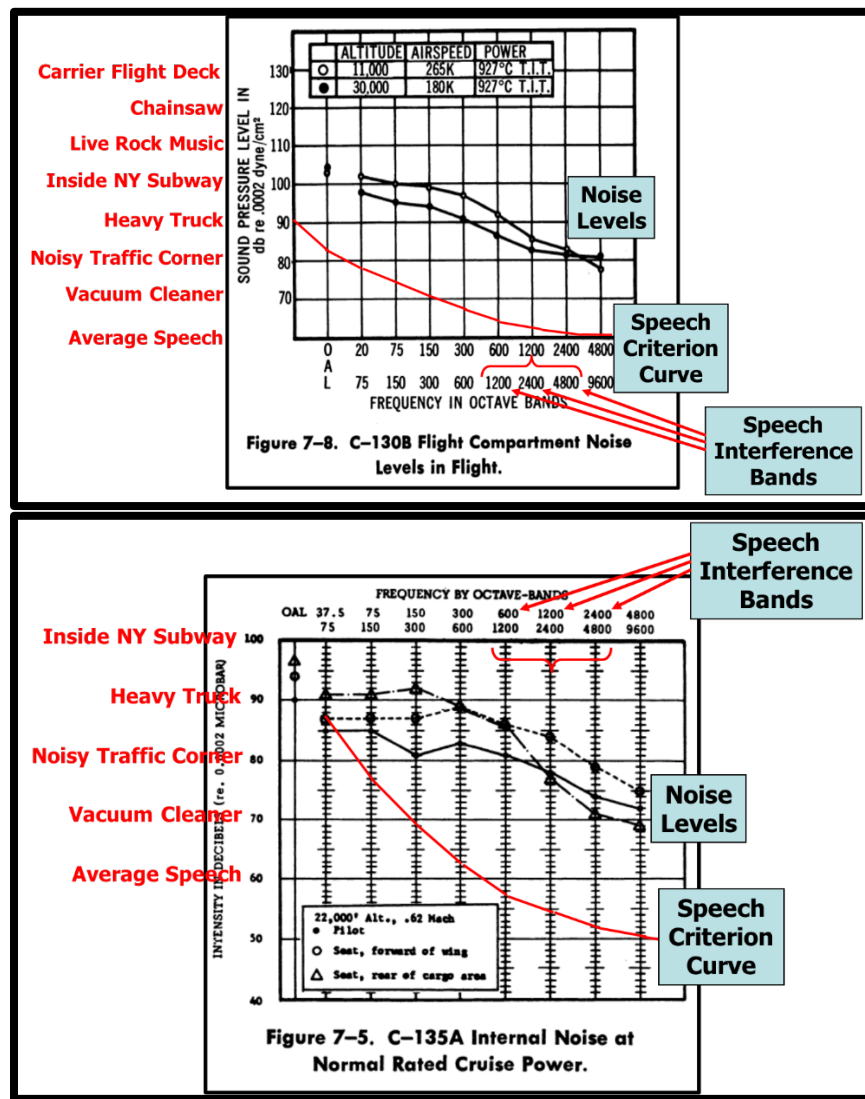
4.5.1 Description

Noise is ubiquitous across the flightline. All aircraft produce noise. However, military aircraft, with less shielding, are generally noisier than commercial aircraft. (AFI 48-307 Vol 1, 2017) As a result, there is a higher likelihood of interference with hearing thresholds, rest and sleep, as well as communication. (AFP 161-18, 1968) In fact, it has been shown that simulated military aircraft noise can have both physiological and performance impacts on CCATT nurses, specifically an increase in respiratory rate and decrease in critical care scores (i.e., increased errors and omissions). (McNeill, 2018)

The noise originates mainly from the engines and aerodynamic friction, and, to a lesser extent, airflow within the cabin. Aerodynamic friction (boundary turbulence between the aircraft skin and atmosphere) predominates at the nose of the aircraft, engine operation and aerodynamic friction in front of the wing, and engine exhaust and aerodynamic friction behind the wing. (Ozcan, 2006; AFI 48-307 Vol 1, 2017; Zevitas, 2018)

There are five phases to a mission --- enplaning, take-off, cruise, landing, and deplaning. As expected, the take-off, cruise, and landing are loudest. Depending on the model, commercial airliners' take-off noise averages around 78-86 decibels (dB), peaking as high as > 110 dB; landing averages around 76-85 dB, again peaking as high as > 110 dB. Fortunately, both take-off and landing persist for just minutes; whereas, cruise can last for hours. Commercial cruise noise averages around 78-83 dB, peaking as high as > 110 dB. (Ozcan, 2006; Zevitas, 2018)

As patients generally experience, at most, only a few take-offs and landings, it is cruise noise that has greatest import. Noise data on the three primary AE aircraft are limited. Although the C-17 sound level during cruise is claimed to be 86 dB, there is no readily available data. (McNeill, 2018) With the C-130 and the KC-135 sound levels are better documented, the C-130 ranging 80-100 dB across frequency bands, while the KC-135 ranges 70-90 dB. Interestingly, noise levels at the cabin periphery may be as much as 6 dB higher than at its center. (AFP 161-18, 1968; Rood, 2016) See Figure 6.



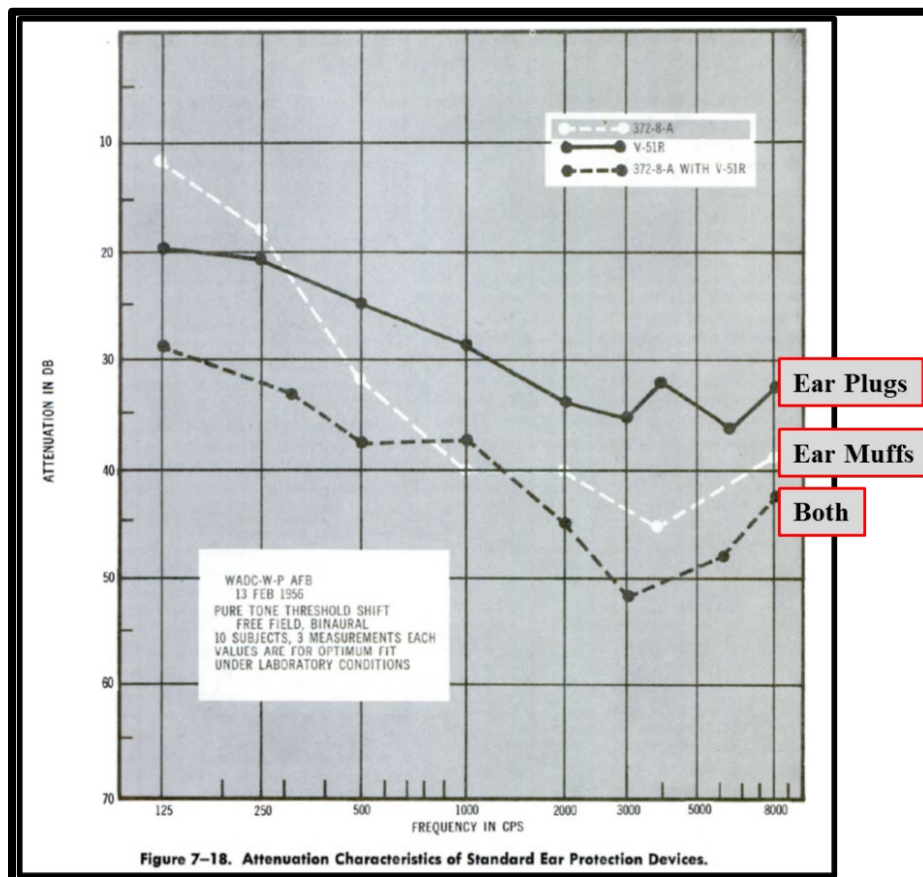
Note: Graphics taken from AFP 161-18 (1968), pages 7-7 and 7-8. Speech Interference Bands and Speech Criterion Curve created by and courtesy of Lt Col Daniel Cole (USAFR, MC, FS). The Speech Criterion Curves (aka sound/speech perception thresholds) are drawn based on depictions found in the literature. (Fletcher, 1933; Quam, 2012; Blamey, 2015) US government product not subject to copyright.

Figure 6. Sound Level Distribution Across Frequency Bands for the C-130 and KC-135

The Occupational Safety and Health Administration defines the action level for sound as 85 dB over an 8-hour time-weighted-average. (Zevitas, 2018) Without protection, the individual is at risk of auditory damage and hearing loss. Many AE patients, particularly those critically ill, are unable to protect themselves. At the same time, hearing protection is not necessarily a high clinical priority for the AE crew. As a result, the TVFS must be cognizant of this risk for patient flying near or in excess of 8 hours cruise. This is certainly a potential issue for long-haul flights originating in the Pacific, Africa, and Europe.

4.5.2. Countermeasures

Measures to reduce noise exposure are limited. However, as long as the noise levels drop below 75-80 dB, risk of hearing loss/deafness does not appear heightened. (Rood, 2016) To mitigate the risk, there are essentially only two interventions open to the TVFS, ear plugs and ear muffs. (AFP 161-18, 1968; Blumen, 1995; Dufour, 2003) Either measure offers up a ~10-40 dB level of protection. Used together, they deliver ~30-50 dB of protection. (AFP 161-18, 1968) See Figure 7. A patient undergoing an extended AE of 8⁺ hours should be prescribed hearing protection. Table 1 lists the various countermeasures.



Note: Graphic taken from AFP 161-18 (1968), page 7-13. US government product not subject to copyright. DB (decibels), CPS (cycles per second).

Figure 7. Noise Attenuation Afforded by Ear Plugs and/or Ear Muffs

4.6 Vibration

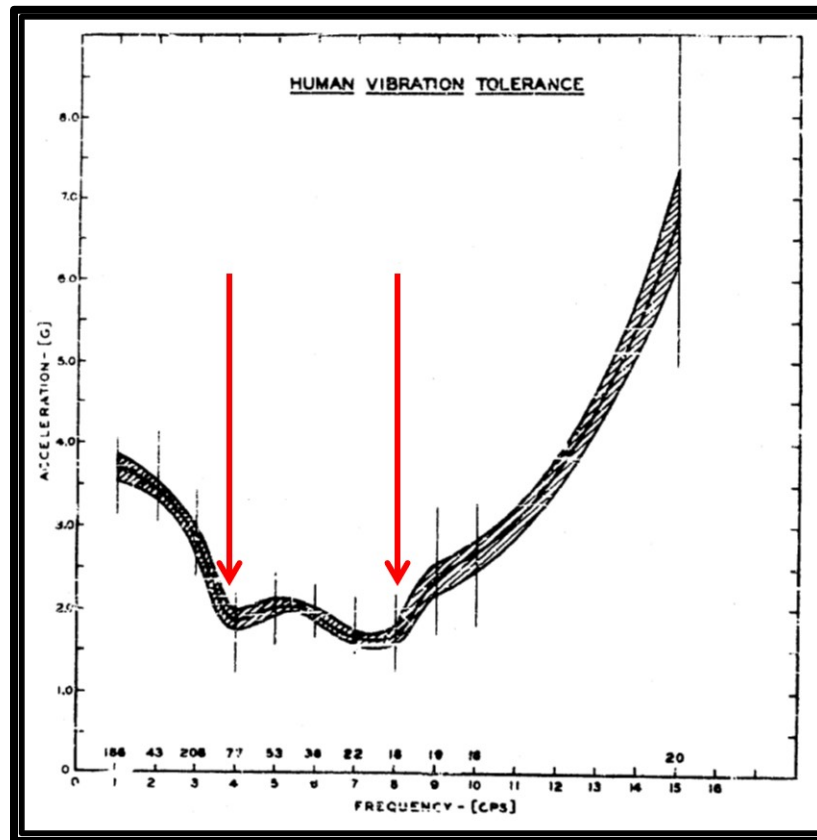
4.6.1. Description

Vibration is inherent to fixed-wing, motorized air travel. It is an oscillatory motion characterized by frequency (oscillations or cycles per second or Hertz [Hz]) and amplitude (oscillation excursion distance over a single cycle of oscillation [meters [m]]). Vibration can be focused in any of three linear and/or angular directions. Linear bearings consist of G_x , G_y , and G_z , while angular tracks are roll, pitch, and yaw. Vibration is best transmitted by direct contact with the vibrating source (e.g., direct contact with the aircraft cabin). It can be resonated (i.e., amplified) when transmitted into a substance that complements the frequency and magnifies the amplitude. On the other hand, it can be damped (i.e., checked) when transmitted into a substance that inhibits the frequency and diminishes the amplitude. With air travel, the most common sources of vibration are the engines and the environment. **(Blumen, 1995; Dufour, 2003; Hopcroft, 2005; Stott, 2016; AFI 48-307 Vol 1, 2017)**

Jet engines generate high frequency vibration as do propeller engines; whereas, the environmental, aerodynamic forces produce lower frequency vibration. Peak inflight vibration of take-off and landing is short-lived, originating from the engines, while the much longer inflight cruise vibration is sourced predominately from the cabin-environment interface. **(Magid, 1960; MIL-STD-810Cw/Change 1, 2014)** As such, it is cruise vibration (lower frequencies) that is of greatest concern for AE patients.

Propeller engines operate at a frequency of around 100 Hz, while single stage and dual stage jets operate at around 130 Hz and 230 Hz, respectively. **(Gibson, 2010)** More specifically, the C-130, a propeller-driven cargo aircraft, appears to vibrate in the 15-500 Hz range with peaks, depending on the model, at 16 Hz, 68 Hz, and 100 Hz. At the fuselage side-wall adjacent to the propellers, vibration has been measured at 220 Hz. **(Thomas, 1962; Smith, 2002; Hopcroft, 2005; Smith, 2006)** In addition, both the C-17 and the KC-135 jet-driven cargo aircraft appear to vibrate in the 10-1,000⁺ Hz range with peaks ranging between 100-800 Hz. **(MIL-STD-810Cw/Change 1, 2014)** Notably, vibration intensity drops as distance from the engines increase, whether moving fore, aft, or center. **(Thomas, 1962)**

When it comes to vibration effects on the human, the lower end of these aircraft vibration profiles certainly offer up the potential for physiological impact. Indeed, the human is least tolerant of vibration between 4-8 Hz. **(Ziegenruecker, 1959; Magid, 1960; Stott, 2016)** See **Figure 8**.



Note: Graphic taken from Ziegenruecker & Magid, July 1959, Aeromedical Report 59-391 (DTIC 227341), page 7. US government product not subject to copyright. CPS (cycles per second).

Figure 8. Frequency Range for “Least” Human Vibration Tolerance

Within this range of frequencies, various tissues can resonate and produce resultant symptoms. With higher frequencies, there is an increasing tolerance that is unless the amplitude of the vibration rises. In that setting, physiological impact is possible. (Shoenberger, 1972)

For a seated human, two vibration peaks appear relevant. The first is 3-5 Hz which affects both the head and shoulder girdle, the latter being most affected. At the same time, a second peak is seen at 11-15 Hz; in this instance the former is most affected. For a supine human, above 10 Hz, the head is most affected. (Stott, 2016) See **Table 3** for specific vibration frequency effects.

Table 3. Physiological Effects of Various Vibration Frequencies

Vibration Impact on the Human Body				
Body Region	Symptoms	Frequency (resonant)	Comment	Reference
Eye	Eye Eye	40Hz 60-90 Hz 10-25 Hz 20-40 Hz; 60-90 Hz	resonant frequency resonant frequency blurring blurring	AFP 161-18, 1968 Hopcroft, 2005 Hopcroft, 2005 Stott, 2016
Head-Neck	Head Head Head -- Head sensations -- Pharynx -- Jaw -- Phonation	30 Hz > 10 Hz 12-15 Hz 13-20 Hz 12-16 Hz 6-8 Hz 13-20 Hz	resonant frequency resonant frequency (supine) resonant frequency (seated) dull, aching; congested feeling dull, aching; congested feeling thoracoabdomino-mechanical dysjunction; laryngeal transmission	Hopcroft, 2005 Stott, 2016 Stott, 2016 Magid, 1960 Magid, 1960 Magid, 1960 Magid, 1960
Maximum Tolerance	Head Pain	4-10 Hz	dull, aching pain	Magid, 1960
Thorax	Thorax Heart & Lungs -- Upper Trunk -- Sternum -- Respiration -- Dyspnea -- Pain -- Valsalva Maneuver	10-12 Hz 3-8 Hz 4-5 Hz 8 Hz 4-8 Hz 1-4 Hz 5-9 Hz 4.5-10 Hz	resonant frequency resonant frequency resonant frequency (seated) resonant frequency (supine) chest motion interference chest motion impaired precordial pain performed reflex-like	Hopcroft, 2005 Carchietti, 2013 Stott, 2017 Magid, 1960; Hopcroft, 2005 Magid, 1960 Magid, 1960 Magid, 1960 Magid, 1960
Maximum Tolerance	Chest Pain Dyspnea	3-9 Hz 1-4 Hz	precordial/substernal/across chest chest motion impaired	Magid, 1960 Magid, 1960
Abdomen	Abdomen Abdomen Organs	4-8 Hz 8 Hz 5-10 Hz 4.5-9 Hz 4.5-10 Hz	resonant frequency resonant frequency (supine) resonant frequency maximum voluntary contraction umbilical/RUQ	Hopcroft, 2005 Stott, 2016 Carchietti, 2013 Magid, 1960 Magid, 1960 Magid, 1960
Maximum Tolerance	Abdominal Pain	3-9 Hz	umbilical/RUQ pain	Magid, 1960
Pelvis	urge to micturate urge to defecate back pain	10-18 Hz 10.5-16 Hz 8-12 Hz	severe urge severe urge lumbosacral	Magid, 1960 Magid, 1960 Magid, 1960 Magid, 1960
Maximum Tolerance	Testicular Pain	7-10 Hz	colicky/groin centric	Magid, 1960
Musculo-skeletal	Shoulder Girdle Knee	4-5 Hz 8 Hz 13-20 Hz	resonant frequency (seated) resonant frequency (supine) involuntary tightening (lower extremities, back neck, head)	Stott, 2016 Stott, 2016 Magid, 1960
Maximum Tolerance	reflex contraction edema	20-100 Hz 30-50 Hz	Tonic Vibration Reflex leg edema	Stott, 2016 Mittermayr, 2003
General Discomfort	ill-defined discomfort	4.5-8 Hz		Magid, 1959
Maximum Tolerance	ill-defined discomfort	1-10 Hz	muscles, joints, thorax, abdomen	Magid, 1960
Anxiety				
-- Motion Sickness		< 0.5-1.0 Hz		Hopcroft, 2005; Stott, 2016
Maximum Tolerance		3-10 Hz		Magid, 1960
Physiologic	injury interface friction muscle contraction clot fluidization muscle contraction	26-54 Hz 10-50 Hz 50-100 Hz 10-50 Hz	helicopter vibration upped venous return physicochemical deconstruction whole body vibration exercise	Carchietti, 2013 Carchietti, 2013 Carchietti, 2013 Cardinale, 2005; Carchietti, 2013 Stott, 2016
-- Muscle Activity	increased	20-50 Hz	akin to gentle exercise	Cardinale, 2005; Cardinale, 2006; Yasar-Fisher, 2014; Stott, 2016; Wollersheim, 2017
-- Metabolic Rate				Stott, 2016
-- Respiratory Rate	hyperventilation	variable	mild drop in P _a CO ₂	Stott, 2016
-- Tonic Vibration Reflex	muscle contraction	20-100 Hz		Cardinale, 2006; Stott, 2016

Note: RUQ (right upper quadrant), Hz (Hertz, cycles per second), PaCO₂ (arterial partial pressure of carbon dioxide).

Relevant to AE, vibration also has a number of specific effects on a patient, among them pain, bleeding, muscle contraction, metabolic activity, and tissue edema. Whole body vibration of any injury will move discontinuous (aka injured) tissues stimulating pain receptors. The most obvious such tissues are fractured bones. Indeed, because bone is of high mass and stiffness, it resonates at lower frequencies, those most commonly seen during the cruise phase of an AE flight. In addition, vibration, especially at frequencies between 50-100 Hz, will promote physicochemical deconstruction of organic compounds such as clots (aka “fluidization” of clots), the result bleeding. (Carchietti, 2013) Muscles are also activated, contracting as in gentle exercise, producing both an increase in venous return which can potentially up bleeding and an increase in metabolic activity accompanied by a rise in oxygen consumption, carbon dioxide production, and energy expenditure. (Cardinale, 2005; Cardinale, 2006; Yarar-Fisher, 2014; Wollersheim, 2017) This muscle activation is akin to exercise which, when conjoined to altitude, has an exacerbative effect on the expected drop in both SpO₂ (hemoglobin saturation with oxygen as measured by pulse oximetry) and PaO₂ (arterial oxygen partial pressure). (Schacke, 2007; Martin, 2015) Lastly, vibration has been associated with the development of tissue edema, the exact mechanism as yet undetermined. (Lundborg, 1987; Mittermayr, 2003)

4.6.2. Countermeasures

The natural human counter to vibration consists of contracting muscle and osteoarticular stiffening. In other words, an intact Tonic Vibration Reflex damps the effect of 10-100 Hz vibration. (Carchietti, 2013) For most patients, this is enough. However, for those critically ill patients, maybe not. Often, the critically ill are being ventilated under neuromuscular blockade which effectively abrogates the Tonic Vibration Reflex, eliminating its damping effect. (Carchietti, 2013) The result may well be an amplifying of resonant frequency effects. (Stott, 2016) For instance, a head injury may experience a physiological *second hit* with 12-15 Hz vibrations. A clotted, pain-free stabilized fracture may see renewed bleeding and pain around 50-100 Hz. An upped need for oxygen (vibration-activated muscle) and a drop in its diffusivity (vibration-induced tissue edema) may be found at 10-50 Hz.

A number of imperfect damping interventions are available to the TVFS. One relatively easy prescription is to position the patient away from the engines and the cabin wall, the farther the better. In other words, center the patient in the cabin as far forward or aft of the engines as feasible. (Dufour, 2003)

Another means of damping is to isolate the patient from the vibration, suspending the patient away from the cabin walls. (Stott, 2016) Floating the patient on an air-bead mattress is impracticable, but suspending the patient hammock-like is partially doable. The C-130 litter stanchions are designed to have a fixed attachment on one side and a strap suspension attachment on the other. Although both are fixed to the cabin wall, neither is an ideal vibration transmitter, especially the strap which dampens better than transmits. Preferentially prescribing a C-130 is possible intratheater, but intertheater is problematic. As a result, patient isolation techniques are generally not readily available.

Much more practical is litter cushioning. (Blumen, 1995; Dufour, 2003) Standard cushions provide some damping; however, contoured cushions, jelly (gel) cushions, and air cushions are much preferred. In fact, air cushions have been shown to have the greatest damping effect, especially above 6-8 Hz. (Smith, 2010; Wright, 2010) See Figure 9. However, despite an air cushion’s damping effect, its Boyle’s Law response presents issues. At altitude air

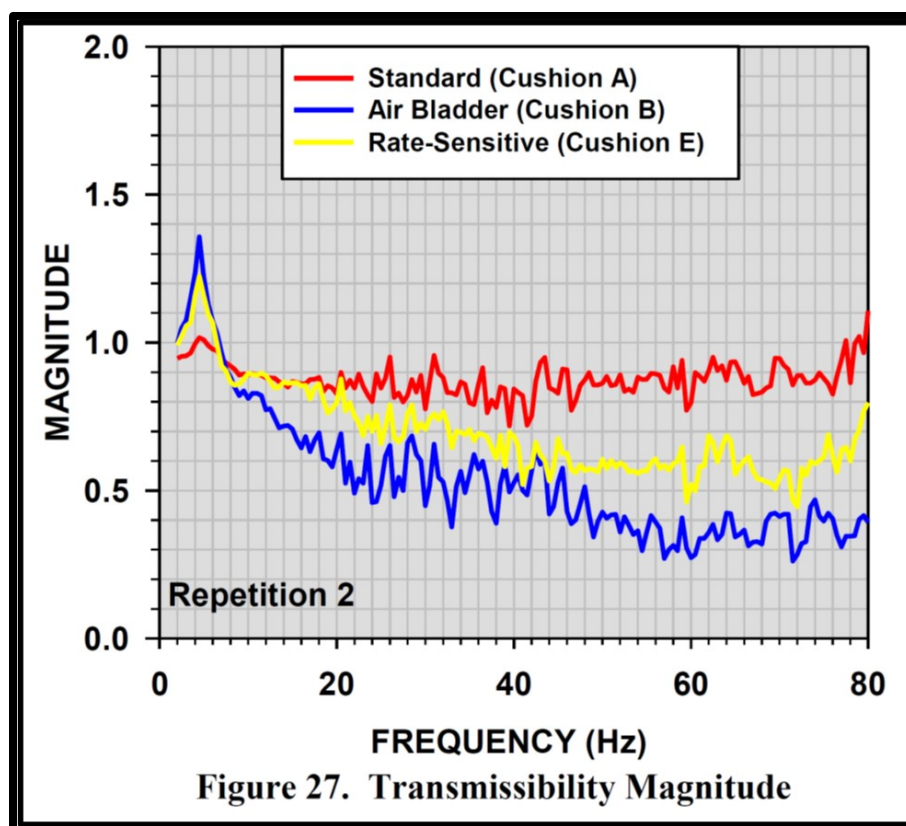
cushions expand and, if manufactured with baffles, expand unevenly and, if subjected to a rapid decompression, blow up massively and asymmetrically. (unpublished research, personal communication, L. Michelle Bryce, DO, MTM&H). In such a setting, a pelvic fracture or femur fracture or spinal injury could be seriously exacerbated.

To date, no specifically designed vibration-damping AE litter cushion is readily available. However, inquiry is ongoing. Vibration-mitigating litter research is actively underway by the Army with its Aeromedical Stabilization & Evacuation System.

(<https://techshot.com/defense/program/aeromedical-evacuation-stabilization-system/>)

Concurrently, the Air Force is also evaluating the level of human spine immobilization, within a vibrating environment, of the standard litter, the Stryker Wedge Turning Frame, the Vacuum Spine Board, and the Aeromedical Transport Litter for Immobilization and Stabilization.

(Dooley, 2020) Findings from such research will undoubtedly contribute to the development of vibration-mitigating litter cushions/systems.



Note: Graphic taken from Wright et al, January 2010, AFRL-RH-WP-TR-2010-0083, page 36. US government product not subject to copyright. Hz (Hertz, cycles per second).

Figure 9. Damping Effect of Cushions on Vibration

Lastly, non-damping prescriptions, such as an upped analgesic dosing for anticipated inflight pain exacerbation and aircraft routing to maximize clear air and minimize turbulent air, should be considered.

Thus, the best options, at this time, for the TVFS are patient position (e.g., center cabin, far forward or aft of the engines) and extra litter padding (e.g., an extra standard litter cushion and/or extra underlying blankets). As for vibration-mediated edema, there are no countermeasures currently available. **Table 1** lists the various countermeasures.

4.7 Hypobaria

Hypobaria or less than ground equivalent barometric pressure has three primary flight stressor effects: Boyle's Law Effects, Venous Gas Emboli Effects, and Altered Tissue Dynamics Effects.

4.7.1. Boyle's Law Effects

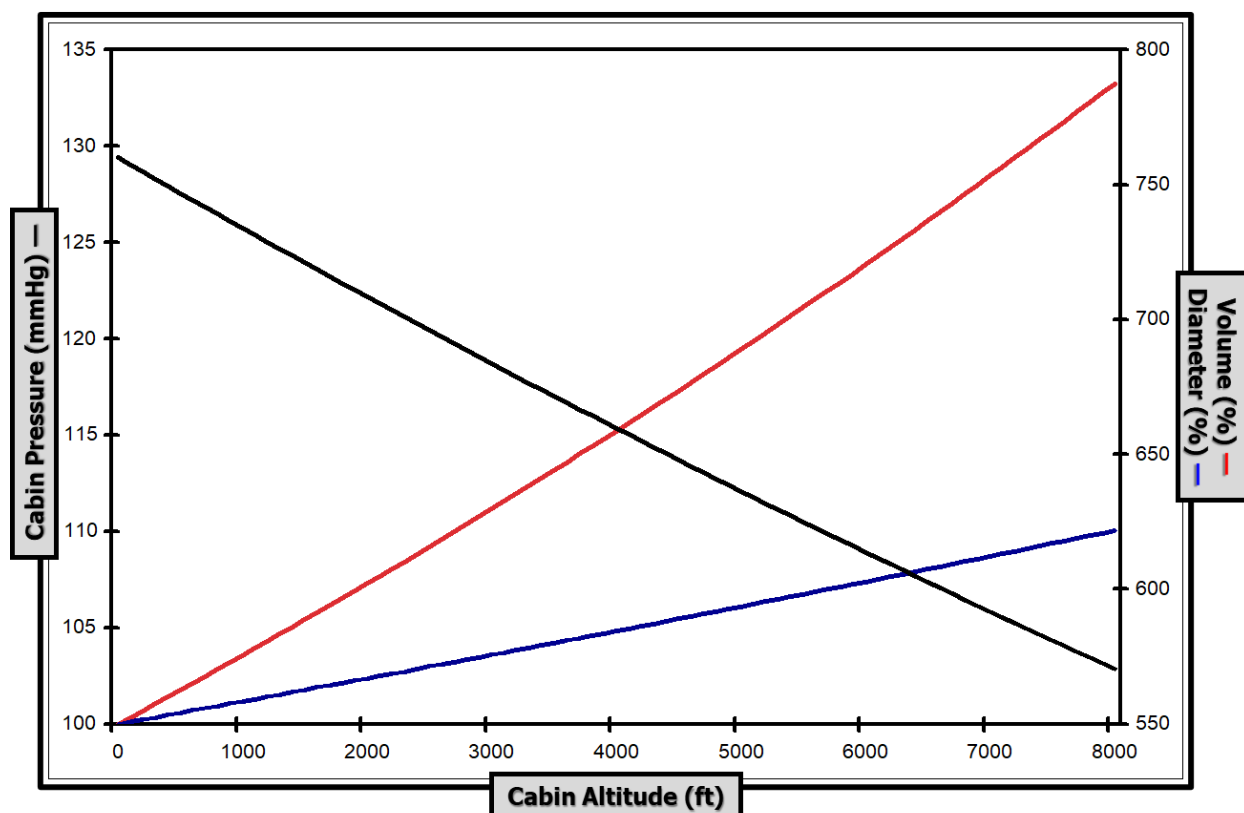
Boyle's Law refers to the physical relationship, a linear inverse relationship, between the pressure and volume of a fixed mass of gas, while at the same time keeping the temperature constant. It is best expressed by the following formula,

$$P_1 * V_1 = P_2 * V_2 , \quad (1)$$

where P_1 is the initial pressure, P_2 is the final pressure, V_1 is the initial volume, and V_2 is the final volume. (**Gradwell, 2016a**) This relationship can be graphically expressed as well. See **Figure 8**. Assuming the gas is configured in the form of a "bubble" (aka sphere), the diameter of the bubble also changes in relation to the pressure, just not as rapidly. This is best expressed by

$$V = 4/3 \pi r^3 , \quad (2)$$

where V is volume, $\pi = 3.14$, and r is the bubble radius. (**Edmonds, 2016**) See **Figure 10**.



Note: Graphic created by and courtesy of Lt Col Daniel Cole. (USAFR, MC, FS). mmHg (millimeters mercury pressure), % (percent), ft (feet).

Figure 10. Pressure-Volume-Diameter Relationships with Increasing Altitude

These pressure-volume-diameter relationships come into play when air, trapped in a physiologic space, undergoes a change in pressure. The result can be barotrauma. With descent, ambient pressure rises squeezing the trapped air. Without a means of equalizing the trapped air space to ambient pressure, a relative vacuum is created, producing engorged mucous membranes, eventual tissue rupture, and bleeding. Examples include middle ear and sinus squeeze barotrauma. With ascent, ambient pressure drops and trapped air expands. Without an outlet for the extra volume, pressure is exerted on tissues and perfusion impaired. With an abnormal outlet, trapped air can track into unusual locations. Examples include pneumocephalus and pneumomediastinum. A variety of equalization techniques --- Valsalva, Frenzel, Toynbee, Lowry, Edmonds --- offer barotrauma prevention/relief. (**Edmonds, 2016**)

For AE patients, barotrauma can happen as mentioned above, but, more likely, can result from abnormally retained air found with trauma, surgery, neoplasm, and/or gas-producing infections. Such abnormal air collections --- pneumocephalus, pneumothorax, pneumomediastinum, pneumopericardium, pneumoperitoneum, and pneumatosis oculi --- must be addressed by the TVFS. But, before looking at each of these entities individually, it is appropriate to focus on what happens to the trapped air.

Generally, left to itself, air within tissue will undergo uneventful resorption. Trapped air (aka “bubble”) is predominantly made up of nitrogen, followed by oxygen, water vapor, and

carbon dioxide. In fact, nitrogen, for all intents and purposes, drives the “bubble” existence. Indeed, nitrogen gradually dissipates into the blood and tissue along its natural low-grade pressure gradient with the excess, non-equilibrated nitrogen excreted from the lungs. At the same time, water vapor and carbon dioxide essentially equalize across the trapped gas, blood, and tissue; whereas, oxygen, highly metabolic, is consumed by the blood and tissues. As oxygen rapidly moves from the “bubble” to venous blood, the “bubble” volume drops and the surrounding tissue recoils. That, conjoined with the surrounding ambient pressure, returns the “bubble” to ambient pressure levels. The process then repeats itself. See **Table 4**. As a result, the “bubble” gradually shrinks until surface tension and surrounding tissue pressure force its collapse. (**Henderson, 1932; Edmonds, 2016**) Although gas pressures dominate this process, other factors include gas solubilities, tissue perfusion, and surface area involvement. (**Chadha, 1983**)

Table 4. Trapped Air Resorption Gradients

Trapped Air Resorption					
Gases	Trapped Air Pressures (mm Hg)	Breathing Air (mm Hg)			
		Arterial Pressures (mmHg)	Venous Pressures (mmHg)	Tissue Pressures (mmHg)	Trapped Gas Moves Into
Oxygen (O ₂)	158	95	40	30	arterial/venous/tissue
Nitrogen (N ₂)	596	573	573	573	arterial/venous/tissue
Water Vapor (H ₂ O)	5.7	47	47	47	equilibrium
Carbon Dioxide (CO ₂)	0.3	40	46	46	equilibrium
	760			696	
Gases	Trapped Air Pressures (mm Hg)	Breathing 100% Oxygen (mm Hg)			
		Arterial Pressures (mmHg)	Venous Pressures (mmHg)	Tissue Pressures (mmHg)	Trapped Gas Moves Into
Oxygen (O ₂)	158	636	54	30	venous/tissue
Nitrogen (N ₂)	596	0	0	573	arterial/venous/tissue
Water Vapor (H ₂ O)	5.7	47	47	47	equilibrium
Carbon Dioxide (CO ₂)	0.3	40	46	46	equilibrium
	760			696	

Note: Table derived from data presented by Addis, Chadha and Cohn, Ivezic et al, and Edmonds et al. (**Addis, 1965; Chadha, 1983; Ivezic, 2006; Edmonds, 2016**). mmHg (millimeters mercury pressure).

Breathing 100% oxygen accelerates “bubble” resorption. The nitrogen gradient, now very steep, forces nitrogen to rapidly move from both the “bubble” and tissues into the blood; the excess, again, excreted from the lungs. Water vapor and carbon dioxide equilibrate while tissue continues consuming any oxygen, whether it be from the “bubble” or the blood. As a result, the “bubble” collapses and disappears much more quickly. See **Table 4**. (**Edmonds, 2016**)

The time needed for “bubble” resorption varies, to some degree, as to the location affected as well as the gas involved. As a TVFS, having a grip on this sort of information permits a data-driven decision as to the “when” and “how” to transport a patient with trapped air. See **Table 5**.

So, with this introduction, it is possible to examine each of the following abnormal air collections --- pneumocephalus, pneumothorax, pneumomediastinum, pneumopericardium, pneumoperitoneum, and pneumatosis oculi --- and offer up specific prescriptions with which the TVFS can counter their effects during an AE flight.

Table 5. Tissue-Trapped-Air Resorption Times

Tissue-Trapped-Air Resorption Times			
Tissue	Time (days)	Comment	Reference
Pneumocephalus			
--- subarachnoid	1	pneumoencephalogram 20-120 ml [avg = ~30 ml]	Tondreau, 1985
--- subarachnoid	1	pneumoencephalogram	Davidoff, 1951
--- intraventricular	2-3	pneumoencephalogram "few days"	Dandy, 1919
--- intraventricular/subdural	1	50% air resorbed	Davidoff, 1951
	2	67% air resorbed	
	3	75% air resorbed	
--- unspecified	7	85% of cases	Goldman, 1986; Chan, 2000; Tran, 2010; Javan, 2011
--- unspecified	7-14	85% of cases	Dabdoub, 2015
--- unspecified	14-21	< 2 ml may persist 1-2 wks	Ani, 2016
--- unspecified	21	up to 25% of cases persist 3 wks	Donovan, 2008
--- unspecified	21	post-surgery air may persist 3 wks	Willson, 2014
--- oxygen treated (68%) [24 hrs O ₂]	reduced	65% drop vs 31% in 24 hrs 1.4 ml/hr w/ O ₂ vs 0.7 ml/hr	Gore, 2008 (PCT)
--- oxygen treated (100%) [3 hrs O ₂]	reduced	81% drop vs 68% in 24 hrs 3.6 ml/hr w/ O ₂ vs 2.9 ml/hr	Hong, 2015 (PRCT)
Pneumothorax			
--- room air (bedrest)	---	1.25%/day*	Kircher, 1954
--- room air (outpatient)	---	1.8%/day***	Flint, 1984
--- room air (outpatient)	---	2.2%/day**	Kelly, 2006b
--- oxygen treated (50-60%) [continuous O ₂]	2 3-4	minimal pneumothorax ~ 25% pneumothorax	Panjwani, 2017
--- oxygen treated (bedrest) [2-4 L/min, continuous O ₂]	---	4.3%/day** [Room Air = 2.1%/day]	Park, 2017
--- oxygen treated (100%) [rebreather, continuous O ₂]	3	4.2%/day* [range = 1.5%/day-8.3%/day]	Chadha, 1983
Pneumomediastinum			
--- room air (bedrest)	2	3x faster with O ₂	Putukian, 2004
--- room air (bedrest)	1-7	pneumomediastinum in Israeli pilots	Grossman, 2005
--- room air (bedrest)	2-4		Morgan, 2007; Szymanski, 2010
--- oxygen treated (bedrest)	---	6x faster with O ₂	Kouritas, 2015
Pneumopericardium			
--- room air (bedrest)	3	case report	Hamp, 2015
--- room air (outpatient)	7	case report	Sherrier, 2020
--- room air (bedrest)	8	case report	Mishra, 2016
--- oxygen treated (40-50%)	2	case report	Levin, 1996
Pneumoperitoneum			
--- room air (laparotomy) [children: 2 days to 8 years old] [x-rays]	1	19/19 (100%) cleared	Hope, 1958
--- room air (herniorrhaphy) [children: 8 wks to 8 years old] [x-rays]	2	9/12 (75%) cleared [10-110 ml air injected at closure]	
--- room air (appendectomy) [children: 4-16 years old] [x-rays]	5	46/46 (100%) cleared [60 ml air injected at closure] hrs to resorption = 69.72 + 3.96*(age - 11.52)	Svartholm, 1969
--- room air (laparotomy) [CT scans]	3	13% cleared (max 5.8 ml)	Earls, 1993
	6	50% cleared (max 3.1 ml)	
--- room air (laparotomy) [CT scans]	1-3	53% cleared (mean = 7.5 ml)	Gayer, 2000
	4-7	69% cleared (mean = 4.0 ml)	
	8-18	70% cleared (mean = 1.2 ml)	
--- room air (laparotomy) [CT scans]	0-3	0% cleared (mean = 29 ml)	Malgras, 2017
	0-5	19% cleared (mean = 22 ml)	
	6-15	59% cleared (mean = 5 ml)	
	≥ 16	90% cleared (mean = 7 ml)	
Pneumotosis oculi			
--- perfluoromethane (CF ₄)	---	t _{1/2} = 1 days ---- human = up 3-5x	Lincoff, 1984 [New Zealand red rabbit model]
--- perfluoroethane (C ₂ F ₆)	---	t _{1/2} = 2 days ---- human = up 3-5x	
--- perfluoropropane (C ₃ F ₈)	---	t _{1/2} = 6 days ---- human = up 3-5x	
--- perfluoro- <i>n</i> -butane (C ₄ F ₁₀)	---	t _{1/2} = 12 days ---- human = up 3-5x	
--- room air	7	17% bubble (1 ml)	Ivan, 2003
--- xenon (Xe)	1-2	17% bubble (1 ml)	
--- sulfur hexafluoride (SF ₆)	10-14	17% bubble (1 ml)	
--- perfluorocarbon gases (C _n F _n)	10-65	17% bubble (1 ml)	Alvarez, 2003
--- sulfur hexafluoride (SF ₆)	14	AsMA Guideline (time to < 30% bubble)	
--- perfluoropropane (C ₃ F ₈)	42	AsMA Guideline (time to < 30% bubble)	
--- sulfur hexafluoride (SF ₆)	13-24	18 ± 2.9 days (30% bubble)	Kontos, 2017; Kanclerz, 2018
--- hexafluoroethane (C ₂ F ₆)	28-44	34.5 ± 3.3 days (20% bubble)	
--- perfluoropropane (C ₃ F ₈)	59-79	67.7 ± 5.5 days (15% bubble)	
--- perfluoroethane [100% O ₂ treated]		albino rabbit model no effect on resorption or volume	Lincoff, 1989b

Note: *Denotes area-based two-rectangle estimate of pneumothorax size (Kircher, 1954); **Denotes volume-based estimate of pneumothorax size (Collins, 1995); ***Denotes an undefined technique for estimating pneumothorax size.

Note: In detecting pneumothoraces, as compared to the gold standard chest CT scan, the supine chest x-ray (50% sensitivity) is less sensitive than the upright chest x-ray (92% sensitivity) is less sensitive than the ultrasound (92-100% sensitivity). (Ball, 2009a)

Note: avg (average), % (percent), ml (milliliter), wk (week), hr (hour), w/ (with), O₂ (oxygen), PCT (prospective controlled trial), PRCT (prospective randomized controlled trial), L (liter), min (minute), CT (computed tomography), t_{1/2} (half-life).

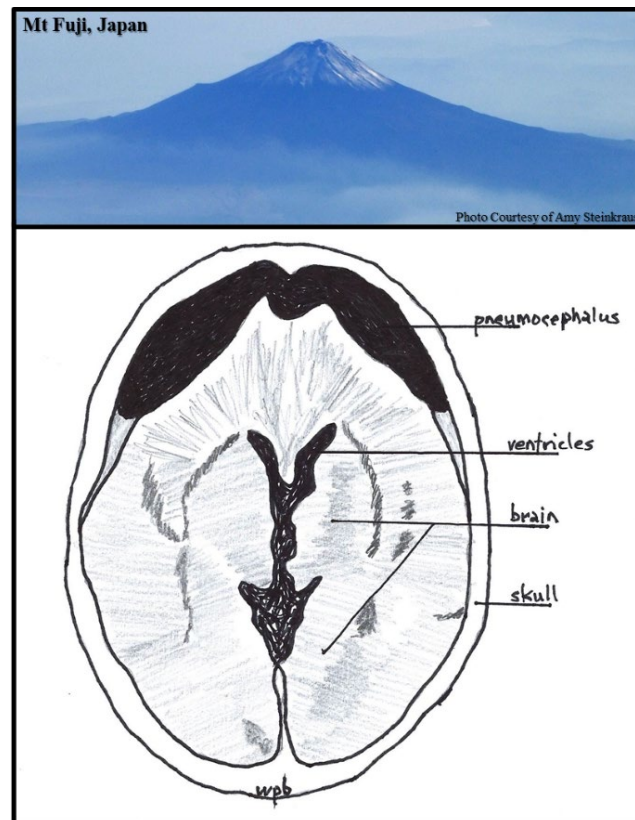
4.7.1.1A *Pneumocephalus Description*

Pneumocephalus can result from direct barotrauma whether it be diving or flying. Most commonly, there is an associated bony defect within the sphenoid sinus, the tegmen tympani, petro-squamous suture, or along the superior semicircular canal. (**Canavan, 1991; Chan, 2000; Jensen, 2004; Cortes, 2005; Budal, 2011; Zeba, 2010; Remenschneider, 2013**) Failed equalization finds the expanding volume tracking through one of these defects. Alternatively, the air can be forced intracranially with an excessively forceful Valsalva Maneuver. (**Goldman, 1986**) Although normal Valsalva performance pressures range from 30-40 mmHg, high force Valsalva pressures can rise upwards to 120-300 mmHg. (**Edmonds, 2016**) Such high pressure air insufflation can potentially open a bony defect. Once the air track is established, air entry generally follows one of two mechanisms --- “ball-valve” where the tissue acts as a one-way valve for air entry blocking air exit and “inverted bottle” where the escape of cerebrospinal fluid (CSF) exerts a siphon-like effect drawing in air. (**Donovan, 2008; Leong, 2008; Javan, 2011; Willson, 2014; Dabdoub, 2015**) Mostly benign --- with transient symptoms such as headache, nausea, and confusion --- barotraumatic pneumocephalus, similar to its diagnostic counterpart, the pneumoencephalogram, can be fatal. (**Dandy, 1919; Davidoff, 1951; Canavan, 1991; Hermans, 1992; Chan, 2000; Cortes, 2005; Zeba, 2010; Woodside, 2019**) Even though inflight barotraumatic pneumocephalus is possible, short of precipitous and catastrophic symptoms, the AE crew and TVFS would be unaware. It would be a postflight inpatient diagnosis.

Preflight pneumocephalus, on the other hand, is not unknown to the TVFS. This is particularly true with trauma where up to 70-90% of craniofacial trauma is associated with pneumocephalus. (**Chan, 2000; Leong, 2008**) And, from 77-100% pneumocephalus is seen with surgery, especially semi-sitting posterior fossa surgery. (**Donovan, 2008; Hong, 2015**) During Operation Iraqi Freedom and Operation Enduring Freedom, head trauma and intracranial surgery were common. What is more, traumatic brain injury (TBI), often called the signature injury for those conflicts, was seen with upwards of 8-22% of the wounded soldiers. (**Harmon, 2005; Okie, 2005; Martin, 2008**) Consequently, pneumocephalus was frequently encountered. In fact, Donovan et al reported a case series of 21 AE patients with pneumocephalus flown from Kuwait to Landstuhl (~8 hour flight). Calculated volumes ranged from 0.6-42.7 ml with a mean volume of 9.3 ml and median volume of 4.2 ml. One patient, feet-first loaded, was noted to have a transient ICP rise of almost 5 mmHg with take-off. However, there were no sustained ICP elevations, nor was there any temporary or sustained neurologic decline. Cabin pressure was maintained between 5,000-8,000 feet, though details were not available. (**Donovan, 2008**) Similarly, another report documented a 45-minute commercial flight in a patient with a 0.5 ml pneumocephalus; there were no adverse sequelae. (**Willson, 2014**) Taking these pneumocephali to a cabin maximum altitude of 8,000 feet, volume would be expected to increase by 30⁺%. (**Andersson, 2003; Javan, 2011; Huh, 2013**) The highest volume reported by Donovan et al of 42.7 ml would present at altitude ~55.5 ml. Both the initial and at-altitude volumes are well within that suggested for a tension pneumocephalus, that is > 25-65 ml. (**Monajati, 1982; Dabdoub, 2015; Heidari, 2016; Pillai, 2017**)

Tension pneumocephalus is life-threatening. Mortality may be as high as 10%. (**Ani, 2016**) In one case series, 2 of 20 patients died. (**Pillai, 2017**) It is characterized by mass effect upon the brain, symptoms (e.g., headache, confusion, nausea), and an elevated ICP. (**Monajati, 1982; Harvey, 2016; Heidari, 2016; Pillai, 2017**) Pathognomic to it is the Mt Fuji sign, a CT

finding whereby the frontal lobes are compressed and their tips separated creating an image suggestive of Japan's iconic Mt Fuji. (Ishiwata, 1988; Harvey, 2016) See Figure 11. Averting tension pneumocephalus is paramount for the TVFS.



Note: Photograph taken by and courtesy of Amy Steinkraus.
Drawing by and courtesy of the author (WPB).

Figure 11. Graphic Depiction of the Mt Fuji Sign

4.7.1.1B Pneumocephalus Countermeasures

For the TVFS, avoidance of tension pneumocephalus is paramount. Almost as important is minimizing the effect of pneumocephalus volume expansion. Although there is no evidence that volume expansion and its accompanying mass effect upon injured brain tissue produces a *second hit*, it is hard not to imagine the threat.

As a result, the TVFS will want to hasten the resorption of pneumocephalus. Recent clinical models and controlled trials suggest that 40-100% oxygen will hasten resorption, perhaps as much as 1.4-3.6 ml/hr. At the same time, the controlled trials reported no hyperoxic sequelae. (Dexter, 1996; Gore, 2008; Hong, 2015) See Table 5. This, despite recent animal studies suggesting hyperoxic morbidity. (Skovira, 2016; Proctor, 2017) Consequently, mild to moderate prescribing of supplemental oxygen, as opposed to 100% oxygen, seems prudent.

Despite adding oxygen to speed trapped air resorption, the TVFS cannot assume the patient's pneumocephalus will not be a factor during AE. The patient can be positioned to

minimize the potential ICP ramifications of acceleration of take-off and deceleration of landing. See **Section 4.2 Acceleration/Deceleration for details**. Briefly, head-first loading of supine litter patients means take-off unloads blood volume to the brain while landing loads blood volume. (**Blumen, 1995; Dufour, 2003; McLean, 2011; Green, 2016**) Slow, steady take-offs and long, slow landings minimize ICP fluctuations. And, head of bed elevation to 30-45 degrees changes the plane of gravitational force from the G_z axis to the G_x axis, where gravitational forces are much better tolerated. (**Green, 2016**)

Besides the patient's position, the patient's activity must be considered. When fractures extend intracranially (e.g., maxillofacial fractures, sinus fractures, basilar skull fractures), the equalization maneuvers on descent (e.g., Valsalva Maneuver) as well as unrequited air expansion of ascent can introduce additional air to an extant pneumocephalus. These events must be avoided. For descent, the TVFS must proscribe active equalization insufflations. In alert patients, this means using the Toynbee Maneuver, which involves a passive opening of the eustachian tube. (**Edmonds, 2016**) For ascent, most likely an issue with sedated and/or ventilated patients, this could well mean a prescription for tympanostomy with pressure equalization tubes or insertion of a sinus catheter drain. (**Helling, 2005**) Another, very practical, option for ascent is a CAR.

If the pneumocephalus has an open track to the ambient atmosphere (e.g., unclosed craniotomy, open communicating trauma), air will expand into the atmosphere with ascent and will flow into the cavity with descent. However, this is probably an unlikely scenario for the TVFS; most likely the pneumocephalus will be non-communicating. That said, CAR should be prescribed in any pneumocephalus patient with an intracranial volume that would expand at altitude into the tension pneumocephalus > 25-65 ml range. Able to obtain air volume from a CT report is unusual. However, there are other means. Estimating the volume of air on CT scan, per Donovan et al, multiplies the length by width of a given air pocket by the CT slice thickness, then adding the various slices together. This calculates the air as a three-dimensional block and definitely overestimates, making for a built-in safety factor. (**Donovan, 2008**) A quicker, though somewhat less elegant, calculation is to treat the CT air as a bubble using the longest dimension as its diameter; this, too, produces a built-in safety factor. See **Table 6**.

Table 6. Trapped Air Volume at Sea Level

Trapped Air Volume at Sea Level		
Measured Diameter (cm)	Radius (cm)	Volume (ml)
1.0	0.5	0.5
2.0	1.0	4.2
3.0	1.5	14.1
4.0	2.0	33.4
5.0	2.5	65.3
6.0	3.0	112.8
7.0	3.5	179.1
8.0	4.0	267.3
9.0	4.5	380.6
10.0	5.0	522.0
11.0	5.5	694.8
12.0	6.0	902.1

Note: Table derived with ideal application of $V = 4/3 \pi r^3$.
cm (centimeters), ml (milliliters).

Unfortunately, the tension pneumocephalus volume threshold is not written in stone, as normal brain tissue, specifically throughout the diagnostic pneumoencephalogram days, has been known to tolerate 20-120 ml. (**Dandy, 1919; Davidoff, 1951; Tondreau, 1985**) This is upwards to 10% of the intracranial volume of 1,400 ml, an amount not unheard of following semi-sitting posterior fossa surgery. (**Jenkins, 2000; Reite, 2010; Hong, 2015**) In addition, Donovan et al has documented safe air travel within the > 25-65 ml range. (**Donovan, 2008**) Still, minimizing the mass effect of the pneumocephalus seems prudent by prescribing a CAR such that the volume expansion be limited to no more than 15 or 20%, cabin altitudes of 4,000 or 5,000 feet, respectively. **See Table 7.**

Table 7. Trapped Air Pressure-Volume-Diameter Relationships

Pressure-Volume-Diameter Relationships			
Altitude (feet)	Pressure (mmHg)	Volume Change (%)	Diameter Change (%)
10000	523	45.3	13.3
9000	543	40.0	11.8
8000	565	34.5	10.4
7000	587	29.5	9
6000	609	24.8	7.7
5000	632	20.3	6.3
4000	656	15.9	5
3000	681	11.6	3.7
2000	707	7.5	2.4
1000	733	3.7	1.2
500	746	1.9	0.6
Sea Level	760	0	0
33	1520	-50	-21
66	2280	-67	-31
99	3040	-75	-37
132	3800	-80	-41
165	4560	-83	-45

Note: Table derived with ideal application of Boyle's Law ($P_1 \cdot V_1 = P_2 \cdot V_2$) and $V = 4/3 \pi r^3$. mmHg (millimeters mercury pressure), % (percent).

Thus, to best prepare a patient with pneumocephalus for an AE flight, it seems wise for the TVFS to prescribe supplemental oxygen at a ground equivalent FiO_2 of at least 40%. In addition, proscribing active equalization maneuvers in favor of the Toynbee Maneuver and prescribing tympanostomy and/or sinus drains should be considered. Moreover, the patient should be loaded head-first with, if clinically able, head of bed elevation. Smooth slow, steady take-off and long, slow landing should also be prescribed along with a CAR, preferably 4,000 or 5,000 feet. **Table 1** lists the various countermeasures.

4.7.1.2A Pneumothorax Description

Pneumothorax is a relatively common occurrence. It, as pneumocephalus, can result from trauma, surgery, neoplasm, gas-producing infection, and/or barotrauma. However, it is spontaneous pneumothorax that is most often encountered. Incidence rates range from 2-46 per 100,000 population with a peak at 20-29 years and another at 50-70 years. (Voge, 1986; Kipp, 2014) After an initial episode, there is ~50% recurrence rate, after the second episode, ~60%, and after a third episode, ~80%. (Flux, 1969; Voge, 1986; Baumann, 1997; Kipp, 2014) Interestingly, spontaneous pneumothorax has happened both inflight and within the altitude chamber, at least 32 inflight cases and 12 altitude chamber cases. (Fuchs, 1967; Flux, 1969; Ho, 1975; Neidhart, 1985; Voge, 1986; Robb, 1994) Treatment consists of observation, supplemental oxygen, needle aspiration, and/or chest tube. (Voge, 1986; Devanand, 2004) See Figure 12.



Note: Chest x-ray depicts almost complete pneumothorax (see arrows). CT scan depicts emphysematous bleb etiology located on superior aspect of the left lower lobe (see arrows). Figure is a US government product not subject to copyright and used with permission of the author. (Butler, 2000)

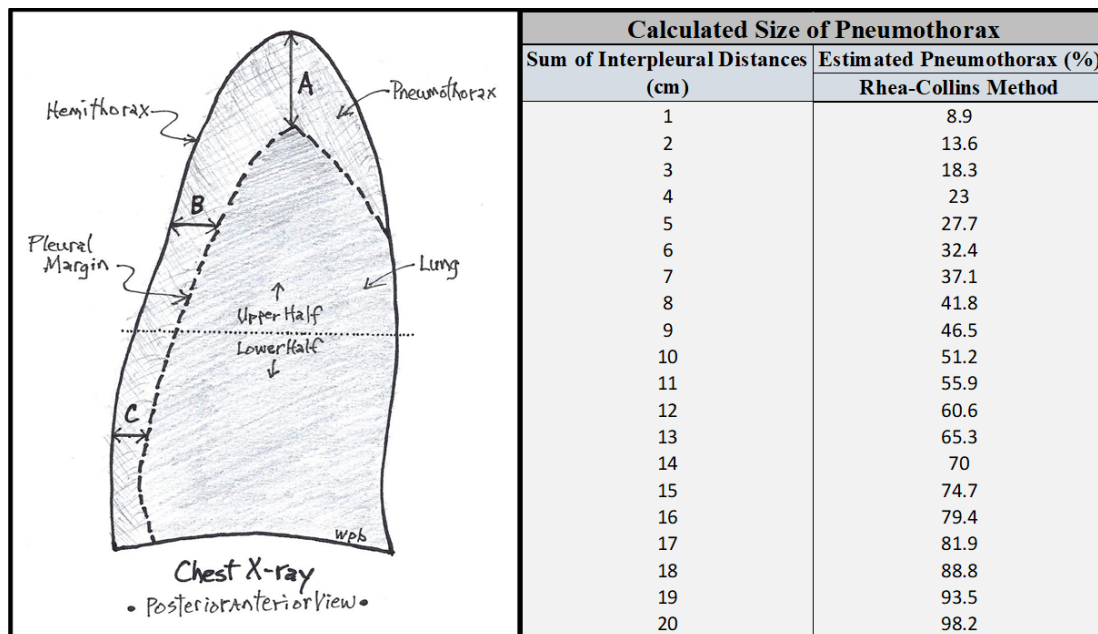
Figure 12. Chest X-Ray & CT Scan of Barotraumatic Pneumothorax

Generally, an extant pneumothorax is considered a contraindication to flight. Underpinning that declaration is fear for the physiological consequences of intrathoracic volume expansion. (AsMA, 2003; BTS, 2011) This fear is for good reason as there are no less than two cases of inflight death by tension pneumothorax. (Neidhart, 1985; Tiemensma, 2010) Tension pneumothorax is a life-threatening consequence of an expanding pneumothorax. With the unrelenting influx of air into the pleural space, the sponge-like lung is gradually compressed and the mediastinal organs (e.g., heart, trachea, and esophagus) are ultimately pushed into the contralateral lung space. As a result, ventilation and perfusion are compromised. Without aggressive treatment, death can ensue. (Roberts, 2015)

When considering a patient with pneumothorax for AE, the TVFS must ponder the extent of volume expansion and the potential for tension pneumothorax. It is generally reckoned that

needle or chest tube thoracostomy is required with either a symptomatic patient or a patient with > 15-20% pneumothorax. (Kircher, 1954; Panjwani, 2017) A 20% pneumothorax, considering a hemithorax to be around 3,000 ml, would be ~600 ml. (Szymanski, 2010; Kipp, 2014) This being the case, the TVFS would want no greater than a 20% pneumothorax at a cabin altitude of 8,000 feet. Volume, at 8,000 feet, expands by 30-35%, making for a ground requisite volume of no more than ~450 ml, or ~15% pneumothorax. See **Table 7**.

Other than “eye-balling” a chest x-ray, there are several methods for estimating percent pneumothorax. One rather limited method assumes a symmetric lung collapse and asserts that a 2 cm interpleural distance between lung and chest wall, at mid-hilum, approximates a 50% pneumothorax. (MacDuff, 2010) Another uses a two-dimensional, two-rectangle area technique. (Kircher, 1954; Chadha, 1983) Still another, based on a lung model of five elliptical cylindroids, takes the average of a sum of three interpleural distances as plotted against a percent pneumothorax nomogram. (Rhea, 1982) Last, and probably the most useful, is the method developed by Collins et al and validated by Kelly et al. It employs the sum of the already-mentioned three interpleural distances as related to helical CT scan measurements. This relationship is described by the regression equation *Percent Pneumothorax = 4.2 + (4.7 * Sum of Interpleural Distances)*. (Collins, 1995; Kelly, 2006a) See **Figure 13**. Knowing the relative size of a pneumothorax gives the TVFS a good starting reference point.



Note: Adapted from data and methods presented in Rhea et al, Collins et al, and Kelly et al. (Rhea, 1982; Collins, 1995; Kelly, 2006a) Regression equation correlating plain chest x-ray with CT volumetrics is $Y = 4.2 + [4.7 * (A+B+C)]$ ($r = 0.98$, $p < 0.0001$). (Collins, 1995) Drawing by and courtesy of the author (WPB). cm (centimeters), % (percent).

A = maximum interpleural distance at lung apex;

B = interpleural distance at midpoint of upper half of lung;

C = interpleural distance at midpoint of lower half of lung.

Figure 13. Estimated Pneumothorax Size Employing the Rhea-Collins Method

With this reference point, the TVFS can determine the extent of volume expansion and then consider the potential for clinical impact, especially tension pneumothorax. Tension pneumothorax is relatively uncommon (1-3%), but it is frequently lethal. In fact, there is a clear dichotomy in tension pneumothorax lethality between the awake patient and ventilated patient, ~7% versus ~23%, respectively. (Roberts, 2015) Furthermore, their presentations are different. See Table 8.

Table 8. Tension Pneumothorax Characteristics, Awake versus On Ventilator

Tension Pneumothorax Characteristics		
Characteristic	Awake	On Ventilator
Etiology		
-- Trauma	~20%	~14%
-- Barotrauma	~4%	~52%
-- CVP Catheter	~2%	~17%
Clinical Setting		
-- Emergency Department	~52%	~11%
-- ICU	~5%	~26%
-- Operating Room	~4%	~47%
Symptoms		
-- Pleuritic Chest Pain	~52%	---
-- Dyspnea	~38%	---
-- Shortness of Breath	~31%	---
-- Agitation	+++	---
Physical Findings		
-- Tracheal Deviation	~18%	~2%
-- Subcutaneous Emphysema	~11%	~31%
-- Hyper-resonance	~27%	~8%
Vital Signs		
-- Tachycardia	~43%	~31%
-- Hypotension	~16%	~66%
--- Development	Progressive	Rapid
-- Hypoxia	~40%	~87%
--- SpO ₂ Drop	Progressive	Immediate
-- PaO ₂ /FiO ₂ < 300	~77%	~96%
-- Upped Ventilation Pressure	---	+++
Time Course	Progressive	Rapid
Respiratory Arrest	~10%	---
Cardiac Arrest	---	~30%

Note: Table derived from data presented by Roberts et al and Leigh-Smith & Harris; percentages approximate the authors' findings. (Leigh-Smith, 2005; Roberts, 2015) The table depicts how much more at risk of rapid death a ventilated patient with a tension pneumothorax is compared to an awake patient. CVP (Central Venous Pressure), ICU (Intensive Care Unit), SpO₂ (pulse oximetry peripheral hemoglobin saturation), PaO₂ (arterial partial pressure of oxygen), FiO₂ (fraction

of oxygen in inspired air).

In an awake patient, tension pneumothorax progressively develops, manifesting respiratory symptoms until hypoxia and hypotension appear, followed by respiratory arrest. This time course most likely represents a “flap-valve” mechanism where inspired air leaves the lung for the pleural cavity through an open trap-door-like flap of tissue, but is unable to return to the lung because that flap of tissue is closed. Consequently, air within the pleural cavity gradually accumulates until tension is attained. **(Leigh-Smith, 2005; Roberts, 2015)**

In contrast, the ventilated patient reaches tension swiftly and precipitously, frequently attended by sudden cardiac arrest. Air insufflated by the ventilator, delivering positive pressure, rapidly pushes its way from the lung into the pleural space, not only compromising respiration, but also cardiac output. The result, cardiac arrest. Such a tension pneumothorax not infrequently follows ventilator-associated pulmonary barotrauma or iatrogenic central venous pressure catheter insertion. **(Leigh-Smith, 2005; Roberts, 2015)**

Needless to say, the TVFS does not want an inflight tension pneumothorax to occur. Accordingly, differentiating the potential for a tension pneumothorax in an awake patient versus a ventilated patient must be made.

4.7.1.2B Pneumothorax Countermeasures

When a patient with a pneumothorax is submitted for AE, the TVFS must first consider the awake-ventilated dichotomy. Next comes the potential, occult, and extant nature of the pneumothorax. From these considerations, a validation prescription is reached.

In the awake patient, the potential for inflight spontaneous pneumothorax is rare and, without underlying lung injury or disease, requires no serious TVFS attention. On the other hand, an awake patient suffering blunt or penetrating trauma with a negative supine or upright chest x-ray may well have an occult pneumothorax. In fact, the incidence of occult pneumothorax in those patients undergoing CT scan approaches 15%. **(Ball, 2009a)** Indeed, the incidence may be seriously higher. One retrospective study detected a 55% incidence, while a prospective study detected a 76% incidence; the retrospective predictors included female sex, pulmonary contusion, rib fracture, and subcutaneous emphysema, while the prospective predictors included only subcutaneous emphysema. **(Ball, 2005; Ball, 2009b)** Another predictor is chest wall contusion. **(Ball, 2009a)** Interestingly, occult pneumothoraces, despite the term “occult” suggesting trivial, are not necessarily diminutive. In truth, occult and extant pneumothoraces are similar in both size and distribution. **(Ball, 2009a)** Consequently, a trauma patient being evacuated without a chest CT, but with a pulmonary contusion, chest wall contusion, rib fracture, and/or, especially, subcutaneous emphysema requires a chest CT to rule out an occult pneumothorax.

An occult or extant pneumothorax > 15-20% requires treatment with a chest tube or needle thoracostomy prior to AE. The chest tube or needle should be placed to either a Heimlich valve or self-contained suction water seal. In this way, inflight expansion of any undetected lingering air can be eliminated. **(Polk, 2003a; Stephens, 2003)** With detectable preflight residual air, despite needle and/or chest tube, water seal is preferred. On the other hand, an occult or extant pneumothorax < 15-20% is often treated without a chest tube or needle thoracostomy. **(Chadha, 1983; Flint, 1984; Putukian, 2004; Panjwani, 2017)** In such an instance, AE without a chest tube or needle can be considered. This approach mandates a patient with no respiratory compromise and a cabin altitude at the origin elevation. **(Grissom, 2003)** Should an origin elevation CAR not be possible, the CAR prescribed should limit pneumothorax

expansion no more than 15-20%, 4,000-5,000 feet. See **Table 7** and **Figure 11**. In addition, supplemental oxygen should be applied to hasten resorption of the intrapleural air, preferably a ground-level equivalent FiO_2 of 50-100%. (**Chadha, 1983; Panjwani, 2017; Park, 2017**) See **Table 5**.

What then of a patient having had a chest tube removed? Depending on the guidelines, anywhere from 1-3 weeks should pass prior to flying. (**AsMA, 2003; BTS, 2011**) However, these recommendations are certainly not hard and fast. In a survey of thoracic surgeons looking at air travel following postoperative pneumothorax, 44% of the surgeons, on average, permitted flight 13.8 days after pneumothorax resolution. In contrast, 46% allowed flight with residual pneumothorax, ranging from 5% to 50%. Only one of the 66 surgeons reported a complication, inflight thoracic pain. (**Szymanski, 2010**) Similarly, a retrospective case series of 80 patients found 77% flying ~9 days after chest tube removal. Ten of the patients flew with small stable pneumothoraces. There were no complications. (**Sacco, 2014**) Even more convincing was a prospective hypobaric chamber study where 14 of 20 patients entered the chamber ~18.5 hours after chest tube removal; the other 6 patients were treated without a chest tube. Chest x-rays were obtained preflight, inflight, and postflight. At 8,400 feet, the residual apical pneumothorax went from ~4.5 mm to ~10 mm and then back to ~3.8 mm; at 12,650 feet, it went from ~3.2 mm to ~8.7 mm and back to ~4.4 mm. At 8,400 feet, 5 patients required supplemental oxygen to maintain saturations above 88%; whereas, at 12,650 feet, only 1 patient experienced an issue, chest pain presumed from rib fractures. (**Majercik, 2014**) Based on this data, it seems reasonable to consider flying a patient shortly after chest tube removal as long as there is, at most, only a very small residual pneumothorax. Conjoined to such a decision is the prescription of supplemental oxygen at a ground-level equivalent FiO_2 of 50-100%. (**Chadha, 1983; Panjwani, 2017; Park, 2017**) This will not only mitigate potential desaturations inflight, but also accelerate ongoing air resorption. (**Edmonds, 2016**) At the same time, a CAR of 4,000 feet or 5,000 feet will limit expansion to 15% or 20%, respectively. See **Table 7**.

Turning to the ventilated patient, an occult or extant pneumothorax must be treated with a chest tube placed to suction water seal prior to AE. Here, the threat of precipitous tension pneumothorax with concomitant cardiac arrest is very real. This is especially true for those patients ventilated with large tidal volumes, high levels of PEEP (e.g., 15-20 cm H_2O), and/or recently placed central venous pressure lines. (**Roberts, 2015**) In such cases, the TVFS will want to discuss lung protective ventilation with the patient's intensivist and/or surgeon. This ventilation technique, if clinically possible, works with lower tidal volumes and lower levels of PEEP protecting the aveoli from iatrogenic pressure trauma and overt barotrauma. (**ARDSNet, 2000**) In addition, supplemental oxygen and a CAR are indicated.

Thus, an awake trauma patient without chest x-ray evidence of a pneumothorax, but with lung contusion, chest wall contusion, rib fracture, and/or, especially subcutaneous emphysema must undergo a chest CT looking for an occult pneumothorax. An awake patient with an occult or extant pneumothorax < 15-20% may be evacuated with supplemental oxygen (ground equivalent FiO_2 = 50-100%) and a CAR (4,000 feet or 5,000 feet). However, an awake patient with an occult or extant pneumothorax > 15-20% should be treated with a needle or chest tube thoracostomy placed to either a Heimlich valve or suction water seal. Additionally, the TVFS should prescribe both supplemental oxygen (ground equivalent FiO_2 = 50-100%) and a CAR (4,000 feet or 5,000 feet). Lastly, in a ventilated patient, the TVFS should look for lung protective ventilation techniques (low tidal volumes and low levels of PEEP), ensure that the chest tube is placed to suction water seal, and prescribe both supplemental oxygen (ground

equivalent $\text{FiO}_2 = 50\text{-}100\%$) and a CAR (4,000 feet or 5,000 feet). See **Table 9**. **Table 1** lists the various countermeasures.

Table 9. TVFS Prescribing Approach for Patients with Pneumothorax

Pneumothorax Prescribing Considerations					
Pneumothorax	Awake		Percent	On Ventilator	
	Factors	TVFS Prescription		TVFS Prescription	Factors
Potential Pneumothorax (no pneumothorax on CXR)	rib fracture pulmonary contusion chest wall contusion subcutaneous emphysema	chest CT scan	-- not detected --	chest CT scan	rib fracture pulmonary contusion chest wall contusion subcutaneous emphysema
Occult/Extant Pneumothorax	no respiratory distress origin altitude maintained	-- consider no needle or chest tube -- supplemental O_2 -- CAR	< 15-20%	-- chest tube to suction water seal -- lung protective ventilation -- supplemental O_2 -- CAR	tension pneumothorax threat -- high tidal volume -- high levels of PEEP -- insertion of CVP line
		-- in-place needle or chest tube -- Heimlich valve or suction water seal -- supplemental O_2 -- CAR	> 15-20%	-- chest tube to suction water seal -- lung protective ventilation -- supplemental O_2 -- CAR	
Post Chest Tube Removal	after 24 hours small stable residual	-- consider supplemental O_2 -- consider CAR		should not fly	within 24 hours ventilated
	1-3 weeks	no intervention		see Occult/Extant Pneumothorax	extubated & awake after 24 hours stable residual
				no intervention	1-3 weeks

Note: CXR (chest x-ray); CT (computed tomography), O_2 (oxygen), CAR (cabin altitude restriction), % (percent), PEEP (positive end-expiratory pressure), CVP (central venous pressure).

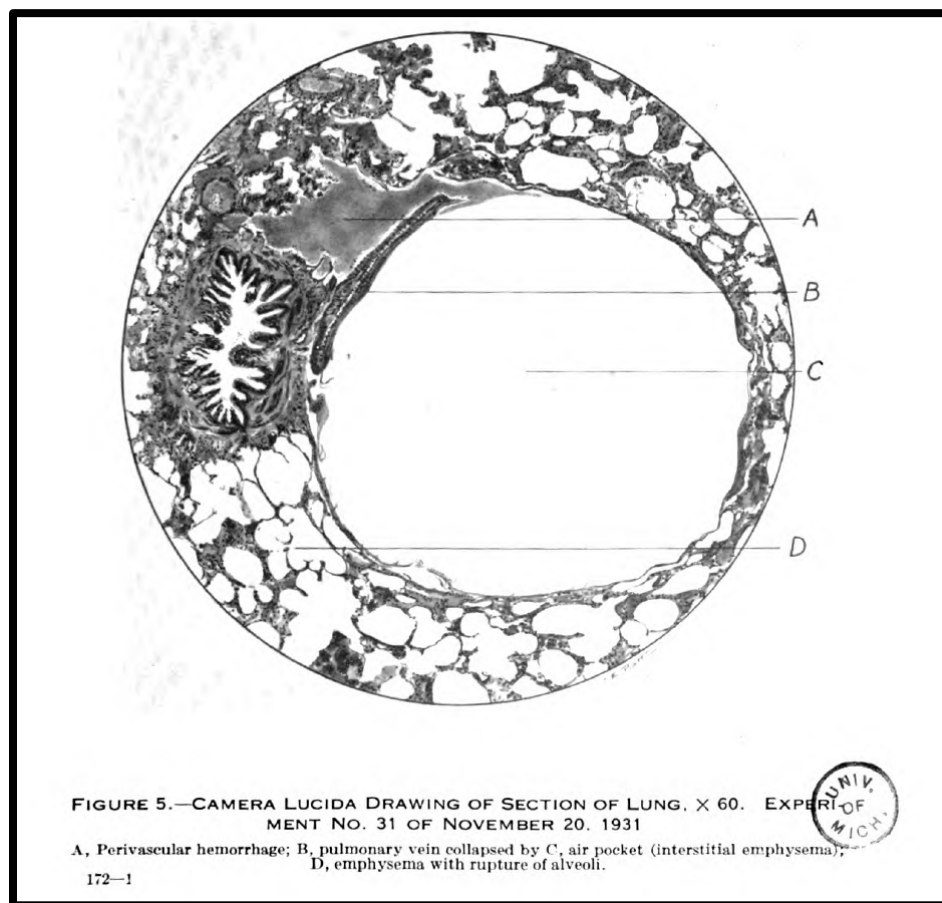
4.7.1.3A Pneumomediastinum Description

Pneumomediastinum is distinguished by air within the mediastinum, that chest area bound laterally by the pleural cavities, inferiorly by the diaphragm, superiorly by the thoracic inlet, anteriorly by the sternum, and posteriorly by the thoracic vertebrae. Pneumomediastinum stems from trauma, surgery, perforated viscous, pregnancy, neoplasm, infection, and unidentified (aka spontaneous). (Sahni, 2013; Bakhos, 2014; Kouritas, 2015; Amine, 2018)

Primary, or spontaneous, pneumomediastinum is not uncommon with a general incidence of 1:44,000, 1:25,000 between the ages of 5-34 years, 1:10,000 hospitalizations, and 1:100,000 pregnancies (during labor). (Morgan, 2007; Sahni, 2013; Kouritas, 2015; Amine, 2018) It presents usually with chest pain, dyspnea, and neck pain (subcutaneous emphysema). Other symptoms include rhinolalia and hoarseness. Although Hamman's "crunch," a rhythmic crackling-crunching sound originating from the heart beating against the mediastinal air, is heard in only about 18% of patients, when heard, it is pathognomonic. Diagnosis is by chest x-ray (90%), especially the lateral view, where the "ring" sign, an air band surrounding either a blood vessel or bronchiole, is pathognomonic. (Sahni, 2013; Bakhos, 2014; Kouritas, 2015)

Not infrequently, spontaneous pneumomediastinum is associated with coughing fits, asthmatic exacerbations, and severe straining Valsalva-like maneuvers (e.g., second stage of labor, constipating stool impaction). (Sahni, 2013; Kouritas, 2015; Amine, 2018) Each of these activities is typified by alveolar overinflation with sudden rises in airway pressure. Indeed,

high force Valsalva pressures can reach upwards to 120-300 mmHg. (Edmonds, 2016) Such pressures can easily overwhelm an alveolus, particularly those conjoined to blood vessels. In cats and dogs, intratracheal pressures of 10-220 mmHg and 80-90 mmHg, respectively, have produced alveolar air leaks. (Polak, 1932; Macklin, 1939; Schaefer, 1958) In human cadavers, alveolar air leaks were recognized at 73-80 mmHg. (Malhotra, 1961) Once alveoli leak, the now interstitial air can track along bronchovascular sheaths towards the hilum only to break free into the mediastinal space. As the normal mediastinal interstitial tissue pressure of -4 mmH₂O poses little impediment, continued air entraining can readily dissect into the retropharyngeum, pericardium, retroperitoneum, peritoneum, thorax, spine, and extremities. (Polak, 1932; Jessup, 1931; Macklin, 1944) See Figure 14. The result of this so-called Macklin Effect: subcutaneous emphysema, pneumopericardium, pneumoperitoneum, pneumothorax, and pneumorrhachis.



Note: Figure is a US government product not subject to copyright. (Polak, 1932)

Figure 14. Section of Dog Lung Following Alveolar Overinflation/Overpressurization

Unabated, progression to the respiratory and cardiac compromise of the “malignant” pneumomediastinum and a fatal outcome is undisputed. In fact, there are many such reports from the early 20th century. (Macklin, 1939; Macklin, 1944; Kouritas, 2015) See below a classic clinical description of a “malignant” (aka tension) pneumomediastinum as experienced during the 1918 influenza epidemic.

The point which struck us here was the intense dyspnea, with little cardiac disturbance, cyanosis, great air hunger, and erection of the chest fixed in a state of hyperinspiration, with only tidal air movement. As the muscles of respiration failed, exitus occurred, a respiratory death, in contradistinction to the toxic circulatory or vasomotor death commonly seen in the early days of true pneumonia. The pulse impressed us as being slowed as if under the influence of cardiac vagotonic inhibition, as in high pulmonary pressure ... Very soon the accessory muscles of respiration were the only effective ones giving a lift to the upper chest ... already so distended that any gain in capacity was impossible. Sternal tympany became more marked, assuming a box-like character. Marked stasis of all the veins entering the chest and those drained by the superior vena cava was manifest. Cyanosis became more profound and in the end stage there was an ashen lividity of the whole face and chest.

When in apparent respiratory *extremis*, frequently a patient would begin to complain of pains, substernal and in the jugular fossae, and crepitation would be noted in the subcutaneous tissue at the root of the neck, and immediate marked subjective relief was apparent, rapidly followed by a noticeable improvement in the respiratory excursion of the chest, and the most striking decrease in cyanosis and jugular distention ... As the intrathoracic pressure was thus relieved these apparently moribund patients often went on to recovery.

A number of patients dying in this early stage of emphysema came to autopsy. The cause of death was evidently the mechanical obstruction of the return flow of the venous blood from the general circulation to the interior of the chest by the thoracic fixation interfering with the mass movement of the blood ... The lungs of bronchitic emphysema showed a great similarity in gross pathology as well as in clinical findings. The surface ... showed the rib markings and emphysematous bullae, which were plainly visible under the visceral pleura. The emphysema was such that *the lungs could not be collapsed by pressure*. The tissue, while apparently solid, was always found to be air-containing, floated in water ... Regarding treatment it must be said that no routine treatment was shown to be of value after the bronchitic emphysema was established.

Note: This is an excerpt taken from the Torrey and Grosh clinical description of a patient with “malignant” (aka tension) pneumomediastinum during the 1918 influenza epidemic. (**Macklin, 1944**)

Clearly, the TVFS wants to prevent progression of a pneumomediastinum into the “malignant” state. Even without persistent air entraining, the 35% volume expansion with an 8,000-foot cabin altitude could potentially have respiratory and/or cardiac impact. Consequently, the TVFS must exercise care when evacuating a patient with an established pneumomediastinum.

4.7.1.3B *Pneumomediastinum Countermeasures*

The most important consideration for the TVFS is whether or not there is persistent air entraining. Serial chest x-ray evidence for extension of mediastinal air must be sought. Such progressive spread demands a closer look. Should the mediastinal air be more inferiorly located, a perforated viscous (e.g., esophagus, stomach) must be excluded. (**Bakhos, 2014**) An undiagnosed/untreated perforated viscous can often lead to acute mediastinitis. Taken to altitude might well mean a fulminant mediastinitis. Mortality can be as high as 40⁺%, ranging from 11-42%. (**Pierce, 2000; Macri, 2003**) In this setting, the TVFS cannot permit flight until a perforated viscous is ruled out.

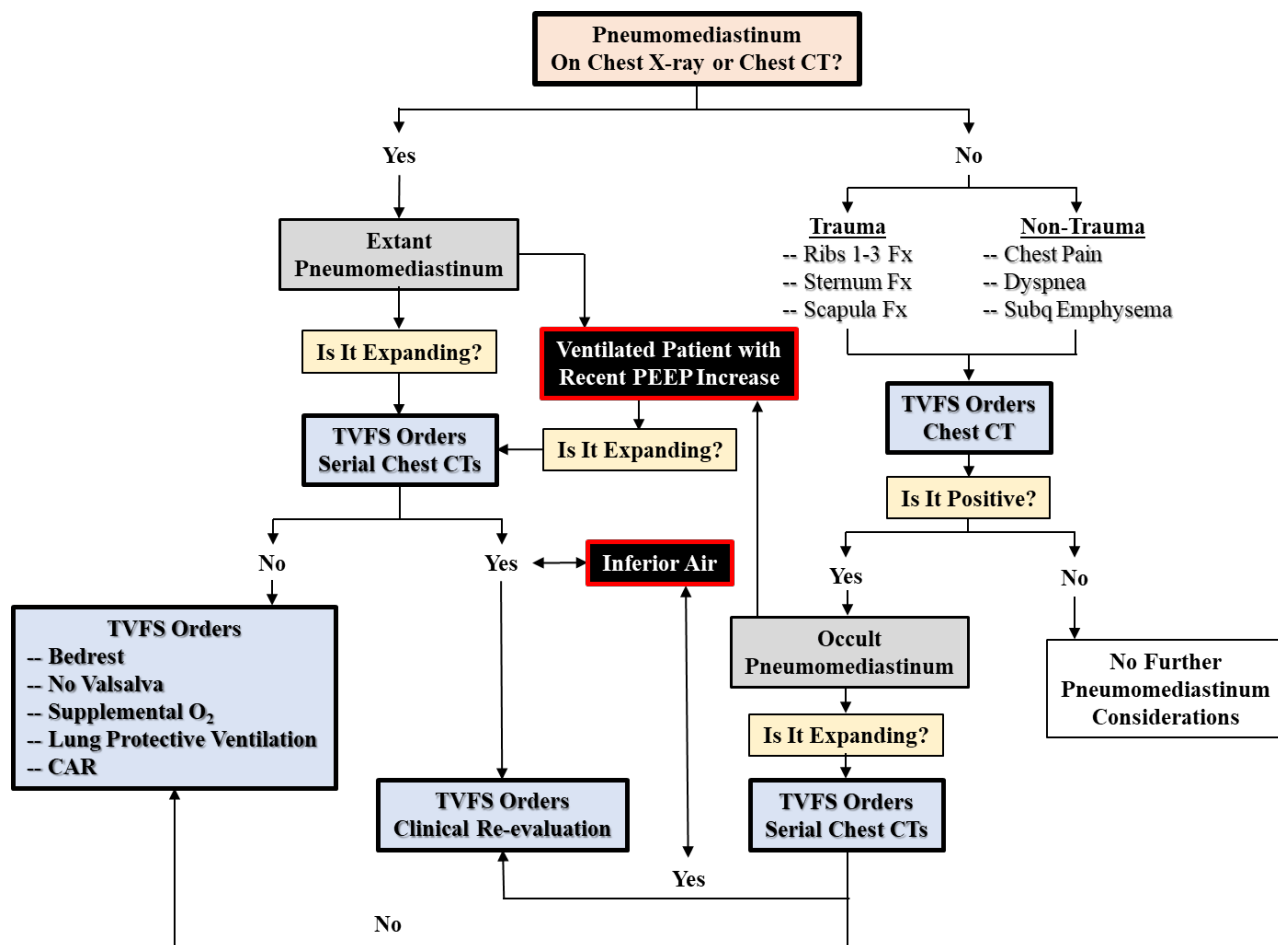
Along the same line of thought is the patient with a stable pneumomediastinum who is also ventilated. Though most patients should be supported with lung protective ventilation, ventilator settings and timing must be scrutinized. (**ARDSnet, 2000**) Any recent increase in PEEP is worrisome because it could theoretically re-open alveolar leaks and entrain pressurized

air. Serial chest CT scans should be sought prior to validation. In this way, an expanding pneumomediastinum can be detected. Until aggressively treated, a patient with an expanding pneumomediastinum should not be validated for AE.

In the trauma patient, particularly with blunt chest trauma, there is a 5-8% incidence of an occult pneumomediastinum; in the acute asthmatic, it may be as high as 30%. (**Rezende-Neto, 2010; Bakhos, 2014**) Despite the occasional asthmatic evacuation, trauma is much more frequent. A patient without a chest CT, but with accompanying fractures of the first three ribs, sternum or scapula, should not be flown without a chest CT. These sorts of fractures suggest a severe compressive force to the chest which, when coupled with a deeply held breath, can not only overinflate, but also over-pressurize alveoli producing air leaks. (**Macklin, 1944; Rezende-Neto, 2010**) This scenario, though to a somewhat lesser degree, is not unlike traumatic asphyxia where both pneumothorax and pneumomediastinum have been reported. (**Richards, 2005; Eken, 2009**) At the same time, a non-traumatic patient presenting with chest pain, dyspnea, subcutaneous emphysema, and a negative chest x-ray should not be flown without a chest CT. Indeed, under these circumstances, the TVFS should issue no validation until a negative chest CT and no occult pneumomediastinum are confirmed.

The patient with a stable, unchanged pneumomediastinum can be validated for flight. However, Boyle's Law volume expansion of the mediastinal air can be expected. As such, it will track along the interstitial tissue planes. Although generally benign, this can cause chest pain, lead to shortness of breath, and generate subcutaneous emphysema. (**Sahni, 2013; Bakhos, 2014; Kouritas, 2015**) In order to minimize these symptoms, the TVFS should prescribe a CAR, supplemental oxygen, no Valsalva, and bedrest. (**Sahni, 2013; Kouritas, 2015**) A CAR of 4,000-5,000 feet will limit volume expansion to 15-20%, respectively. See **Table 7**. Supplemental oxygen at 40-100% will speed air resorption by 3-6 fold over room air. (**Putukian, 2004; Kouritas, 2015**) See **Table 5**. No Valsalva diminishes any sudden upsurge of intratracheal pressure with its potential for alveolar leaks and/or air entrainment. (**Jessup, 1931; Macklin, 1944; Edmonds, 2016**) And, bedrest will moderate any symptoms that present.

Thus, to validate a patient with a pneumomediastinum, the TVFS must ensure that no persistent air entraining is happening, whether by high force coughing, perforated viscous, or recent increases of PEEP in ventilated patients. This requires serial chest x-rays or, preferably, CT scans. A patient with an expanding pneumomediastinum cannot be validated for AE, but must be referred back for clinical intervention. Once the pneumomediastinum is confirmed stable, AE can proceed with CAR, supplemental oxygen, no Valsalva, lung protective ventilation, and bedrest prescriptions. A decision algorithm is helpful. See **Figure 15**. Notably, as only one case of an inflight pneumomediastinum could be found, for all intents and purposes, inflight risk is nil. (**Morgan, 2007**) **Table 1** lists the various countermeasures.



Note: Subq (subcutaneous), PEEP (positive end-expiratory pressure), TVFS (Theater Validating Flight Surgeon), CT (computed tomography scan), O₂ (oxygen), CAR (cabin altitude restriction).

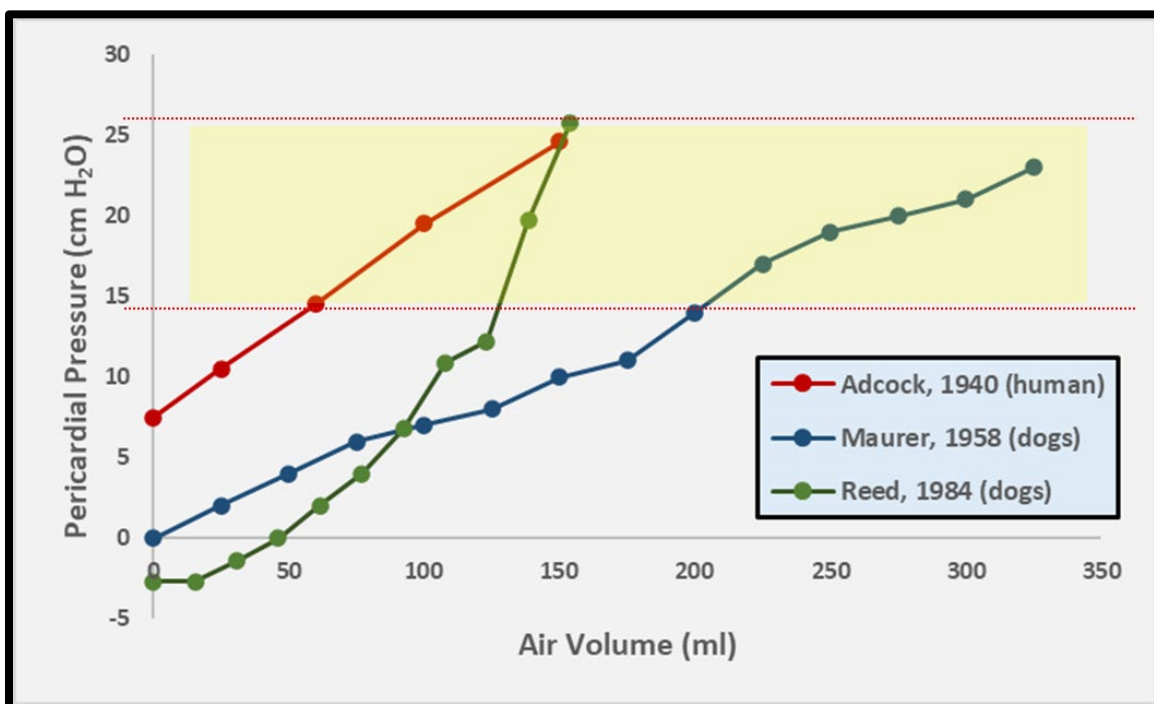
Figure 15. TVFS Prescribing Algorithm for Patients with Pneumomediastinum

4.7.1.4A Pneumopericardium Description

The relatively rare pneumopericardium is defined as air within the pericardial sac. The air accumulates by three potential mechanisms: movement of air from a rent in the pulmonary visceral pleura into the pleural cavity (aka pneumothorax) thence through a rent in the parietal pericardium, movement of air via a fistula (e.g., tracheobronchopericardial fistula, esophagopericardial fistula), and alveolar rupture with air tracking along the bronchovascular sheaths into the pericardial sac. (Polak, 1932; Macklin, 1944; Baum, 1976; Capizzi, 1995)

Clinical consequences from air in the pericardium depend on the amount of air and the rate at which it accumulates. (Visser, 2008) Indeed, a very slow air build up of 500 ml has been tolerated. (Cummings, 1984; Hamp, 2015) More importantly, however, is the intrapericardial pressure. As long as the pressure remains low, the air is accepted. Adcock et al treated a woman with tuberculous polyserositis with a therapeutic pneumopericardium. He demonstrated a physiologic effect at 14.5 centimeters water pressure (cmH₂O) pressure. That is, a rise in venous

pressure and heart rate with a concomitant drop in blood pressure. He took it one step further by provoking a cardiac tamponade at 26.5 cmH₂O pressure. These thresholds took place at 60 ml and 150 ml air, respectively. (Adcock, 1940) Maurer et al obtained similar results with a dog model, producing serious drops in blood pressure with pericardial air pressures 5-16 cmH₂O and volumes 75-150 ml. Of course, a few animals took up to 300 ml and 20⁺ cmH₂O before seeing the blood pressure plummet. (Maurer, 1958) In another dog model, 11 mmHg (15 cmH₂O) resulted in cardiac decline while 12.2 mmHg (16.6 cmH₂O) produced tension; the tension pressure range observed was 12-19 cmH₂O. (Reed, 1984) See Figure 16. Clearly, very little pressure over a very narrow range (0-12 cmH₂O) is tolerated; once into the 12-20 cmH₂O pressures, morbidity and mortality become very real. And, the volumes producing these pressures are not excessive.



Note: The shaded area bounded by dashed lines depicts the pressure-volume ranges associated with clinical cardiac impact. The overall graphic was derived from data presented in several experimental reports. (Adcock, 1940; Maurer, 1958; Reed, 1984) cmH₂O (centimeters water pressure), ml (milliliters).

Figure 16. Pressure-Volume Relationships with Pneumopericardium

Any number of conditions can lead to a pneumopericardium including trauma (blunt more so than penetrating), surgery, infection, neoplasm, and ventilator barotrauma (especially in infants). (Hymes, 1994; Gould, 2001; Hamp, 2015) Even rarer instances of pneumopericardium from Valsalva-like barotrauma have been recorded --- weightlifting by a 14 year old teenager and protracted yelling by a Marine all the while rigorously pursuing physical training. (Baum, 1976; Sherrier, 2020) Any number of signs and symptoms have been described: chest pain, dyspnea, shifting precordial tympany, subcutaneous emphysema, Hamman's crunch, Bruit de Moulin (sloshing murmur), and pulsus paradoxicus. In addition,

Beck's Triad --- hypotension, jugular venous distention, and muffled heart sounds --- is classic for tamponade. (**Visser, 2008; Sherrier, 2020**)

Any of these settings with any of these signs and/or symptoms should prompt investigation, usually by chest x-ray or CT scan. The "halo" sign (heart haloed with air and the thin parietal pericardium), "small heart" sign (serial x-rays demonstrating a shrinking heart size), and "triangle" sign (anterior triangle of air on lateral chest x-ray) all strongly suggest pneumopericardium. Also suggestive is a generalized low voltage electrocardiogram (EKG). (**Cummings, 1984; Capizzi, 1995; Visser, 2008**)

4.7.1.4B Pneumopericardium Countermeasures

For the TVFS, a pneumopericardium is frightening. In and of itself, without serious physiological impact, a stable pneumopericardium will generally dissipate over 3-8 days. Bringing on board supplemental oxygen will hasten resorption. (**Levin, 1996; Hamp, 2015; Mishra, 2016; Sherrier, 2020**) See **Table 5**. However, if it is tamponade, or tension pneumopericardium, that frightens. In two large case series of adults with pneumopericardium, 37% developed tension and 42-56% of them died. Of those with tension, 83% were ventilated. (**Cummings, 1984; Capizzi, 1995**) In another case series, 8 of 9 very sick infants on positive pressure ventilation showed sudden severe deterioration, all dying. At autopsy, each evidenced the Macklin Effect with pulmonary interstitial emphysema, pneumomediastinum and/or pneumothorax, and pneumopericardium. (**Mansfield, 1973**)

As described earlier, large volumes of air and high intrapericardial pressures are not requisite for tension. Even a 35% volume increase (cabin altitude 8,000 feet) could easily bring on tension. In addition, many of the patients for AE with pneumopericardium will likely be trauma victims, either penetrating or blunt, on positive pressure ventilator support. Although lung protective ventilation, with its low tidal volumes and low PEEP, is standard, positive pressure ventilation can pose a serious risk. (**Mansfield, 1973; Cummings, 1984; Capizzi, 1995; ARDSNet, 2000**) With Boyle's Law volume expansion and the threat of ventilator-added air via the Macklin Effect, the TVFS must be risk averse. Tension pneumopericardium, in the best of circumstances, carries high mortality, but inflight is almost certainly fatal.

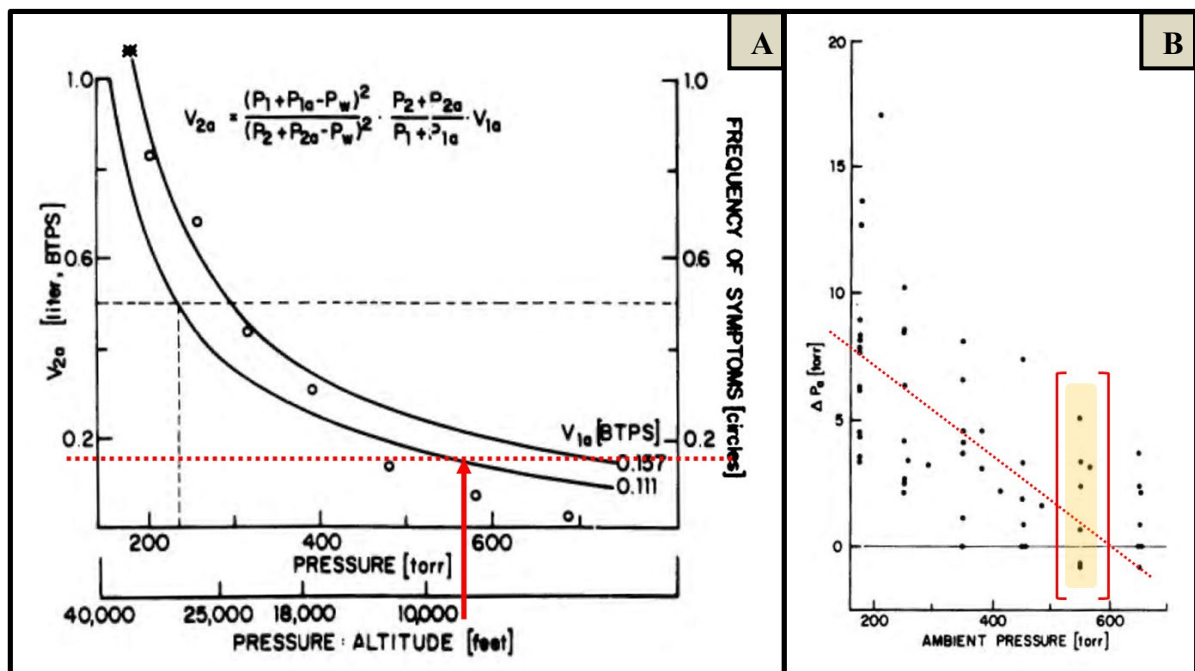
Consequently, supplemental oxygen and Intensive Care Unit (ICU) may be the best course of action for the patient. The oxygen speeds resorption and the ICU offers a comparatively safe and exceedingly capable clinical environment should tension suddenly present. Once the pneumopericardium is resolved, AE becomes much safer and more routine.

On the other hand, exigencies often rule, making AE of such a patient necessary. In that case, supplemental oxygen to heighten resorption, lung protective ventilation with the lowest possible tidal volume and PEEP, bedrest to moderate any symptoms, no Valsalva to block any patient-generated intratracheal pressure jumps, and a CAR of at least 4,000 feet, preferably sea level. (**Levin, 1996; ARDSNet, 2000; Edmonds, 2016**) See **Table 5** and **Table 7**. **Table 1** lists the various countermeasures.

4.7.1.5A Pneumoperitoneum Description

Pneumoperitoneum refers to "free" air, or extraluminal air, within the abdominal cavity and it definitely must be considered by the TVFS when validating a patient for AE. However, intraabdominal air includes not just the pneumoperitoneum, but also intraluminal air.

Intraluminal air is generally not of great concern when validating most patients. After all, most patients have around 100-150 ml of air within the bowel lumen. Even at a standard cabin altitude of 8,000 feet this volume should expand to no more than about 135-203 ml with an accompanying rise in intrabdominal pressure of around 5 mmHg. Short of 1.4 liters of air from consuming 0.6 kg of beans, such change should invoke little physiological impact. (Greenwald, 1967) See Figure 17.



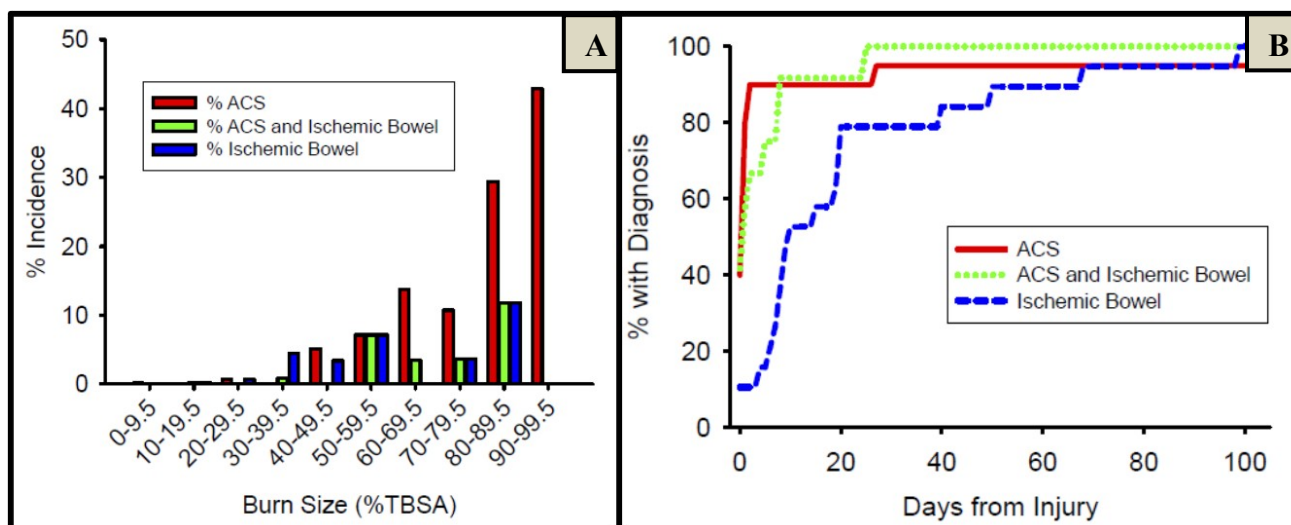
Note: **A** → Arrow denotes approximately 8,000 feet; dashed line demonstrates the upped volume and frequency of symptoms (i.e., feeling of fullness). **B** → Dashed line depicts the relative inverse relationship between ambient pressure and intra-abdominal pressure; shaded area highlights the change in intra-abdominal pressure (~0-5 mmHg) associated with ~8,000 feet cabin altitude. Figure is a US government product not subject to copyright. (Greenwald, 1967)

Figure 17. Normal Abdominal Pressure-Volume Response to Altitude

On the other hand, certain circumstances make intraluminal air effects important. A patient having had a splenectomy, whether in isolation or as part of an overall trauma care strategy, poses a special problem for the TVFS. Post-splenectomy hemorrhage, though uncommon, has an incidence of 1.6%. One of the classic sources of such hemorrhage is release of the secured short gastric arteries, along the greater curvature of the stomach. (Polk, 2003b; Qu, 2013) At the same time, such a patient, especially a multi-trauma patient, will experience postoperative ileus, or propulsive bowel dysfunction. Small bowel dysfunction lasts about 0-24 hours, the stomach 24-48 hours, and the large bowel 48-72 hours. (Luckey, 2003) Such patients are often evacuated to definitive care well within 48 hours. Intragastric air expansion could well pose a serious issue as gastric distention can surely pop-off short gastric artery ties/sutures with resultant life-threatening hemorrhage.

Along the same lines is the patient with an intestinal anastomosis, particularly a colonic anastomosis. Postoperative colonic ileus means that air will remain in place for as long as 72 hours and air is always proximate to an anastomosis. With evacuation, that volume of air will expand upping intraluminal pressure. Enough distensive pressure could burst the anastomosis. In dogs, the immediate postoperative bursting pressure for a stapled anastomosis was ~60 mmHg while that of a sutured anastomosis was ~160 mmHg. By postoperative day 7, bursting pressure in both dogs and rats was ~250 mmHg. (**Bundy, 1993; Polat, 2002; Duraes, 2013**) In bowel surgery, stapled anastomoses are common, technically quicker, and usually pose little threat to a routine patient. However, with an AE patient, peri-anastomotic air distention may well pose a dehiscence risk, especially with stapled anastomoses and early evacuation.

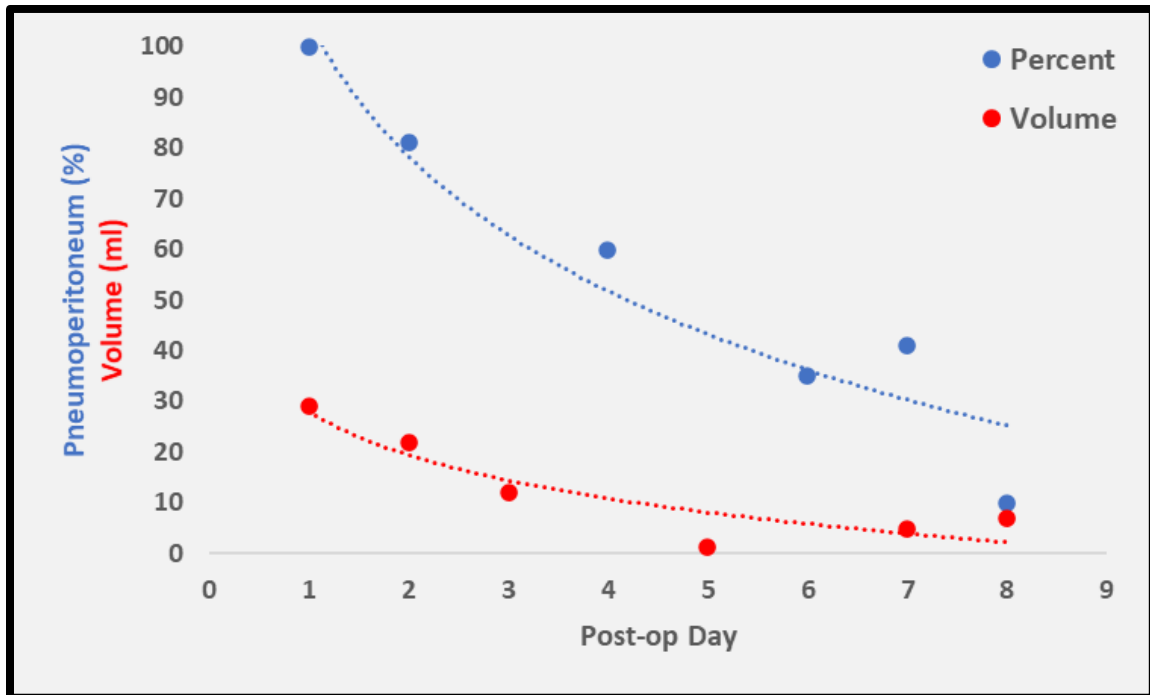
Another intraluminal air consideration for the TVFS is with the severely burned patient. These patients are often at risk for abdominal compartment syndrome. To that end, the Army Institute of Surgical Research (ISR) burn unit defines abdominal compartment syndrome in this setting as intra-abdominal pressure exceeding 30 mmHg conjoined with distention and oliguria. (**Markell, 2009**) These patients suffer both local and generalized capillary leak. Resuscitation regularly requires large amounts of fluids and, depending on other injuries, sometimes massive transfusion. Inhalation injury is not uncommon, usually requiring ventilator support. (**Hunt, 1988; McDonald, 1999; Barillo, 2003**) In addition, there is frequent gastric dilatation and intestinal ileus. (**Jonason, 1983**) As a result, the gastrointestinal tract is edematous, the diaphragms are pressed into the abdominal cavity, the stomach dilated, and the intestines unable to pass flatus. Evacuating such a patient is guaranteed to increase the intra-abdominal pressure, perhaps even to the point of compartment syndrome. Although relatively infrequent at 2.8%, the ISR reported an associated mortality of 78%. And, when abdominal compartment syndrome happened, it happened fast, within the first 3 days of injury. (**Markell, 2009**) See **Figure 18**. To evacuate such a patient seriously challenges the TVFS.



Note: **A** → Denotes the rising incidence of abdominal catastrophe (e.g., abdominal compartment syndrome) with the increasing percent total body surface area burned. **B** → Denotes the relative timing of abdominal catastrophe (e.g., abdominal compartment syndrome). Figure is a US government product not subject to copyright. (**Markell, 2009**) ACS (abdominal compartment syndrome), TBSA (total body surface area).

Figure 18. Abdominal Compartment Syndrome in the Burn Patient

Also challenging is extraluminal air. Pneumoperitoneum comes with surgery, trauma, disrupted viscous, infection, and the Macklin Effect; most commonly surgery, which is when the TVFS will encounter it. Generally, the postoperative pneumoperitoneum will be relatively small, typically at the low end of the 5.8-143 ml range. Most are resorbed within a week, though occasionally will persist to 3 weeks. And, children resorb the air much quicker than adults. (Hope, 1958; Svartholm, 1969; Earls, 1993; Gayer, 2000; Malgras, 2017) Interestingly, Hope and Cramer reported 84% of children, within 30 minutes of laparotomy, had clear x-rays, not to mention 9 of 12 children, following 10-110 ml air injection, being clear within 48 hours. (Hope, 1958) A decade later, Svartholm and Zwetnow injected 60 ml air into 46 post-appendectomy children; all were clear of the air within 5 days. (Svartholm, 1969) See Table 5 and Figure 19. Consequently, AE of a patient with uncomplicated abdominal surgery probably offers little issue for the TVFS.



Note: Progressive decline in percent and volume pneumoperitoneum as determined by CT scan. The overall graphic was derived from data presented by Malgras et al. (Malgras, 2017) % (percent), ml (milliliters).

Figure 19. Natural History of Postoperative Pneumoperitoneum Resorption

However, when taken to cabin altitude, a large pneumoperitoneum (such as one exacted from the Macklin Effect), a progressing pneumoperitoneum (such as one with a leaking anastomosis or one with air tracking via an intraperitoneal drain), and/or a pneumoperitoneum in the face of major trauma/burns can develop intra-abdominal hypertension. Normal intra-abdominal pressures range from 5-7 mmHg, while hypertensive pressures are > 12 mmHg. Progressive hypertension will gradually decrease abdominal perfusion (abdominal perfusion pressure = mean arterial pressure - intra-abdominal pressure; normal > 60 mmHg) by way of

impaired venous return, cardiac output, renal perfusion, splanchnic perfusion, not to mention pulmonary excursion and gas exchange. By the time intra-abdominal pressures exceed 20 mmHg and organ dysfunction is seen, the diagnosis of abdominal compartment syndrome is made. (**Lukianow, 2012; Maluso, 2016; Rogers, 2018**)

Intra-abdominal hypertension is a harbinger of abdominal compartment syndrome and may be observed in 30-70% of critically ill medical, surgical, and trauma patients, while abdominal compartment syndrome may be present in 10-35%. Specific risk factors include high-volume resuscitation (severe burns, major trauma, massive transfusion, coagulopathy requiring component therapy, hypothermia, sepsis, pancreatitis), increased abdominal content (severe ileus, large neoplasm, pancreatitis, critical illness with hepatic ascites, mechanical ventilation with PEEP > 10 cmH₂O), and decreased abdominal wall compliance (large torso burns, ventral hernia repair with tight closure, prone positioning, prolonged open abdomen). (**Luckianow, 2012; Maluso, 2016**) To avoid abdominal compartment syndrome, intra-abdominal hypertension must be lowered. Therapy targets the risk factors and consists of sedation, diuresis, nasogastric tube, paracentesis, colonoscopic decompression, escharotomy, and neuromuscular blockade, among others. Once established, however, it must be treated with decompressive laparotomy. It is anathema to the TVFS for a patient to develop abdominal compartment syndrome during or shortly after AE. Aggressive action by the TVFS is key.

4.7.1.5B Pneumoperitoneum Countermeasures

Occasionally, the TVFS is presented a patient for transport with an open abdomen. Although such a patient poses challenges, there is no real risk from the intra-abdominal air. That air is in relatively direct contact with the ambient atmosphere (e.g., wound vac device, moist dressings) and can readily equalize with any altitude changes. (**Rogers, 2018; Martin, 2019**) However, keys to countering the effects of closed intra-abdominal air are knowing the clinical situation and having a good feel for the air present. The location and amount of air are paramount.

Intraluminal air basically poses three concerns: disruption of vascular pedicles (e.g., splenectomy), disruption of bowel integrity (e.g., anastomoses), and development of intra-abdominal hypertension (e.g., ileus accompanying pancreatitis). The TVFS counters these with mechanical removal of the air, accelerated resorption of the air, mechanical compression of air, and blocked accumulation of pressure by prescribing nasogastric tube to suction, supplemental oxygen, and CAR, respectively. (**Qu, 2013; Polk, 2003b; Edmonds, 2016**) Furthermore, positioning the patient supine at bedrest will limit pressure peaks. (**Luckianow, 2012; Maluso, 2016**)

Extraluminal air is more than anything else a potential impediment to perfusion. At cabin altitude, volume expands ~35%. See **Table 7**. This expansion takes a normal person's sea level intra-abdominal pressure of 5-7 mmHg up another ~0-5 mmHg. (**Greenwald, 1967**) Any added extraluminal air taken to altitude can potentially make the semi-rigid abdominal cavity hypertensive (> 12 mmHg). Small amounts of air are probably not significant, that is ~5-30 ml immediately following uncomplicated surgery. (**Earls, 1993; Gayer, 2000; Malgras, 2017**) But, as larger amounts of air accumulate, intra-abdominal pressure rises. (**Greenwald, 1967**) Perhaps even to hypertensive levels, threatening abdominal compartment syndrome which, of course, is not viewed in terms of volume, but rather pressure. And, rising pressures mean increasingly perturbed perfusion and organ dysfunction --- cardiac, pulmonary, renal, splanchnic.

Those very same pressures, in a rat model, have not only weakened, but also inflamed anastomoses. (**Polat, 2002**) As a result, rising intra-abdominal pressures, even those not yet reaching 20 mmHg, must be viewed in light of the size of pneumoperitoneum, criticality of the patient (e.g., ventilator dependent), and risk factors (e.g., large volume resuscitation, increased abdominal content, and abdominal wall compliance). In order to evacuate such a patient, the TVFS must position the patient supine, declare bedrest, ensure nasogastric tube to suction, mandate supplemental oxygen, and apply an aggressive CAR (i.e., at least 4,000 feet). This time the CAR is not just for Boyle's Law compressive effect, but more so for edema reduction effects (**Butler, 2016; Fouts, 2017; Butler, 2018; Butler, 2020**) See **Section 4.7.3**.

Thus, with intra-abdominal air, the TVFS will variously prescribe bedrest, supine positioning, supplemental oxygen, nasogastric tube to suction, and CAR. Which prescription and to what level will depend on the clinical setting. See **Table 5** and **Table 10**. **Table 1** lists the various countermeasures.

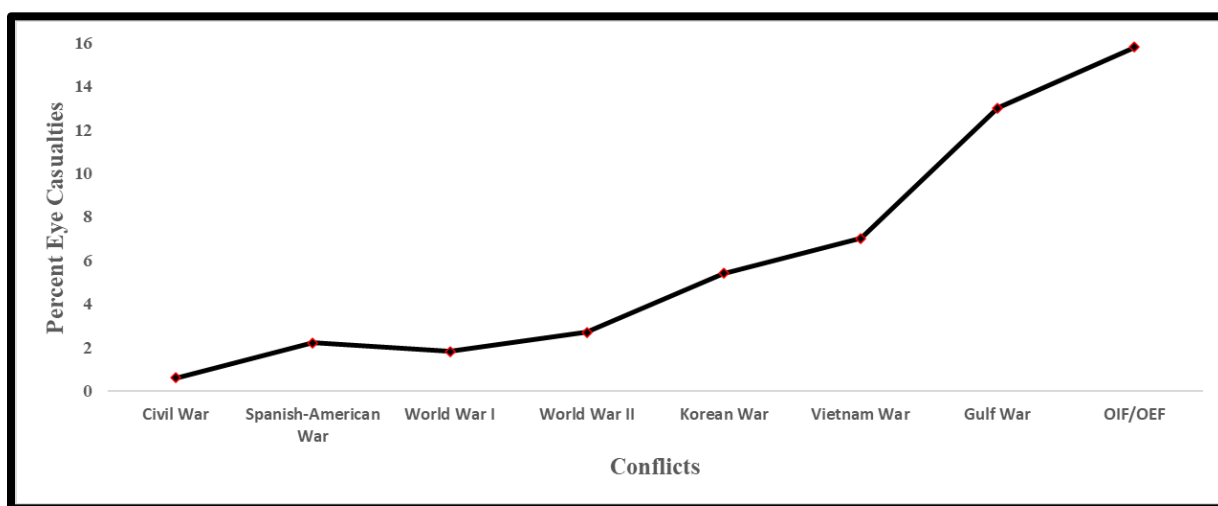
Table 10. TVFS Prescribing Approach for Patients with Intra-Abdominal Air

Intra-Abdominal Air Prescribing Considerations		
Intraluminal	Prescriptions	Extraluminal
Uncomplicated Normal	nothing specific	Uncomplicated Surgery
	nothing specific	Surgery with Drains (minimal air)
Splenectomy (large air, impaired, no suction)	NGT to suction CAR	
	supplemental O ₂ , CAR	Surgery with Drains (large air)
Anastomoses (peri-anastomotic air)	NGT to suction supplemental O ₂ , CAR	
	supplemental O ₂ supplemental O ₂ , CAR, supine, bedrest	Pneumoperitoneum (minimal air) IAH risk.....(large air)
Ileus (minimal air) (large air).....IAH risk	supplemental O ₂ , CAR NGT to suction, supplemental O ₂ , CAR, supine, bedrest	
Sepsis, Ascites (abdominal edema).....IAH risk	NGT to suction, supplemental O ₂ , CAR, supine, bedrest	Major Trauma/Burns IAH risk...(abdominal edema)
Intra-abdominal Hypertension (ACS risk)	NGT to suction, supplemental O ₂ , CAR, supine, bedrest	Intra-abdominal Hypertension (ACS risk)

Note: NGT (nasogastric tube), O₂ (oxygen), CAR (cabin altitude restriction), IAH (intra-abdominal hypertension), ACS (abdominal compartment syndrome).

4.7.1.6A Pneumatosis Oculi Description

Air, inside and outside the eye, is most commonly associated with trauma. The incidence of peacetime eye injury is 1.7-2.4%; whereas, the incidence of wartime eye injury is much higher. In Vietnam, it was 5-9%; in the Gulf War, it was ~13%; and, in the recent Operations Iraqi Freedom and Enduring Freedom, it was 10-15%. Indeed, the globe and orbit sustain over 40% of such injuries. (Ivan, 2003; Ari, 2006; Cho, 2014) See **Figure 20**. Interestingly, the eye makes up only 0.27% total body surface area, yet yields an incidence of injury 20-50 fold more than expected. (Ivan, 2003) This fact is a consequence of the increasing use of fragmentary weapons (e.g., improvised explosive devices) conjoined with the sporadic wear of eye protection. (Ari, 2006)



Note: Graphic derived from collated data as presented in the literature. (Ari, 2006; Cho, 2014)

Figure 20. Percent of Casualties with Eye Injuries, Over Time

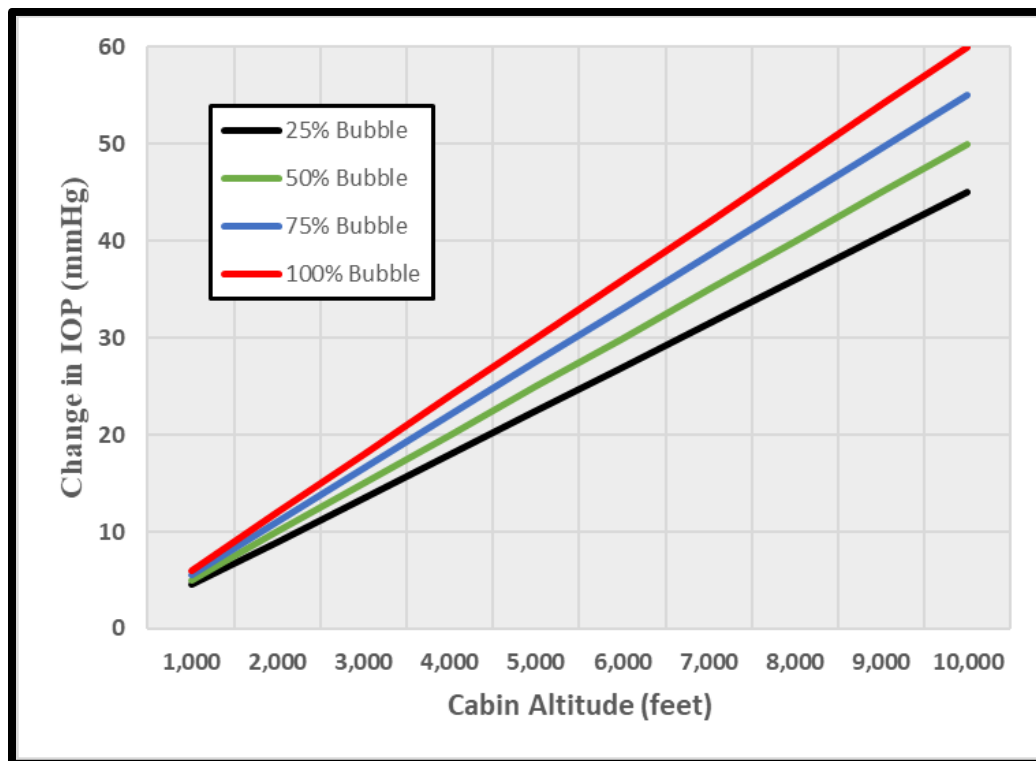
Air outside the eye is termed orbital emphysema. The usual causes include motor vehicle accidents, falls, and assaults. Surgery, positive pressure ventilation, compressed air injury, and forceful sneezing/vomiting/nose-blowing have all been implicated as well. Over 90% of the time there is an orbital fracture, two-thirds violating a sinus medially (e.g., ethmoid). Most resolve within 24-48 hours; however, if a ball-valve mechanism is in place, air can accumulate and, without relief, orbital compartment syndrome ensues. Though rare, vision loss from ischemic optic neuropathy is possible. (Birrer, 1994) The TVFS must be cognizant of that when validating any patient with peri-orbital/orbital air.

Air within the globe proper results from penetrating trauma or surgical insertion. With penetrating trauma the globe may be violated by a deep corneal laceration, a chorioretinal tear, or, more commonly, direct globe rupture. Wounds < 10 mm, sharp intraocular foreign bodies, and $\geq 20/200$ acuity bode a relatively good prognosis. (Abrames, 2012) An open globe communicating with the ambient pressure environment will not pose a trapped air problem for the patient and, thus, is not a TVFS concern. However, primary surgical repair with a watertight closure is preferred, making any retained air trapped and a serious TVFS concern. As the air

expands, an ocular foreign body may be dislodged, upped intraocular pressure (IOP) may impair arterial flow or damage ocular tissue, and the suture line may be disrupted expelling global content. (Ivan, 2003; Abrames, 2012; Cho, 2014)

On the other hand, surgically inserted gas is generally heavy, expansile, and of variable persistence. Gas tamponade is used in the treatment of retinal detachment, approximating the retina to its underlying structures facilitating both reattachment and healing. (Ivan, 2003) Air is retained around 7 days, xenon 1-2 days, and the more commonly employed perfluorocarbons 5-79 days. Resorption exhibits first order kinetics taking between 5-6 half-lives to essentially rid the gas. (Alavrez, 2003; Ivan, 2003; Kanclerz, 2018) Notably, supplemental oxygen does not appear to affect either resorption rate or volume, at least in a rabbit model. (Lincoff, 1989b) See Table 5.

The normal globe has a volume of ~6 ml, a semi-rigid diameter of ~24 mm, and an intraocular pressure of ~15 mmHg (ranging from 12-22 mmHg). (Lincoff, 1989b; Ivan, 2003; Hammer, 2010; Gsellman, 2016) An inserted bubble, when taken to altitude, will grow in volume per Boyle's Law. See Table 7. Because the globe is semi-rigid, as the intraocular gaseous volume expands, the IOP will rise. This rise is linear and, depending on the bubble size, will range from 4-6 mmHg per 1,000 feet. (Dieckert, 1986; Lincoff, 1989a; Lincoff, 1989b; Fromow-Guerra, 2016; Gsellman, 2016; Joondeph, 2018) See Figure 21.



Note: Graphic derived and extrapolated from experimental animal (New Zealand white rabbit) data as presented by Fromow-Guerra et al. Pressure conversions, rabbit to human, were by the Friedenwald methodology. The inserted intraocular bubbles (SF₆) were 25%, 50%, and 100% intraocular volume; human-converted IOPs rose approximately 4.5, 5.0, and 6.0 mmHg per 1,000 feet cabin altitude, respectively. The pressure differences between bubbles were not significant. (Fromow-Guerra, 2016) IOP (intraocular pressure), mmHg (millimeters mercury pressure), % (percent).

Figure 21. Estimated Rise in IOP with Each 1,000 Feet of Cabin Altitude

Despite this sort of pressure change, the eye can adapt through choroidal compression, scleral expansion, and upped aqueous outflow. However, should these physiologic maneuvers fail, IOP can rise to the point of eye pain and loss of vision. In fact, central retinal artery occlusion has been observed with IOPs ranging 48-110 mmHg (average ~79 mmHg). (**Dieckert, 1986; Lincoff, 1989a; Kokame, 1994; Mills, 2001**)

The actual rate of IOP rise is dependent upon bubble size, peak altitude, and ascent rate. In a monkey model, Dieckert et al took first a 0.25 ml bubble (6% bubble) to 8,100 feet at 300 feet/minute and then 5,000 feet/minute; IOP rose 30 mmHg and 42 mmHg, respectively. They next took a 0.5 ml bubble (13% bubble) to 8,100 feet, at 300 feet/minute and 5,000 feet/minute, followed by a rapid decompression from 8,100 feet to 35,000 feet; IOP rose 34 mmHg, 49 mmHg, and 145 mmHg, respectively. (**Dieckert, 1986**) Clearly, it is imperative for the TVFS evacuating a patient with surgically inserted gas to maximize adaptive physiology and optimize flight characteristics.

4.7.1.6B Pneumatoxis Oculi Countermeasures

Peri-orbital/orbital air with overlying soft tissue injury is generally open to the ambient atmosphere and does not pose an expansion issue for the patient. If, however, the wounds have been closed or the injuries do not include soft tissue disruption, expanding air can not only deform surrounding tissue, but also exert compressive pressure, even to the point of ischemic optic neuropathy. (**Birrer, 1994**) To avoid such an event, the TVFS can postpone validation for 24-48 hours over which time most, if not all, the air will be resorbed. If postponement is not possible, prescribing supplemental oxygen should up air resorption while, at the same time, offering up an antibacterial effect to contaminated tissues. (**Henderson, 1932; Chadha, 1983; Earnest, 2012; Edmonds, 2016**) In addition, ensuring that tissues are decongested and adequately humidified, especially in the face of sinus and/or nasopharynx disruption, lessens tissue edema. Prohibiting active coughing, Valsalva, and/or lifting will avoid the potential for entraining and retaining air via a ball-valve mechanism. (**Birrer, 1994**) And, lastly, imposing a CAR will diminish the expansive impact of cabin altitude. A moderate or large amount of tissue emphysema should prompt a CAR of 5,000 (20% expansion) or 4,000 feet (15% expansion), respectively. Thus, for closed peri-orbital/orbital air, the TVFS should consider delayed validation and/or supplemental oxygen, humidification, decongestants, Valsalva/lifting avoidance, and a 4,000-5,000 foot CAR. At the same time, consulting the attending ophthalmologist for his/her maximum acceptable peri-orbital/orbital air volume can also aid in CAR determinations. See **Table 11**.

Table 11. TVFS Prescribing Approach for Patients with Pneumatosis Oculi

Pneumatosis Oculi Prescribing Considerations	
Conditon	Prescriptions
Peri-orbital/Orbital Emphysema	
--- open communicating soft tissues	nothing specific
--- closed soft tissues	delayed validation; supplemental O ₂ , humidification, decongestants, no Valsalva/lifting, CAR
Penetrating Trauma	
--- open globe	nothing specific
--- closed globe	CAR, slow take-off/landing, recline w/ HOB elevated, supplemental O ₂ , antibiotics, bilateral patching estimated IOP < 50 mmHg per (baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg})
Inserted Gas	
--- general guidance	delayed validation until bubble at least < 30%
--- bubble < 20%	upright posture, CAR, aircrew counseled, sxms prompt cabin drop ≥ 2,000 feet; supplemental O ₂ as needed for retina (of questionable resorption benefit) estimated IOP < 50 mmHg per (baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg})
--- bubble ≤ 10%	upright posture, aircrew counseled, sxms prompt cabin drop ≥ 2,000 feet, estimate IOP to invoke "no CAR"; supplemental O ₂ as needed for retina (of questionable resorption benefit) estimated IOP < 50 mmHg per (baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg})

Note: O₂ (oxygen), CAR (cabin altitude restriction), HOB (head of bed), IOP (intraocular pressure), mmHg (millimeters mercury pressure), % (percent).

An open globe, though generally safe to fly, is not among the better ophthalmologic treatment options. As a result, the disrupted globe will usually be surgically closed. Retained, trapped air then becomes a TVFS issue. Its expansion at altitude can dislodge an embedded foreign body resulting in added damage. It can up IOP to the point of impaired central retinal artery flow, 50-110 mmHg. (Dieckert, 1986; Lincoff, 1989a; Mills, 2001; Ivan, 2003) It can up IOP to the point of optic neuropathy, which may well be the most worrisome IOP effect. (BJ Schwent, MD, personal communication) And, it can up IOP to the point of suture disruption and possible expelled global content, ~70 mmHg. (Ivan, 2003; Jun, 2012) With 4-6 mmHg added IOP with each 1,000 feet of altitude, an injurious IOP can easily be attained at 8,000 feet, not to mention the unlikely, but real risk of rapid decompression in combat. (Dieckert, 1986; Fromow-Guerra, 2016) Moreover, the already injured eye's compensatory mechanisms will

certainly not be optimal. Thus, the TVFS's primary prescription should be a CAR. **Figure 17** can offer up guidance as to the level of CAR to be prescribed, though it is primarily referable to inserted gas bubbles.

Notably, some have advocated a strict $\leq 2,000$ foot CAR, especially in the casualty setting. (**Dieckert, 1986; Ivan, 2003**) However, this sort of dogmatic approach may not be best. A physiologically flexible approach may be better. Integral to CAR level is avoidance of IOPs in excess of 50 mmHg (baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg} should be < 50 mmHg). Performing such calculations while employing **Figure 17** can yield a more reasoned and logical CAR prescription. At the same time, consulting the ophthalmologist for his/her maximum acceptable intraocular bubble volume can also aid in CAR determinations.

The TVFS can augment the CAR effect by prescribing slow, smooth take-offs and long, slow landings, so avoiding rapid altitude change. (**Dieckert, 1986; Mills, 2001**) In addition, reclining the patient with head of bed elevation will position the bubble away from the suture line. (**Ivan, 2003; Kanclerz, 2018**) Supplemental oxygen and antibiotics are important infection control prescriptions. (**Earnest, 2012; Abrames, 2012**) Lastly, protective patching of the eye must be ensured along with contralateral pinhole patching. The contralateral patching mitigates the rare potential (0.3%) for sympathetic ophthalmia (i.e., contralateral blindness). (**Abrames, 2012**) Thus, CAR, slow take-off/landing, head of bed elevation, supplemental oxygen, antibiotics, and bilateral patching are elemental to evacuating a patient suffering penetrating eye trauma with intraocular trapped air. See **Table 11**.

When it comes to an inserted gas bubble for the treatment of retinal detachment, the best course of action for the TVFS is to postpone transport until the gas has been fully resorbed. After all, evacuation in this setting is elective as definitive surgery has already taken place. However, the TVFS can be consulted when such a patient wants to travel by commercial air home or go on vacation prior to bubble dissolution. The Aerospace Medical Association (AsMA) guidance suggests no flight until the bubble is < 30% eye volume, that is 2 weeks wait if sulfur hexafluoride (SF₆) and 6 weeks wait if perfluoropropane (C₃F₈). (**Alvarez, 2003**) Although excellent general guidance, it is not the be all. For instance, after careful consideration, a patient with a 65% bubble flew safely between the Hawaiian Islands without sequelae. (**Kokame, 1994**)

To better individualize for the patient, the TVFS must take into account the cruising cabin altitude, bubble size, and the gas inserted. The cruising cabin altitude depends on the aircraft itself and the flight's cruising altitude. In 1988, Cottrell, over 204 commercial flights, found a mean cabin altitude of 5,673 feet (range = sea level to 8,915 feet); in 2013, Hampson et al, over 207 flights, found a mean cabin altitude of 6,341 feet (range = 232 to 8,549 feet); and, in 2020, Nazarali et al, over 113 flights, found a mean cabin altitude of 6,309 feet (range = 4,232 to 7,956). (**Cottrell, 1988; Hampson, 2013; Nazaralie, 2020**) Likewise, Kelly et al, found a median cabin altitude of 5,191 feet in 45 flights of the Boeing 747-400. (**Kelly, 2007**)

These altitudes are well below the requisite ceiling of 8,000 feet (14 CFR 25.841); however, despite this ceiling, commercial cabins will sometimes exceed it. Consequently, it is best if the TVFS knows the specific flight plan and aircraft being engaged. Regrettably, that is often not possible. In such a case, a tabular compendium of commercial aircraft inflight cabin characteristics may prove useful. See **Table 12**.

Table 12. Commercial Cabin Altitudes at a Cruising Altitude of 35,000 Feet

Aircraft Type	Differential Pressure (PSI)†	Cabin Altitude (ft)
Boeing 727	8.6	5,400
Boeing 757	8.6	5,400
Boeing 767	8.6	5,400
Boeing 747	8.9	4,700
Boeing 737	7.45	8,000
DC8	8.77	5,000
DC9	7.76	7,300
DC10	8.6	5,400
A-300	8.25	6,100
A-320	8.3	6,000
L-1011	8.4	5,800
BAC-111	7.5	7,900
Concord	10.7	1,000

* Cabin altitude is the design specification at a flight altitude of 35,000 feet. Cabin altitude varies with flight altitude. Reprinted with permission from reference 9.
†1 psi = 51.7 mmHg. Differential pressures were supplied by the manufacturer or the Federal Aviation Administration.

Note: Reprinted with permission. (Kokame, 1994) psi (pounds per square inch), ft (feet).

This table, in conjunction with **Figure 18**, permits a rough estimate of the increased IOP. As noted above, baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg} should be < 50 mmHg. (Mills, 2001; Fromow-Guerra, 2016) Generally, a bubble ≤ 20% is considered flyable with a CAR while a bubble ≤ 10% may not need a CAR. (Lincoff, 1989b; Mills, 2001; Hammer, 2010) But, be aware there is a report of vision loss with nerve damage flying a 10% bubble without a CAR. (Muzychuk, 2011)

Knowing the gas employed is also important. If the patient has a 100% bubble, knowing the specific gas permits the TVFS to estimate when the bubble might be flyable. For example, a C₃F₈ bubble, with a lifespan up to 80 days and a half-life of around 20[±] days, should be prohibited from flying for around 40 days (essentially the AsMA Guideline). At that time, a 25% bubble would be anticipated and flying could be considered.

At the same time, the patient should not be supine. This avoids block of the aqueous outflow permitting ready eye adaptation to altitude. (Ivan, 2003; Kanclerz, 2018) And, lastly, the patient should be advised to notify the commercial flight crew of his/her situation preflight. They well understand Boyle's Law physics and should the patient experience eye pain and/or loss of vision, they well understand the need for cabin descent. In such an instance, the cabin altitude should be dropped at least 2,000 feet, which should simultaneously drop the IOP by ~50%. (Lincoff, 1989b) Slow, smooth take-offs and long, slow landings are also advised, minimizing rapid IOP changes while maximizing natural adaptation by the eye. (Dieckert,

1986; Lincoff, 1989a; Kokame, 1994; Mills, 2001) Notably, such take-offs and landings are not really an issue as commercial flights routinely execute them for passenger comfort.

Thus, the TVFS should strongly advise against any patient flying with intraocular gas until the bubble is < 30%, preferably < 20%. Even so, the potential IOP should be estimated preflight and be < 50 mmHg, prompting the imposition of a CAR as needed. A bubble $\leq$ 10% may not need a CAR. That said, however, the patient should remain upright and the commercial aircrew notified. Specific instructions for the aircrew should include at least a 2,000 foot drop in cabin altitude with any eye pain and/or vision loss. See **Table 11**. **Table 1** lists the various countermeasures.

4.7.1.7A *Miscellaneous (Patient Equipment) Descriptions*

Many pieces of patient equipment are affected by the drop in cabin altitude. Without keeping them in mind, the patient could suffer ill effects. Prominent among these items is the endotracheal tube (or tracheostomy tube) and its cuff. With altitude, an air-filled cuff will expand against the tracheal wall. Over a prolonged time, pressure from the cuff can cause tissue ischemia and potentially eventuate into pressure necrosis, not to mention possible rupture or obstruction of the trachea (Parsons, 1982; Blumen, 1995; Grissom, 2003; McLaughlin, 2003) Similarly, bladder catheter balloons, if air-filled, may pose a threat, potentially expanding to the point of rupture.

Surgical drains can also pose inflight problems. Closed drainage systems, such as the Jackson-Pratt™ drain or the Hemovac™ drain, should be opened to the atmosphere during ascent and descent. If not, during ascent, air within the collection device can expand up the drain tubing into the surgical wound and, during descent, drainage effluent may be forced from the collection device back into the surgical wound. (Dawson, 2003)

The wound vac is a special piece of patient equipment best dealt with separately. A discussion dedicated to the wound vac can be found in **APPENDIX A, Brief Overview of the Wound Vac in AE**.

Ostomy appliances, while not a patient threat, can certainly react poorly to gas expansion. Indeed, the ballooning of the bag can dislodge the ostomy releasing intestinal and/or colonic content onto the patient, litter, and/or aircraft. (McLaughlin, 2003; Polk, 2003b)

Air splints and their ilk demand attention. Though effective immobilization devices, when taken to altitude, the expanding air produces a pressure vessel that clamps onto the extremity like a tourniquet. The result, ischemia through both venous and arterial occlusion. (Oreck, 2003)

An interesting sidebar is the epidural catheter. Generally speaking, it is not an air containing or producing device; however, during its insertion, air can be introduced into the pericatheter deep muscle tissues. (Earls, 1993) With ascent, air expansion could well produce deep muscle deformation and accompanying pain.

4.7.1.7B *Miscellaneous (Patient Equipment) Countermeasures*

There are two approaches for dealing with *endotracheal (or tracheostomy) tube cuffs*: 1) the air can be partially removed and replaced or 2) the air can be substituted with saline. (McLaughlin, 2003) The former approach requires air be removed on ascent and replaced with descent, both labor intense during a busy AE flight. In addition, remembering to return air to the

cuff on descent could be forgotten, leading to a loose tube and the potential for accidental extubation. The latter approach simply switches air with saline prior to flight; no other tube maneuvers are needed. (Blumen, 1995; Grissom, 2003; McLaughlin, 2003) *Bladder catheter balloons*, if air filled, should be treated in a like fashion.

Closed drainage systems, should be opened to the ambient atmosphere during ascent and descent. In that way, the air within the system will equilibrate with the atmosphere and no movement of either air or drainage fluid into the wound will occur. (Dawson, 2003)

Ostomies should be vented during ascent and descent. This can be done by “burping” the appliance (i.e., lifting an appliance edge) or “pinholing” (i.e., using a pin to create a small venting hole). These actions avoid unfortunate accidents. (McLaughlin, 2003; Polk, 2003b)

Air splints must be carefully monitored inflight. During ascent air must be vented to prevent tourniquet-like effects and during descent air must be added to prevent loss of immobilization. Labor-intense though they may be, these actions are imperative. It is best to forego the use of air splints for more traditional plaster ones. (Oreck, 2003)

Epidural catheters can be associated with deep muscle air. In fact, Earls et al described three such patients. (Earls, 1993) Consequently, any patient with an epidural catheter should be considered at risk for back pain from air expansion. The AE nursing staff should be made aware of this potential.

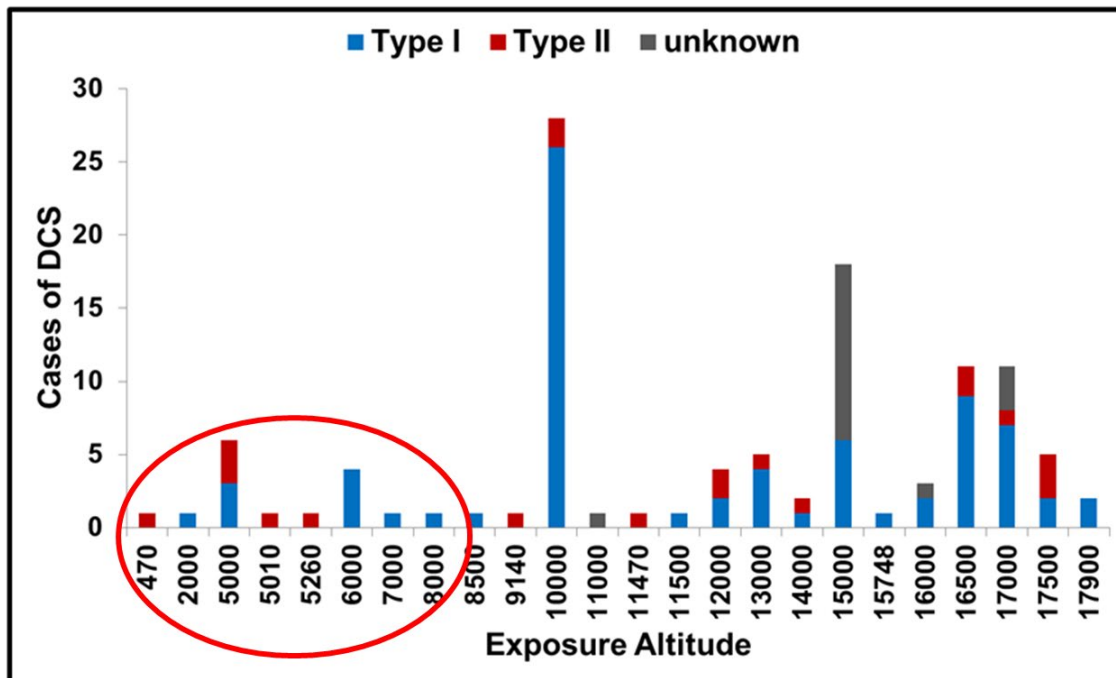
Thus, special attention need be paid to these sorts of patient equipment when the TVFS validates patients for AE. Though these interventions are primarily in the realm of the AE nurse, it is only reasonable for the TVFS to prescribe such actions, if only as a firm reminder. **Table 1** lists the various countermeasures.

4.7.2. Venous Gas Emboli Effects

4.7.2.1 Description

Venous gas emboli in this setting come in two varieties: evolved bubbles and infused bubbles. *Evolved bubbles* consist of nitrogen gas dissolved in tissue (e.g., plasma, muscle, fat). These nitrogen-saturated tissues, upon decompression, become super-saturated to the point where nitrogen bubbles form and then circulate. These bubbles (aka venous gas emboli) are essentially the same bubbles, when accompanied by symptoms that mark altitude decompression sickness (DCS).

Generally speaking, however, altitude DCS as a consequence of an exposure below 18,000 feet has been conceptually suspect. During World War II, a DCS threshold of 30,000 feet was put forward only to be revised to 18,000 feet with the publication of Fryer’s treatise entitled *Subatmospheric Decompression Sickness in Man*. (Gray, 1943; Fryer, 1969) Fryer’s work was based on empiric evidence and the seminal diving research of Boycott, Damant, and Haldane which held that a staged decompression of 2:1 (e.g., sea level to 18,000 feet) would not produce DCS. (Boycott, 1908) In the years between Gray and Fryer, various thresholds were put forward, among them 16,000 feet, 20,000 feet, 26,000 feet, 20,000-25,000 feet. (Kumar, 1990) More recently, 13,000 feet has been modelled and 20,500 feet has been experimentally demonstrated. (Kumar, 1990; Webb, 1998) That said, hyperbaricists occasionally treat a case of DCS originating below 13,000 feet, even to include AE cabin altitudes. (Rudge, 1990) In fact, in a large, as yet, unpublished case series, 17 of 111 cases of low altitude DCS originated < 8,500 feet. See **Figure 22**.



Note: Unpublished data. (Butler, 2013) DCS (decompression sickness), Exposure Altitude (feet).

Figure 22. Altitude Exposures Found in Large Case Series of Low Altitude DCS

At the same time, looking at the USAF High Altitude Research Database, 7 cases of DCS were discovered among the 424 research exposures below 16,500 feet for an incidence of 1.7%. (Butler, 2013) Dixon et al reported similar experimental incidence rates with exposures of 16,520 feet, 1.1% in men and 6.7% in women. (Dixon, 1986b; Dixon, 1988) Such low altitude cases of DCS suggest the presence of evolved bubbles at AE cabin altitudes. Indeed, there is some evidence suggesting a bubble threshold of ~11,500 feet. (Dixon, 1986a; Webb, 1998) Notably, bubbles have been documented experimentally as low as 10,250 feet (personal communication, JT Webb). (Webb, 1992) Moreover, in a swine model, bubbles have been detected as low as 6,562 feet. (Roach, 1995) All this strongly suggests that bubbles regularly evolve during AE.

Evacuating patients with IV fluids or IV medications strongly suggests that *infused bubbles* may well be regularly faced. This is particularly true if blood has been transfused, especially massively transfused. Warming blood from 4C to 37C changes solubility of dissolved gases such that up to 4.5 ml of gas will be generated per 400-500 ml blood. (Mashimo, 1980; Kuzukawa, 2005) A massive transfusion of 10U packed red blood cells (component transfusion) (pRBC) could easily generate 40-45 ml of gas and that gas is mainly inert nitrogen (85%). (Kuzukawa, 2005) Most of the gas is filtered out never being infused; however, emergent massive transfusions can see infusion rates exceedingly 70 ml/min, offering the potential to overwhelm the various in-line safety filters. (Pascale, 1985; Simms, 2014) Even with high transfusion rates and potentially overwhelmed filters, bubble volume is unlikely to ever reach the direct mechanical lethal level of 200 ml, though it is likely to stimulate so-called indirect blood-bubble interface inflammatory reactions. These include fibrin accretions, platelet aggregations, endothelial damage, microparticle generation, and ischemia-reperfusion

phenomenon, all contributing to localized tissue edema. (Ordway, 1974; Kuzukawa, 2005; McGuire, 2013; McGuire, 2014; Carden, 2000; Kaminsky, 2002; Butler, 2020a) Intracranial venous gas emboli and white matter hyperintensities offer up direct and indirect evidence for direct and indirect bubble effects. (Thompson, 1999; Tran, 2010; McGuire, 2013; McGuire, 2014) This certainly suggests that infused bubbles and their growth may well need to be considered before and during AE, respectively.

4.7.2.2 Countermeasures

The TVFS must consider the presence of both *evolved* and *infused* bubbles. These bubbles will grow dependent on the altitude at which they form and the time they reside at that altitude. Over a period of 100 minutes, in vitro bubbles at 14,000 feet were shown to grow from detectable to ~1.3 mm. (Olson, 1991) Most AE flights, despite cabins well under 14,000 feet, fully exceed 100 minutes, especially Pacific-based flights, wherein bubbles can continue to grow. Even though the bubbles probably do not pose a serious direct symptom risk (aka DCS threat), they can have physiological impact. This physiological effect is rooted in both mechanical and blood-bubble interface inflammatory mechanisms, where the final common pathway is the accumulation of interstitial fluid, or tissue edema. Thus, from the TVFS viewpoint, direct countermeasures to any evolved and/or infused bubbles are essentially unwarranted as the bubbles do not generally cause specific patient issues (e.g., DCS); however, suppressing the potential for bubble growth and the resultant edema does warrant attention. Here, the CAR prescription may well be indicated. That said, dealing with the impact of tissue edema is an extremely important and core consideration for the TVFS. A full discussion can be found in **Section 5.0**. **Table 1** lists the various countermeasures.

4.7.3. Altered Tissue Dynamics Effects

4.7.3.1 Description

Hypobaria is associated with altered tissue dynamics. Two mechanisms come to mind, that is inflammatory upregulation and Starling interstitial fluid disequilibrium. *Inflammatory upregulation* has been recognized for many years in the mountaineering literature; however, only recently has it been studied in the AE setting. The fact that acute mountain sickness occurs at terrestrial altitudes common to AE cabins suggests that the various inflammatory markers --- cytokines, prostaglandins, thromboxanes, leukotriene B₄, hypoxia inducible factor-1_{alpha}, vascular endothelial growth factor, inducible nitric oxide synthetase --- might well be seen with AE. (Richalet, 1991; Hackett, 2012; Luks, 2015) Indeed, multiple animal studies employing rat, mouse, and swine models, taken to 8,000^{+/-} feet for 1-6 hours, have demonstrated inflammatory upregulation. Markers such as interleukin-6, interleukin-10, thrombomodulin, syndecan-1, hyaluronic acid, macrophage inflammatory protein-1_{alpha}, neuron specific enolase, pulmonary myeloperoxidase, silver-stained axons, microglial/astrocyte activation, neutrophilic/histiocytic inflammation have been observed. (Goodman, 2011; Skovira, 2016; Proctor, 2017; Martin, 2019; Scultetus, 2019; Dayani, 2019; Lopez, 2020) This inflammatory boost poses not only a direct *second hit* threat, but also a reactive, more indirect tissue edema threat to an AE patient.

Concurrently, hypobaria provokes a *Starling disequilibrium*. Here, the usual intravascular-extravascular equilibrium is altered favoring fluid movement from the intravascular space into the extravascular, or interstitial, space. This so-called third spacing, for all intents and purposes, denotes tissue edema. Indeed, peripheral edema (hands, ankles, periorbital, and face) is not uncommon (up to 18% in one study). (Sheridan, 1970; Pines, 1974; Hackett, 1979) In fact,

such edemas have been seen under varied study environments to include mountains, inflight, and altitude chambers. (Gunga, 1995; Mittermayr, 2003; Iblher, 2013; Pescosolido, 2015) As first suggested by Blumen, then Shuster, and then later by Mittermayr et al and Butler et al, the Starling forces best describe the fluid movement physiology (aka edema formation) at altitude. (Blumen, 1995; Shuster, 1996a, 1996b; Mittermayr, 2003; Butler, 2016) Indeed, Starling's fluid flux equation is expressed as:

$$J_v = K_f * [(P_C - P_T) - (\pi_C - \pi_T)], \quad \text{where}$$

J_v is the driving force for fluid movement

($J_v > 0 \rightarrow$ denotes filtration into the interstitial space;

$J_v < 0 \rightarrow$ denotes resorption into the vascular space),

K_f is the capillary permeability factor,

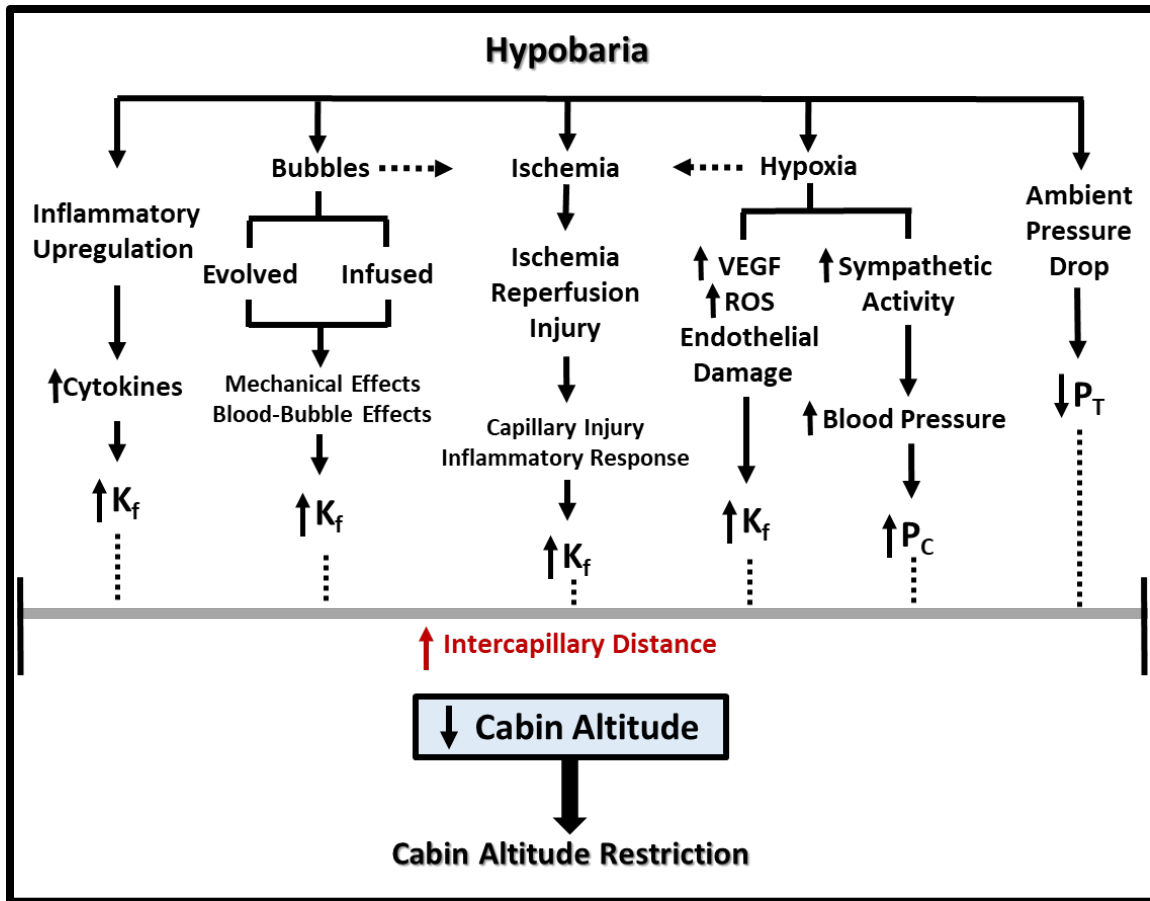
P_C is the capillary hydrostatic pressure,

P_T is the interstitial tissue hydrostatic pressure,

π_C is the capillary osmotic pressure, and

π_T is the interstitial tissue osmotic pressure. (Costanzo, 2011)

Edema formation is most commonly seen with an increased K_f , increased P_C , and/or decreased π_C . (Costanzo, 2011) However, a rise in π_T or drop in P_T could potentially produce edema. It is instructive to examine each of these factors in the AE setting of reduced ambient pressure. **Figure 23** offers a graphic overview of the following discussion.



Note: K_f (capillary permeability), P_c (capillary hydrostatic pressure), P_T (interstitial tissue hydrostatic pressure), VEGF (vascular endothelial growth factor), ROS (reactive oxygen species).

Figure 23. Hypobaria Impact on the Starling Intravascular-Extravascular Equilibrium

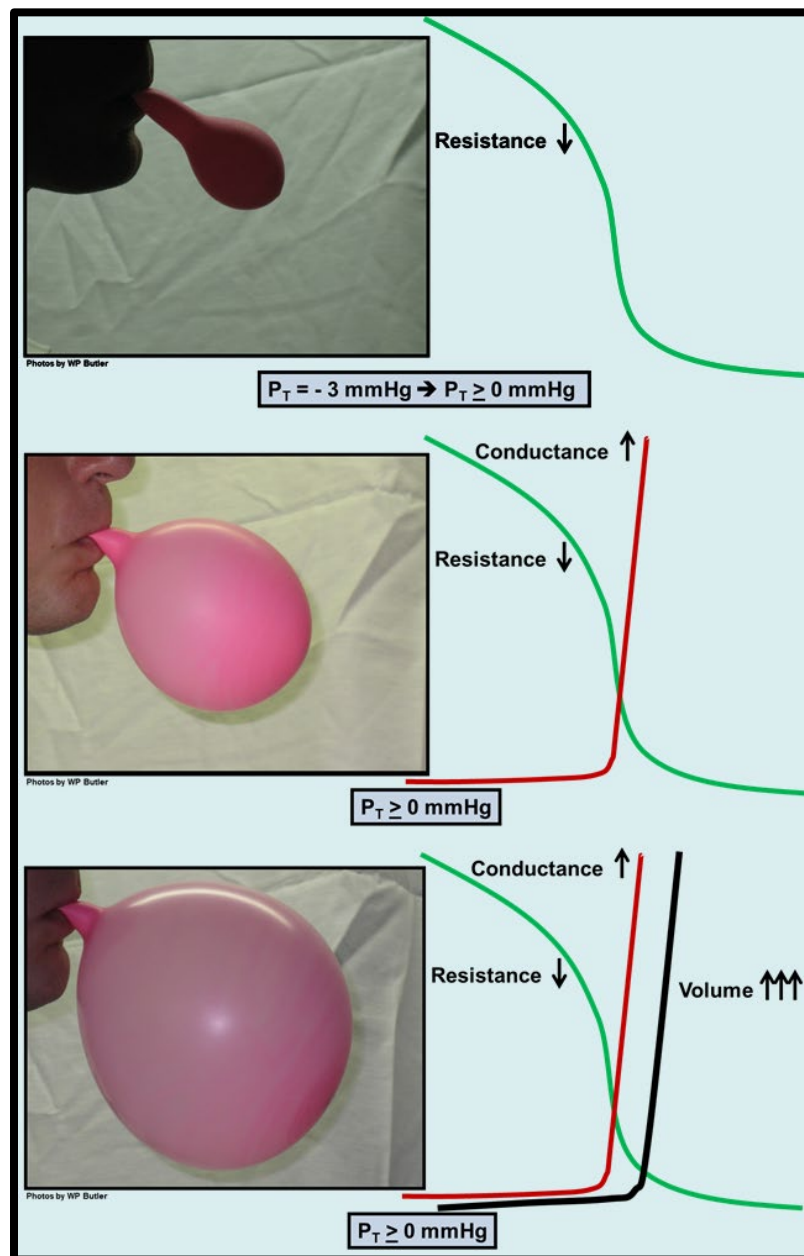
Approaching each formulaic factor, in the most likely order of precedence, follows:

- a) Increased Capillary Permeability (K_f) --- A rise in K_f secondary to hypobaric hypoxia was first implicated in 1932. Since that time, altitude-associated mechanisms for such capillary dysfunction have included both oxygen radicals and adhesion molecules. (Richalet, 1995) In addition, studies into acute mountain sickness have indicted cytokines, hypoxia inducible factor-1 $_{\alpha}$, vascular endothelial growth factor, and inducible nitric oxide synthetase. (Hackett, 2012; Luks, 2015) In fact, movement of albumin into the interstitial space has confirmed the leaky capillaries. (Gunga, 1995) Moreover, recent studies suggest altitude itself upregulates inflammatory activity (Goodman, 2011; Skovira, 2016), infused and/or evolved bubbles may cause capillary dysfunction (Richalet, 1995; Roach, 1995; Butler, 2016), and traumatized and/or burned patients release high levels of histamine and bradykinin (Richalet, 1995; Costanzo, 2010); all effectively upping K_f . Plus in the notion that, upon landing, re-oxygenation of altitude-mediated ischemia may well set in motion leukocyte-mediated endothelial injury, with its associated leaks --- the so-called ischemia-reperfusion phenomenon. (Carden, 2000; Kaminsky, 2002) Lastly,

- vibration appears associated with tissue edema; the mechanism, though unclear, may involve capillary dysfunction. (Lundborg, 1987; Mittermayr, 2003) In sum, K_f almost certainly rises in the evacuated patient and is a key to fluid movement into the interstitium.
- b) Increased Capillary Hydrostatic Pressure (P_C) --- A rise in P_C is expected. A consistent finding at altitude is a rise in blood pressure, both in animals and humans. (Sculletus, 2016; Torlasco, 2015; Parati, 2015) This is especially realized in the lung where pulmonary artery pressure rises with altitude. (Ballmer, 1995) Couple that with dilated arterioles and constricted venules (seen with trauma/burn-mediated release of histamine and bradykinin) and P_C is bound to rise. (Richalet, 1995; Costanzo, 2011) In toto, P_C most likely rises in the evacuated patient and is a key to fluid movement into the interstitium.
 - c) Decreased Capillary Osmotic Pressure (π_C) --- A drop in π_C is an unlikely primary consequence of altitude. Most commonly, fluid movement into the interstitium due to decreased π_C is from significant medical maladies (e.g., nephrotic syndrome, hepatic failure). (Costanzo, 2011) On the other hand, as a secondary effect from rises in K_f and/or P_C , π_C may well drop. After all, movement of albumin from the intravascular space into the extravascular space has been observed with altitude. (Gunga, 1995) So, a drop in π_C may occur, but cannot be considered a key to fluid movement.
 - d) Increased Interstitial Tissue Osmotic Pressure (π_T) --- A rise in π_T is an unlikely primary consequence of altitude. It would be the consequence of albumin movement into the interstitial space associated with rises in K_f and P_C . (Gunga, 1995) So, an increase in π_T may occur, but cannot be considered a key to fluid movement.
 - e) Decreased Interstitial Tissue Hydrostatic Pressure (P_T) --- A drop in P_T is a potential primary consequence of altitude. A number of studies employing lower body negative pressure suggest lowered ambient pressure favors fluid movement into the interstitial tissues. (Brown, 1966; Musgrave, 1969; Lundvall, 1989a, 1989b, 1993) Others have similarly suggested that with a drop in ambient pressure (P_B), interstitial pressure (P_T) "...will fall towards the value of the applied pressure [Pippard]." (Brace, 1977; Pippard, 1989) Generally, P_T is considered to be around -3 mmHg relative to atmospheric pressure (which is considered zero pressure). (Guyton, 1971; Hall, 2011) Flying at 8,000 feet will reduce P_B by almost 200 mmHg. In order for the microcirculation to equilibrate, P_T must drop. To our knowledge, there is no specific literature addressing this question. However, there seems to be abundant indirect evidence to include: increased pulmonary lymph flow with normoxic hypobaria (Roach, 1995); hypobaria without associated albumin movement (Ballmer, 1995); increased forehead tissue thickness with long haul commercial flights unassociated with albumin movement (Mittermayr, 2003); increased corneal thickness associated with normoxic hypobaria (Pescosolido, 2015); subtle cerebral edema on magnetic resonance imagery (MRI) with Inside Observers (on oxygen) following altitude chamber training (Sherman, 2015); and worsening of rat TBI with normoxic hypobaria (Hsieh, 2015). Consequently, decreased P_T may well be a key to fluid movement into the interstitium.

With the movement of fluid into the interstitial space, interstitial hydrostatic pressure rises. As it climbs from around -3 mmHg to and beyond 0 mmHg, there is a sudden drop in tissue

resistance to fluid inflow accompanied by a sudden rise in tissue conductance for fluid inflow. This makes for a rapid high-volume fluid accumulation in the interstitium producing tissue edema. (Guyton, 1966; Guyton, 1968) This process is not unlike that of blowing up a balloon. Once the initial resistance is overcome, the balloon easily accommodates added air, no matter the rate. See **Figure 24**. And, just as excess air is a threat to balloon rupture, tissue edema is indeed a threat to the AE patient, a threat that must be considered by the TVFS.



Note: Photographs taken by and courtesy of author (WPB). Curves depict concepts and data previously published. (Guyton, 1966; Guyton, 1968; Klatzo, 1987; Krasney, 1994) P_T (interstitial tissue hydrostatic pressure), mmHg (millimeters mercury pressure).

Figure 24. Balloon Analogy for Altitude-Mediated Tissue Edema (Starling Physiology)

4.7.3.2 Countermeasures

Hypobaric-induced *inflammatory upregulation* and *Starling disequilibrium* both favor the accumulation of tissue edema. With such edema, a widened intercapillary distance is likely which, in turn, can impede oxygen diffusion. (Leach, 1998; Miserocchi, 2011; Dunn, 2016) The overall result is a potential drop in tissue oxygen delivery (DO_2). To counter this potential drop in DO_2 , the TVFS must actively moderate the edema of altitude. The sole direct counter is a prescription for a CAR. By reducing cabin altitude, the impetus for edema formation is suppressed. See **Section 5.0** for an in-depth discussion detailing how the TVFS can seriously influence DO_2 . **Table 1** lists the various countermeasures.

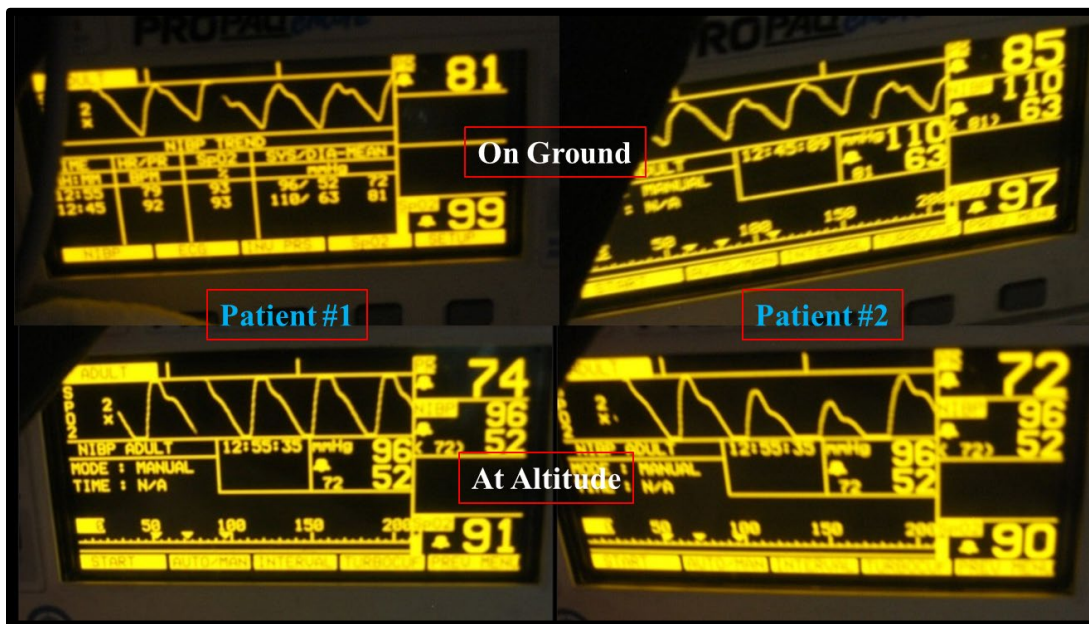
4.8 Hypoxia

4.8.1. Description

Hypoxia comes with altitude; the higher one goes, the greater the degree of hypoxia. Commercial airline cabins, in the United States, have a pressure ceiling of 8,000 feet. (14 CFR 25.841) Studies have recorded mean peak cabin altitudes at 5,673 feet and 6,341 feet, logging between sea level and 8,915 feet. (Cottrell, 1988; Hampson, 2013; Nazarali, 2020) Specifically, commercial jet cabins ranged from 1,421-8,445 feet, regional jets 298-8,549 feet, and turboprops 232-6,112 feet. (Hampson, 2013) In contrast, military cabin altitudes generally range between 8,000 and 10,000 feet. (Borden Institute, 2004)

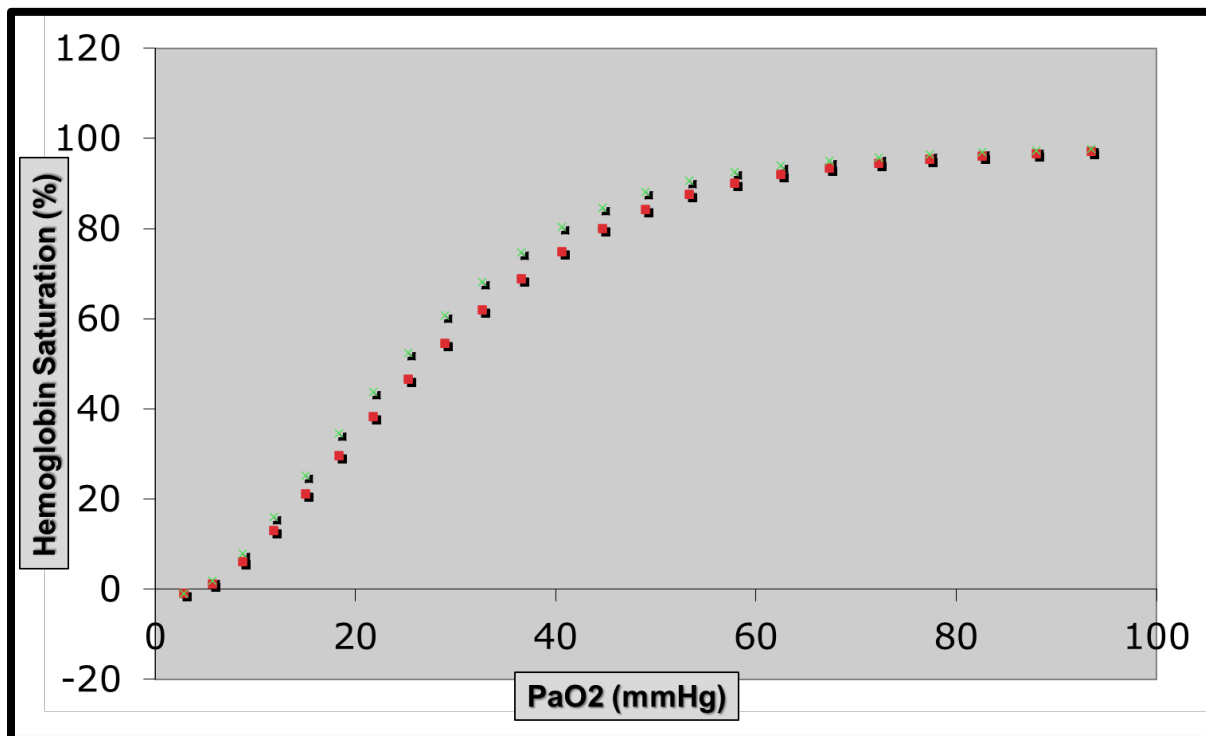
At 8,000 feet, the ambient barometric pressure drops from 760 mmHg to 564 mmHg and the oxygen partial pressure drops from 160 mmHg to 118 mmHg. Thus, the ground level (aka sea level) FiO_2 drops from 21% to 16%. Normal, healthy individuals generally tolerate this level of hypoxia without incident; however, not necessarily so for those very sick or critically ill patients. (Blumen, 1995; Dufour, 2003; McLaughlin, 2003; AFI 48-307 Vol 1, 2017)

Even normal individuals will see hypoxia. In fact, at 8,000 feet, oxygen-hemoglobin saturation will commonly drop to ~90%. This has been anecdotally recorded in both patients and crew. See **Figure 25**. As depicted nicely with the Oxyhemoglobin Dissociate Curve, the ~90% saturation reflects a PaO_2 of around 60 mmHg, a definite issue for AE patients and the TVFS. See **Figure 26**.



Note: Photographs taken by and courtesy of author (WPB).

Figure 25. Oximetry Readings of Two Patients, on the Ground and at Altitude



Note: Graphic created by and courtesy of Lt Col Daniel Cole. (USAFR, MC, FS) Physiological equations derived by Kelman were employed. (Kelman, 1966a; Kelman, 1966b) The **Red Squares** represent the Kelman equation; the **Green Xs** represent the Kelman equation corrected for pH and patient temperature. % (percent), mmHg (millimeters mercury pressure).

Figure 26. Oxyhemoglobin Dissociation Curve

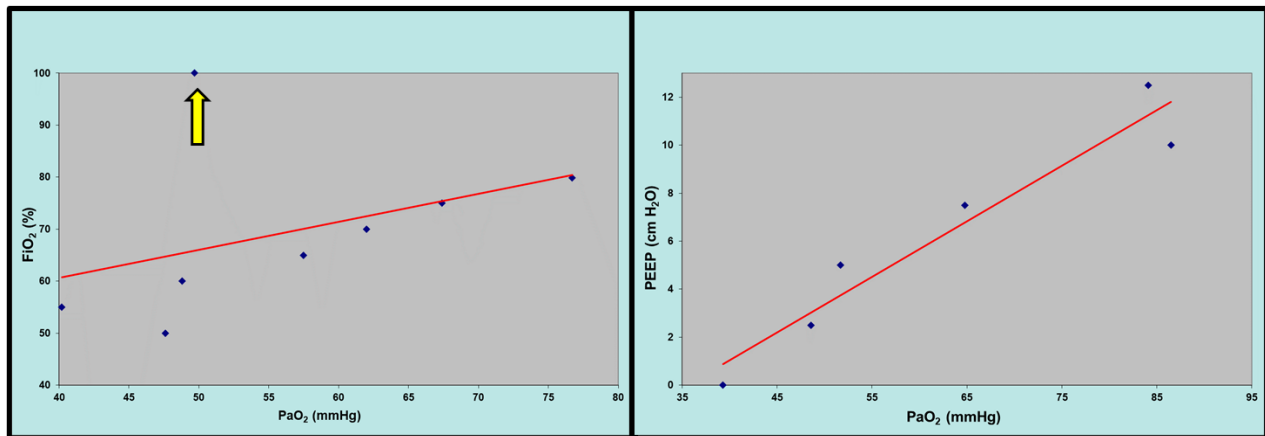
This interlocking notion of altitude-induced reductions in hemoglobin saturation and PaO₂ is well represented in the literature. Cottrell et al, looking at 38 commercial airline pilots, found an average drop in SpO₂ of 8.4% and 20 of the pilots' SpO₂ fell below 90%. (**Cottrell, 1995**) In another study, 84 passengers displayed a mean drop in SpO₂ from 97% to 93%, the lowest recorded being 85%. (**Humphreys, 2005**) Bendrick et al studied 24 coronary artery disease AE patients; the median SpO₂ was 91% (range 85%-96%). A full 21% dropped SpO₂ below 90%, fortunately without symptoms. (**Bendrick, 1995**) Similarly, Johannigman et al followed the evacuation of the so-called "walking wounded." Of 61 patients, 90% exhibited "hypoxemia" (SpO₂ < 90%), while 56% exhibited "critical hypoxemia" (SpO₂ < 85%). Most concerning were the durations of hypoxemia and critical hypoxemia, 4 seconds to 3.9 hours and 6 seconds to 42 minutes, respectively. (**Johannigman, 2015b**) And of greatest import, Henry et al examined inflight PaO₂ in 201 patients evacuated from Vietnam to Japan. Without supplemental oxygen, they found PaO₂ dropped to ≤ 60 mmHg in 47% and ≤ 50 mmHg in 31%. In addition, the higher the cabin altitude the greater the drop in PaO₂ --- cabin altitudes between 6,700-7,500 feet produced a 33% drop while cabin altitudes between 3,000-3,500 feet generated only a 19% drop. (**Henry, 1973**) Throw into this mix the notion that vibration and the intensified metabolism of a critical patient essentially mimic exercise effects, dropping SpO₂ and PaO₂ even further, by around 5-12% and 10-30%, respectively. (**Schacke, 2007; Martin, 2015**) The result, altitude and its concomitant drop in FiO₂, SpO₂, and PaO₂ demand an increased need for oxygen in AE's "stabilized" patients.

At the same time, patients fresh from extubation, whether from the ICU or the Operating Room (OR), present a potential hypoxia and/or airway issue for the TVFS. Although the patient may have the appropriate parameters for extubation while in the ICU, those parameters may not be the best for expeditious enplanement. In those patients who have been extubated after several days of ventilator dependence, re-intubation is not uncommon. In fact, re-intubation is seen anywhere between 2% and 23% of the time (usual reporting period is 72 hours). (**Miller, 1995; MacIntyre, 2004; Frutos-Vivar, 2006; Gowardman, 2006**) This fact strongly suggests a wait of perhaps 24 hours might well be prudent.

Rapid extubation after surgery is a common circumstance. However, the initial 4-6 hours following surgery is a dynamic time demanding close observation in the best setting. This setting is commonly called the Recovery Room (RR) or the Post-Anesthesia Care Unit (PACU). The usual stay ranges from about 50 minutes to almost 4 hours; albeit, longer stays are not unheard of. (**Hines, 1992**) During this time, a number of very serious complications may present including upper airway problems (laryngospasm, laryngeal edema, soft tissue obstruction), lower airway problems (aspiration, bronchospasm, desaturation, non-cardiogenic pulmonary edema, shunting), cardiac depression, and CNS depression. (**Odom, 1993; Ahmad, 2006**) These complications are not uncommon; reports range from 1.3% to 47% with most seeming to be between 10-20%. (**Moller, 1993a; Moller, 1993b; Rose, 1994; Ouchterlony, 1995; Asai, 1998; Tarrac, 2006**) In addition, within the first hour in the RR or PACU, better than half of patients desaturate (some even drop below 80%), hence the almost universal application of supplemental oxygen; and, the deeper the anesthesia, the more likely the complication. (**Canet, 1989; Moller, 1990; Asai, 1998**) Over the ensuing four to six hours, the probability of these problems precipitously falls to the point of tolerating transport either to the ICU or an inpatient bed. At that point, the patient is better suited for AE transport.

4.8.2. Countermeasures

In order to avoid hypoxia, the TVFS must up the oxygen content in the blood. In non-ventilated patients this can be done by prescribing supplemental oxygen (increasing the FiO_2). In ventilated patients, this can be done by upping the FiO_2 and/or the PEEP (positive end-expiratory pressure). Although PEEP appears more effective at altitude, it takes more time for it to work. Lawless et al, in an oleic acid lung-damaged swine model taken to 8,000 feet, demonstrated that raising either the FiO_2 or PEEP can compensate for the falling ambient pressure. Whereas all the PEEP-treated animals maintained oxygenation, only half of the FiO_2 -treated animals maintained oxygenation. (Lawless, 2001) See Figure 27.



Note: Graphic created using tabular data presented by Lawless et al. (Lawless, 2001) Arrow depicts the three swine not meeting PaO_2 despite full 100% FiO_2 . ARDS (Adult Respiratory Distress Syndrome), FiO_2 (oxygen fraction of inspired gas), PEEP (positive end-expiratory pressure), PaO_2 (arterial oxygen partial pressure), % (percent), mmHg (millimeters mercury pressure), cmH₂O (centimeters water pressure).

Figure 27. Effect of FiO_2 and PEEP in Oleic Acid ARDS Swine Model at 8,000 Feet

At altitude, when ventilated patients encounter difficulty with oxygenation, the swiftest remedy, added FiO_2 , is best applied. Here, it is important that the TVFS maximize the PEEP and minimize FiO_2 preflight. In this way, the CCATT has the greatest range of FiO_2 available inflight. Pushing PEEP as high as 12 cmH₂O while keeping FiO_2 as low as possible, in keeping with the ARDSNet ARMA trial will not only protect the lungs from potential barotrauma, but also offer up to the CCATT team excess treatment- FiO_2 inflight. See Table 13. (ARDSNet, 2000; JTS, 2013) To make this happen, discussion with the treating intensivist is crucial. At the same time, the TVFS must also consider imposing a CAR as this will effectively lower the requisite ground equivalent FiO_2 and concurrently increase the oxygen available for CCATT use.

Table 13. CCATT CPG - ARDSNet Lung Protective Ventilator Strategy

PEEP Titration Table - ARDSNet ARMA Trial																	
PEEP	5	5	8	8	10	10	10	12	14	14	14	16	18	18	20	22	24
FiO2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	1	1	1	1
<-----Move across table to keep SaO₂ 92 – 96 %-----> Patients falling in shaded area are not necessarily too sick for flight but risks and benefits should be considered as described in the CPG.																	

Note: Graphic taken from the Joint Trauma System *CCAT Mechanical Ventilation Clinical Practice Guideline*, a US government publication not subject to copyright. (JTS, 2013) CCAT[T] (Critical Care Air Transport [Team]), PEEP (positive end-expiratory pressure), ARDSNet (Acute Respiratory Distress Syndrome Network), ARMA (ARDS Respiratory Management Arm), FiO₂ (oxygen fraction of inspired air), SaO₂ (arterial hemoglobin oxygen saturation (%)), CPG (clinical practice guideline).

Ground level equivalency is an integral part of the TVFS's clinical practice. Any patient taken to altitude should be considered for inflight supplemental oxygen. This is especially true in a patient with serious bone or soft tissue disruption. These sorts of wounds are routinely colonized with bacteria. Taken into the hypoxic AE cabin, these bacteria can become more than just colonizers; they can become infectors. In fact, Earnest et al demonstrated that *Pseudomonas aeruginosa* growth, in a complex wounded/infected caprine model taken to 8,800 feet for 7 hours, could be inhibited with supplemental oxygen. (Earnest, 2012) Ground level equivalency at the very least, as prescribed by the TVFS, could well moderate the potential for an infectious *second hit*.

Similarly, any patient already on supplemental oxygen preflight must fly with at least ground level equivalency. To prescribe ground level equivalent oxygen, several calculations are requisite. (McLaughlin, 2003) The inspired oxygen partial pressure needs to be determined. This can be done with

$$PiO_2 = FiO_2 * (P_{\text{ground level}} - P_{H_2O}), \quad (1)$$

where PiO₂ is the inspired oxygen partial pressure, FiO₂ is the oxygen fraction, P_{ground level} is the barometric pressure at ground level and P_{H₂O} is the partial pressure of water vapor. Water vapor must be considered since the body humidifies all inspired air/gas. Inserting appropriate values permits calculation of ground level (in this case, sea level) inspired oxygen partial pressure.

$$PiO_2 = 0.21 * (760 \text{ mmHg} - 47 \text{ mmHg}) = \sim 150 \text{ mmHg} \quad (2)$$

To determine the ground level equivalent fraction of oxygen at any given altitude (P_{altitude}), the following expression is applied:

$$FiO_2 * (P_{\text{ground level}} - P_{H_2O}) = \text{Required } FiO_2 * (P_{\text{altitude}} - P_{H_2O}) \quad (3)$$

Rearranging the expression:

$$\text{Required } FiO_2 = [FiO_2 * (P_{\text{ground level}} - 47 \text{ mmHg})] / (P_{\text{altitude}} - 47 \text{ mmHg}) \quad (4)$$

Study an example. A patient to be evacuated is breathing 60% oxygen. The AE mission is flown with a cabin altitude of 8,000 feet and ground level is at sea level. Calculating with appropriate values produces:

$$\text{Required FiO}_2 = [\text{FiO}_2 * (\text{P}_{\text{ground level}} - 47 \text{ mmHg})] / (\text{P}_{\text{altitude}} - 47 \text{ mmHg}), \quad (1)$$

$$\text{Required FiO}_2 = [0.60 \times (760 \text{ mmHg} - 47 \text{ mmHg})] / (565 \text{ mmHg} - 47 \text{ mmHg}), \quad (2)$$

$$\text{Required FiO}_2 = [0.60 \times (713 \text{ mmHg})] / (518 \text{ mmHg}) = \mathbf{0.83} \text{ (or } \mathbf{83\%}) \quad (3)$$

So, in order to fly this patient at ground level (in this case, sea level) equivalency, the TVFS will have to prescribe an FiO₂ of 83%. This can be achieved with a high-flow non-rebreather mask. In this manner, any ground level FiO₂ can be calculated for any given cabin altitude. In addition, any destination ground level FiO₂ requirements can also be factored using these equations.

Making these calculations for each patient is not efficient. However, a table using these concepts and calculations can be created permitting rapid FiO₂ determinations. It can also include the devices capable of oxygen delivery. See **Table 14**. When using the table, the TVFS should note that above an FiO₂ of ~75%, sea level equivalency cannot be achieved at 8,000 feet even with the delivery of 100% oxygen.

Table 14. Table for Determining Sea Level Oxygen Equivalency at Altitude

Altitude (Ft)	Atmospheric Pressure (mmHg)	Oxygen 21% (mmHg)	Oxygen Requirements to Maintain Sea Level Equivalency**																		
10000	522	110		32	38	45	53	60	68	75	83	90	98								
9000	543	114		30	36	43	50	58	65	72	79	86	93								
8000	565	119		29	34	41	48	55	62	69	76	83	89	96							
7000	587	123		28	33	40	46	53	59	66	73	79	86	92	99						
6000	609	128		27	32	38	44	51	57	63	70	76	82	89	95	101					
5000	633	133		26	30	37	43	49	55	61	67	73	79	85	91	97					
4000	656	138		25	29	35	41	47	53	59	64	70	76	82	88	94	100				
3000	681	143		24	28	34	39	45	51	56	62	67	73	79	84	90	96				
2000	707	148		23	27	32	38	43	49	54	59	65	70	76	81	86	92	97			
1000	733	154		22	26	31	36	42	47	52	57	62	68	73	78	83	88	94	99		
0	760	160	PiO ₂	150	178	214	250	285	321	357	392	428	463	499	535	570	606	642	677	713	
			FiO ₂	0.21	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	
		O ₂ Source	RA	Nasal Cannula (1-6 L/min)						Non-Rebreathing Mask (7-15 L/min)											
				Simple Mask (5-10 L/min)						Partial Rebreathing Mask with Bag (7-15 L/min)											
				**Pertinent Formula:																	
				$PiO_2 = FiO_2 \times (P_{\text{sea level}} - P_{H_2O})$ $\text{Required } FiO_2 = [FiO_2 \times (P_{\text{sea level}} - 47 \text{ mmHg})] / (P_{\text{altitude}} - 47 \text{ mmHg})$																	

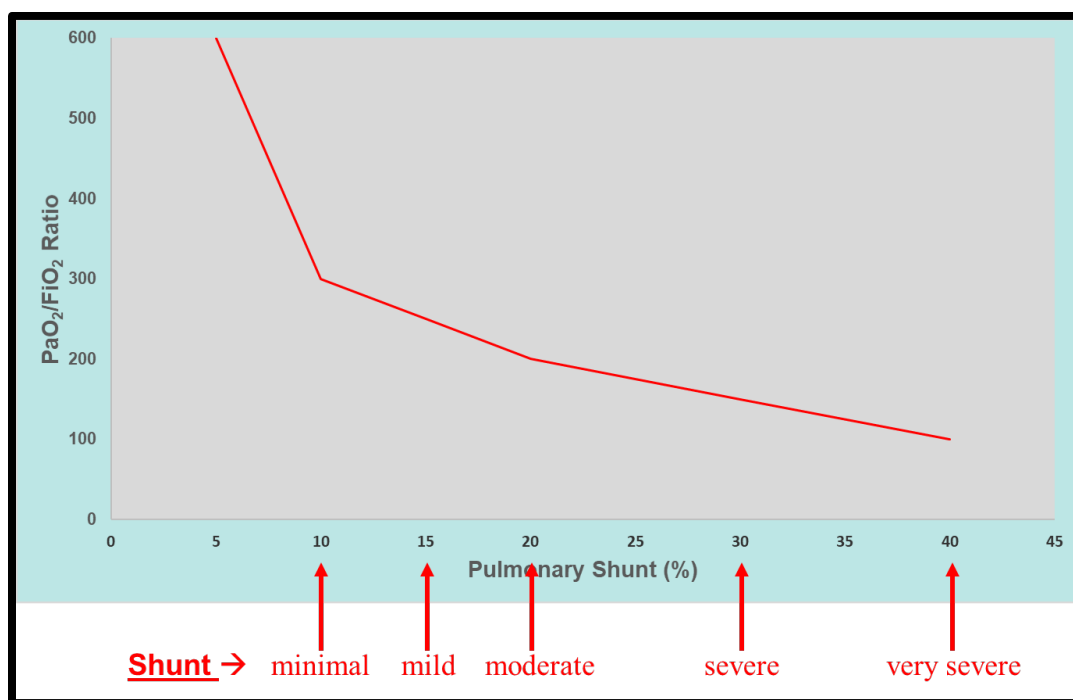
Note: Table employs formulae described by McLaughlin et al and oxygen delivery device capabilities described in the Air Force Instruction. (McLaughlin, 2003; AFI 48-307 Vol 1, 2017) Although this table is determined for sea level equivalency, another could be easily created with any desired ground level equivalency. Rule of Thumb: Nasal Cannula (~4% per L/min); Simple Mask (~6% per L/min); Non-Rebreathing Mask (~4-6% per L/min). Ft (feet), mmHg (millimeters mercury pressure), % (percent), PiO₂ (partial pressure of inspired air), FiO₂ (oxygen fraction of inspired air), O₂ (oxygen), RA (room air), L (liter), min (minute), P (pressure).

Thus, the TVFS should prescribe supplemental oxygen for those patients at risk for infection (e.g., serious bone and/or soft tissue injury) and for those patients already requiring

supplemental oxygen. The FiO_2 at altitude required to maintain ground level equivalency needs to be determined and prescribed. Use of **Table 14** can facilitate the process; however, individualized calculations are always a relatively straightforward option.

Turning now to the immediately postoperative patient. Occasionally, the TVFS is asked to validate this patient. If the patient remains intubated and ventilated, it is uncomplicated. A CCATT team and ground level equivalent supplemental oxygen will counter the flight stressor of hypoxia. However, putting a freshly extubated patient from the OR onto a ready aircraft is much more complicated and probably not the best approach. Consider a couple of examples. A patient, within the first hour of OR extubation, demonstrated a saturation of 92% on room air; within the second hour, he had a 20% pulmonary shunt; and, within 5 hours, had a saturation of 99% ($\text{FiO}_2 = 25\%$) and a fully resolved shunt. Another patient, shortly after extubation, demonstrated a saturation of 96% ($\text{FiO}_2 = 35\%$) with about an 18% shunt; seven hours later, the saturation was 99% ($\text{FiO}_2 = \text{room air}$) with a minimal ($< 10\%$) shunt. Putting such dynamic patients in a vibrating, noisy, poorly lit, hypothermic, low humidity, hypoxic, difficult-access environment is a recipe for shunt exacerbation and desaturation, potentially necessitating inflight intubation and ventilation. And, knowing that 10-20% of patients *will* demonstrate a problem during the first 4-6 hours post-anesthesia, extubation strongly suggests flying be avoided during that timeframe. (Moller, 1993a; Moller, 1993b; Rose, 1994; Ouchterlony, 1995; Asai, 1998; Tarrac, 2006)

To that end, a good guide for determining when this patient can be manifested for AE is the pulmonary shunt ratio, $\text{PaO}_2/\text{FiO}_2$. Over the course of several hours, the shunt will generally return to normal. Following the patient's shunt values against a pulmonary shunt curve will help the TVFS safely time AE. See **Figure 28**.



Note: Graphic created using data presented in Tintinalli's Emergency Medicine. (Glass, 2020) PaO_2 (arterial oxygen partial pressure), FiO_2 (oxygen fraction of inspired air), % (percent).

Figure 28. Pulmonary Shunt Ratio-Percent-Severity Depiction

Should arterial blood gas capability be limited, the pulse oximetry shunt ratio SpO_2/FiO_2 can be substituted. Although the relationship between PaO_2/FiO_2 and SpO_2/FiO_2 was developed to facilitate diagnosis of acute lung injury and acute respiratory distress syndrome, it can be employed by the TVFS to determine a return to normalcy. (Pandharipande, 2006; Rice, 2007; Pandharipande, 2009) See Table 15.

Table 15. PaO_2/FiO_2 versus SpO_2/FiO_2 Pulmonary Shunt Ratio Correlation

PaO_2/FiO_2 Ratio versus SpO_2/FiO_2 Ratio Correlation		
PaO_2/FiO_2 Ratio	SpO_2/FiO_2 Ratio	Clinical Setting
< 400	< 400-512	Acute Lung Injury Acute Respiratory Distress Syndrome
< 300	< 316-357	
< 200	< 214-232	
< 100	< 67-148	

Note: Table developed from calculations based on regression equation $S/F = 64 + (0.84 * P/F)$ and data presented various articles. (Pandharipande, 2006; Rice, 2007; Pandharipande, 2009) S (SpO_2), F (FiO_2), P (PaO_2), PaO_2 (arterial oxygen partial pressure), FiO_2 (oxygen fraction of inspired air).

Thus, the TVFS should resist validating a freshly extubated patient, in particular one directly from the OR. It is better to wait the 4-6 hours requisite for the post-anesthesia shunt to resolve. Alternatively, a patient absolutely needing AE should not be extubated, but rather be transported with a CCATT and ventilator. Of course, ground level equivalent supplemental oxygen should also be prescribed. Table 1 lists the various countermeasures.

5.0 TISSUE OXYGEN DELIVERY (DO₂ PARADIGM) PHYSIOLOGY

5.1 Introduction

Having discussed the various flight stressors and their potential impact upon AE patients along with the countermeasures (aka prescriptions) available to the TVFS, it is now time to discuss DO₂ and the DO₂ paradigm. In the severely ill/injured patients that require AE, DO₂ is critical to a safe flight. See **Figure 2**.

Up until recently, AE was the sole realm of clinically stable patients. In the early 1990s, it became clear that AE was transitioning to the care and transport of “stabilized,” or clinically volatile patients. In other words, ICU patients; hence the creation of the CCATT team. This 3-person team consisting of a critical care experienced physician, nurse, and respiratory technician became a reality in 1994. Its worth has been proven repeatedly. (**Beninati, 2008**)

With the initiation of Operations Iraqi Freedom and Enduring Freedom, ICU level care during AE became not only possible, but also routine. It was important that AE and the TVFS transition to ICU-like clinical thinking.

In late 2006, Grissom et al suggested prehospital supplemental oxygen be added to tactical casualty combat care during mountain operations based on DO₂ modelling. (**Grissom, 2006**) Around the same time, independently, Pollan and Fisher followed by Butler addressed hemoglobin levels during AE using similar DO₂ modelling. (**Pollan and Fisher, 2006; Butler, 2007b**) Although DO₂ had long been part of the critical care world, its incorporation into pre-hospital care and AE was pioneering. In fact, two successive TVFSs, the authors (WPB and LWS), fully integrated DO₂ into their clinical validation deliberations, calling it the DO₂ paradigm. (**Butler, 2020a**)

5.2. Derivation of and Factors Affecting DO₂

Tissue oxygen delivery is crucial to the health and well-being of any person, but particularly so for the very sick and/or critically injured. In these patients, compromised tissues already exist, the *first hit*. Compromise the tissues further with an impaired DO₂, the *second hit*, and extra morbidity and mortality can be expected. Therefore, it is incumbent upon the TVFS to optimize DO₂.

In order to optimize DO₂, the TVFS must calculate DO₂. This can be done with three standard physiological equations and the oxyhemoglobin dissociation curve. The equations are as follows. See **APPENDIX A, Notations from the DO₂ Equations** for details.

Alveolar Gas Equation (**Costanzo, 2011**) → (1)

$$P_{A_{O_2}} = [(P_B - P_{H_2O}) * F_{i_{O_2}}] - P_{a_{CO_2}}/RQ$$

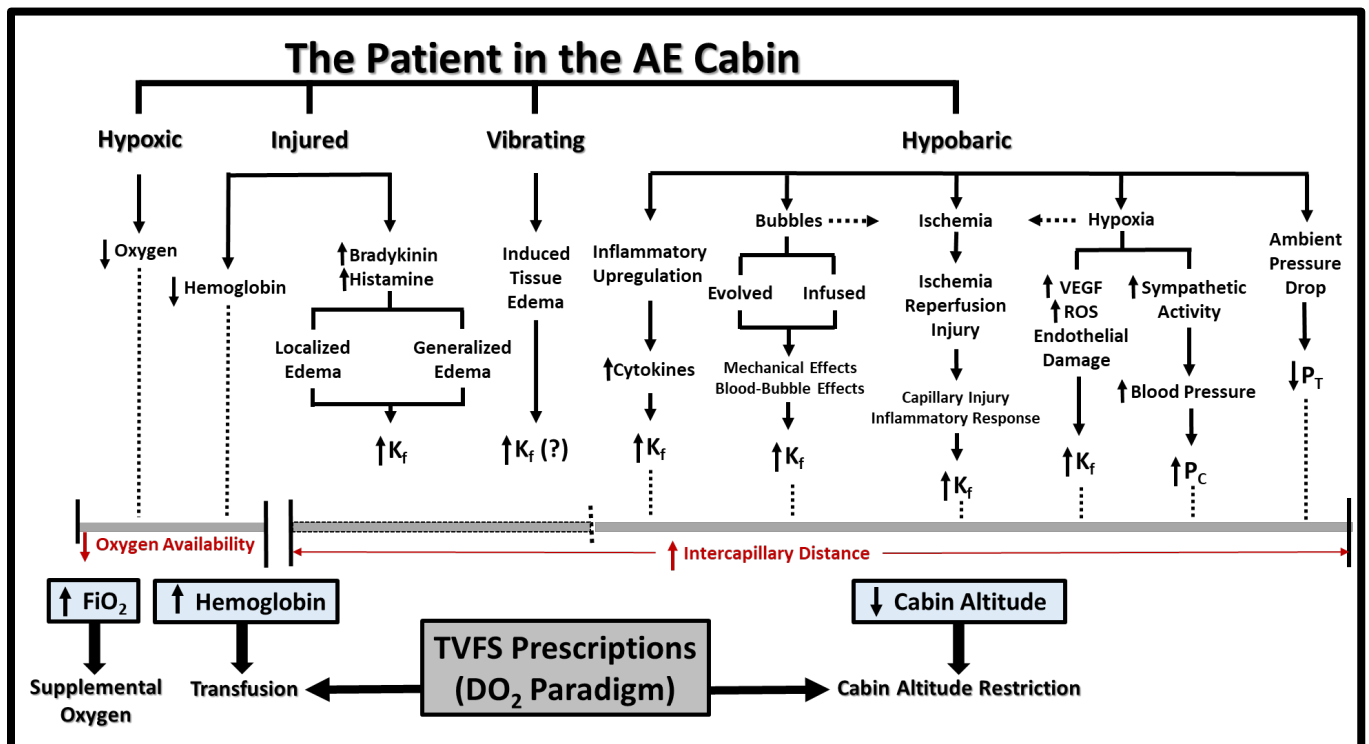
Arterial Oxygen Content Equation (**Costanzo, 2011**) → (2)

$$Ca_{O_2} = (Sa_{O_2} * HgbCC * Hgb) + (0.0031 * Pa_{O_2})$$

Tissue Oxygen Delivery Equation (**Costanzo, 2011**) → (3)

$$DO_2 = (Ca_{O_2} * CO)/W_t$$

From these three equations, seven factors are seen to influence DO_2 . They are ambient barometric pressure (P_B), FiO_2 , hemoglobin content constant (HgbCC), hemoglobin (Hgb), arterial hemoglobin oxygen saturation (SaO_2), plasma oxygen content ($0.0031 * P_{aO_2}$), and cardiac output (CO). The HgbCC is an unchangeable constant (1.34 ml $\text{O}_2/\text{g Hgb}$). Plasma oxygen content is seldom of influence outside of the hyperbaric environment as it makes up only about 0.3 vol% of the overall 20 vol% arterial oxygen content. Likewise, SaO_2 and CO seldom factor for the TVFS, as they have been optimized prior to flight by the intensivists. That leaves three factors within ready reach of the TVFS --- FiO_2 (via supplemental oxygen), hemoglobin (via transfusion), and P_B (via CAR). The following discussion is best followed with **Figure 29**.



Note: Graphic taken from US government technical report and not subject to copyright. (Butler, 2020a) K_f (capillary permeability factor), P_C (capillary hydrostatic pressure), P_T (interstitial tissue hydrostatic pressure), VEGF (vascular endothelial growth factor), ROS (reactive oxygen species), FiO_2 (oxygen fraction of inspired air), TVFS (Theater Validating Flight Surgeon), DO_2 (tissue oxygen delivery).

Figure 29. How Inflight Stressors Influence AE Patient DO_2

Taking the patient characteristics from left to right. The patient is hypoxic. At an 8,000 foot cabin altitude, FiO_2 has a ground level equivalency of 16%, meaning there is a reduced availability of oxygen. The TVFS can remedy this by prescribing supplemental oxygen. See **Section 4.8**.

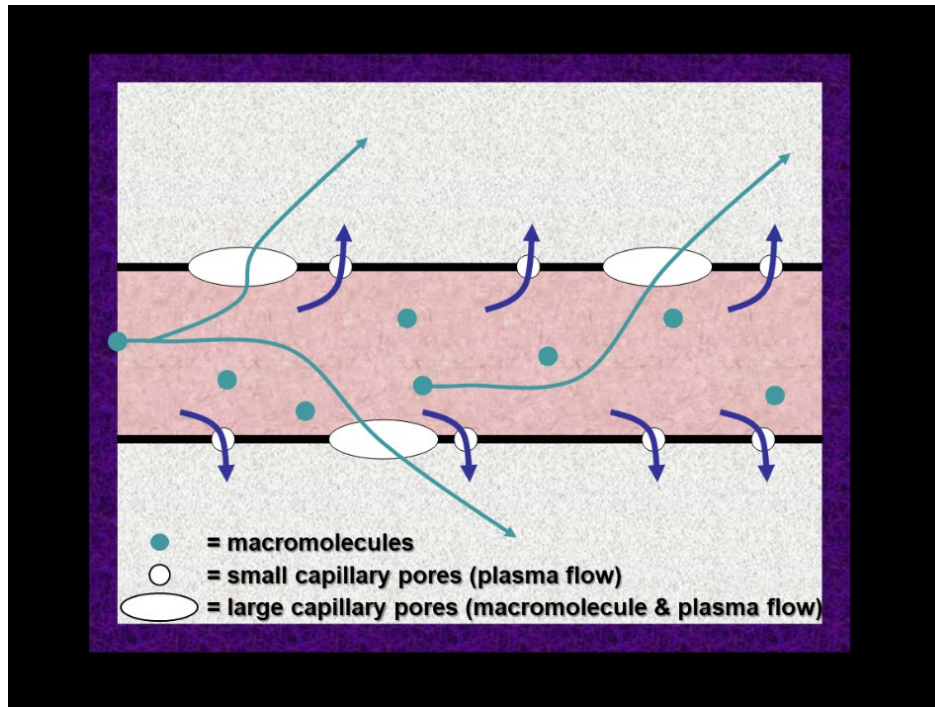
Commonly, the patient is injured, often with low hemoglobin levels. In this instance, supplemental oxygen is of limited value without adequate hemoglobin. At ground level, it appears that DO_2 does not seriously drop until hemoglobin levels drop below 8 g/dl.

(Madjdpour, 2006) See **APPENDIX A, Tables for Calculating DO₂**. At the same time, lowered hemoglobin is has been likened unto being at altitude --- 8 g/dl being like 8,400 feet and 11 g/dl being like 4,800 feet. (Alaska Air Medical Escort Training Manual, 2006) These two observations make low hemoglobin states at altitude problematic. Indeed, in patients with hemoglobin levels < 7 g/dl (chronic anemias) and < 8 g/dl (acute anemias), Air Force guidance on oxygen requirements instructs, “As directed by the AE Validating FS.” (AFI 48-307 Vol 1, 2017) Currently, the Air Force Instruction does not provide any further guidance to the TVFS.

The clinical impact of hemoglobin levels during AE has been studied. Mora et al demonstrated in CCATT patients that hemoglobin levels $\leq$ 8 g/dl were associated with increased inflight transfusions and Hamilton et al demonstrated in CCATT burn patients that hemoglobin levels $\leq$ 10 g/dl were associated with increased ventilator days and mortality. Both studies, however, when subjected to regression analytics, were unable to discern an adverse impact to lower hemoglobin levels. (Mora, 2014; Hamilton, 2015) In contrast, Hannah and Rice studied 90 Canadian orthopedic casualties. They found postflight revisions of proximal amputations were required in 46% of those with hemoglobin levels below 8.0 g/dl versus 15% in those at or above 8.0 g/dl. Logistic regression analytics demonstrated a dose-response relationship. At a hemoglobin of 6.4 g/dl, 55% required revision; at 8 g/dl, 37%; and, at 10 g/dl, 20%. (Hannah, 2013) Although these studies fail to conclusively define an AE threshold for hemoglobin, they do advocate an adequate amount of hemoglobin be present. Even an FiO₂ of 100% in the face of inadequate hemoglobin will be ineffective. So at times, the TVFS will need to prescribe transfusion for the patient, all the while being cognizant of the potential untoward infectious and immunologic effects. (Madjdpour, 2006)

The TVFS must balance FiO₂ (via supplemental oxygen) with hemoglobin level (via transfusion). The oxygen supply must be adequate for tissues and the means of getting the oxygen to the tissues (aka hemoglobin) must be adequate. At the same time, the oxygen arriving at the tissue level must make its way to the tissues. This occurs by way of a diffusion gradient between capillary and tissue. The steeper the gradient and the shorter the travel distance, the more rapid the diffusion. (Leach, 1998; Miserocchi, 2011; Dunn, 2016)

Again, the patient is commonly injured, subjected to the usual physiological response. The body's initial healing response consists of a well-contained inflammatory phase (leukocyte activation as well as histamine and bradykinin release) with localized tissue edema. (Hunt, 1988; Richalet, 1995; McDonald, 1999; Costanzo, 2011) In addition, its response to major systemic injuries (e.g., > 20-30% TBSA burns, major trauma) is generalized body edema. (Barillo, 2003; Huang, 2003; Persson, 2006; Hettiaratchy, 2004) Prior to injury, endothelial gaps and leaky capillaries are rare or absent; however, with major injury both vertical gaps and oblique slits appear which seemingly well correspond to the “two pore” theory. (Rippe, 1994; McDonald, 1999) See **Figure 30**. Here, the TVFS has no direct countering prescription. On the other hand, the TVFS can impose a CAR. At cabin altitude, the Starling physiology favors fluid flow from the intravascular to the extravascular space. In other words, cabin altitude amplifies the natural-occurring tissue edema. See **Section 4.7.3**. This edema extends the intercapillary distance, limiting oxygen diffusion. (Leach, 1998; Miserocchi, 2011; Dunn, 2016) Perhaps, even to the point of tissue ischemia. By prescribing a CAR, the TVFS can restrain this effect.



Note: Graphic created by the author (WPB).

Figure 30. “Two Pore” Leaky Capillary Model, Associated with Major Trauma

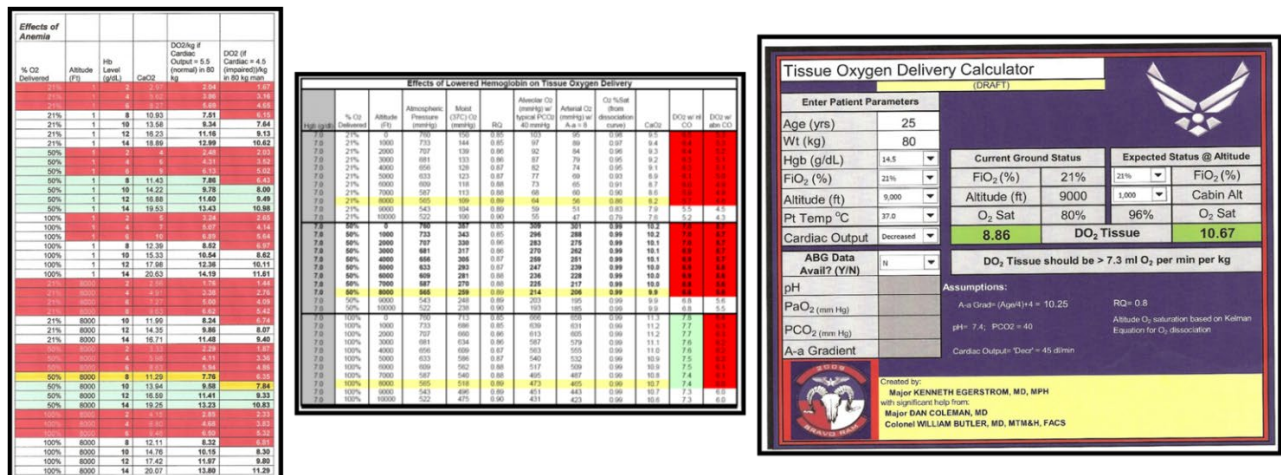
The patient is vibrating, often for hours at a time. Here, the Tonic Vibration Reflex, the physiological counter to external vibration, produces increased muscle contraction and osteoarticular rigidity, upping both muscle activity and energy expenditure. (Wollersheim, 2017) Exercise (aka muscle activity), when taken to altitude, promotes a simultaneous drop in both SpO₂ and PaO₂, 5-12% and 10-30%, respectively, upping oxygen needs. (Schacke, 2007; Martin, 2015) At the same time, vibration also appears to induce tissue edema, the exact mechanism unclear. (Lundborg, 1987; Mittermayr, 2003) This edema expands the intercapillary distance. Alas, outside of neuromuscular blockade (not a commonly viable treatment), the TVFS presently has no really good remedy for these vibrational effects. See **Section 4.6**.

Lastly, the patient is hypobaric. The ambient barometric pressure drop with its associated inflammatory upregulation promotes the movement of fluid from the intravascular to extravascular space, yielding tissue edema. This is also provoked by the direct effects of hypoxia and bubbles as well as their indirect ischemia-reperfusion injury. See **Section 4.7.3**. The tissue edema stretches out the intercapillary distance and, for all intents and purposes, cuts the extent of oxygen diffusion. (Leach, 1998; Miserocchi, 2011; Dunn, 2016) Here, the TVFS can intervene, imposing the CAR prescription.

5.3 Calculation of DO₂

All told, the hypoxic, injured, vibrating, hypobaric patient suffers both decreased oxygen availability and increased intercapillary distance. The result is an impaired supply, transport, and delivery of oxygen to the tissues, or a drop in tissue oxygen delivery. Available within the TVFS's prescriptive armamentarium are supplemental oxygen, transfusion, and CAR --- prescriptions designed to up the DO₂. Up it into the *good* range. *Good* DO₂ is any oxygen delivery exceeding the critical DO₂, or DO_{2crit}. The DO_{2crit} is the level of DO₂ below which tissues suffer ischemia and injury. Certain healthy animal DO_{2crit} thresholds have been defined -- rats at 23 ml O₂/kg/min, fetal lambs at 12-15 ml O₂/kg/min, dogs at 9-10 ml O₂/kg/min, pigs at 8-12 ml O₂/kg/min, and baboons at 3-6 ml O₂/kg/min. (Cilley, 1989; Lieberman, 2000) Not so for the human. The DO_{2crit} has been ascertained only in small populations of critically ill patients (e.g., septic patients, anesthetized cardiac surgical patients, immediately postoperative cardiac patients), ranging from 4.5 ml O₂/kg/min to 8.2 ml O₂/kg/min. (Shibutani, 1983; Komatsu, 1987; Ronco, 1993) Outside of these very specific patient populations, the healthy human DO_{2crit} threshold remains elusive. To date, despite the Dunn et al unsubstantiated declaration of 4 ml O₂/kg/min, only Lieberman et al have the closest healthy human estimate, that being < 7.3 ml O₂/kg/min. (Lieberman, 2000; Dunn, 2016)

Using the afore-mentioned well-established physiological equations (the alveolar gas equation, the arterial oxygen content equation, and the tissue oxygen delivery equation) and the oxyhemoglobin dissociation curve, DO₂ can be and was calculated. (Contanzo, 2014) However, calculating DO₂ by hand proved cumbersome and time-consuming. As a result, tables were constructed. (Pollan, 2006; Butler, 2007b) Despite this improvement, the tables were not especially user-friendly. See **APPENDIX A, Tables for Calculating DO₂**. Eventually, the three equations were combined with Kelman's oxygen dissociation model equation (Kelman, 1966) into a graphic user interface overlaid upon an Excel™ spreadsheet, making for a much more useful tool. (Butler, 2020a; Butler, 2020b) See Figure 31.



Note: The left-most table was created by Pollan and Fisher in 2006; the center series of tables were created by Butler in 2007; and, the right-most graphic user interface was created by Egerstrom, Cole, and Butler in 2009. (Pollan, 2006; Butler, 2007; Butler, 2020b) Graphics taken from US government technical report and not subject to copyright. (Butler, 2020b)

Figure 31. Tools Developed for Calculating DO₂

5.4 Application of DO₂ --- Case Report

Manipulating the FiO₂, hemoglobin level, and cabin altitude within the framework of these equations, the TVFS can assure a *good* DO₂, that is a DO₂ in excess of 7.3 ml O₂/kg/min. (Pollan, 2006; Butler, 2007b) And, a *good* DO₂ should make for a safer AE flight, free of added morbidity or mortality (aka *second hit*). In contrast, a *bad* DO₂ offers added risk to the AE patient.

A good example was briefly mentioned in **Section 2.0**. A severely injured male patient, suffering ARDS and acute renal failure after splenectomy, small bowel resection, and orthopedic repairs was enplaned on postoperative day 7. Prior to boarding, pertinent clinical parameters included blood pressure 73/38 and heart rate 146, ventilator at FiO₂ 100% and PEEP 10 cmH₂O with PaO₂ 52. (Turkan, 2006) Clearly, he was critical, maybe even unstable.

His hypotension and tachycardia suggest under-resuscitation and Class 3-4 hemorrhage. See **Table 16**. Indeed, the only hemoglobin reported was 7.2 dl/g. The patient's pulmonary shunt ratio (PaO₂/FiO₂) was exceedingly low at 52, denoting severe ARDS. See **Figure 28**. These parameters make for a DO₂ around 7.2 ml O₂/kg/min, just barely below Lieberman et al's < 7.3 ml O₂/kg/min cut-point.

The patient was then enplaned with FiO₂ 70%; now, the DO₂ was around 6.8 ml O₂/kg/min. A CAR of 3,800 feet was imposed which essentially did nothing for the DO₂ (~6.7 ml O₂/kg/min). Plainly, AE in this setting was fraught with danger. Indeed, 45 minutes into the flight, he deteriorated and died.

Table 16. Classes of Hemorrhagic Shock

Total Blood Volume	5,000 ml				Total Blood Volume
Blood Loss	≤ 15%	15-30%	30-40%	> 40%	
Blood Pressure	normal	normal	decreased	decreased	
Heart Rate	< 100	100-120	120-140	> 140	
Respiratory Rate	14-20	20-30	30-40	>35	
SHOCK	Class I	Class II	Class III	Class IV	
Blood Loss				> 2,000 ml	
				1,500-2,000 ml	
				750-1,500 ml	
				≤ 750 ml	

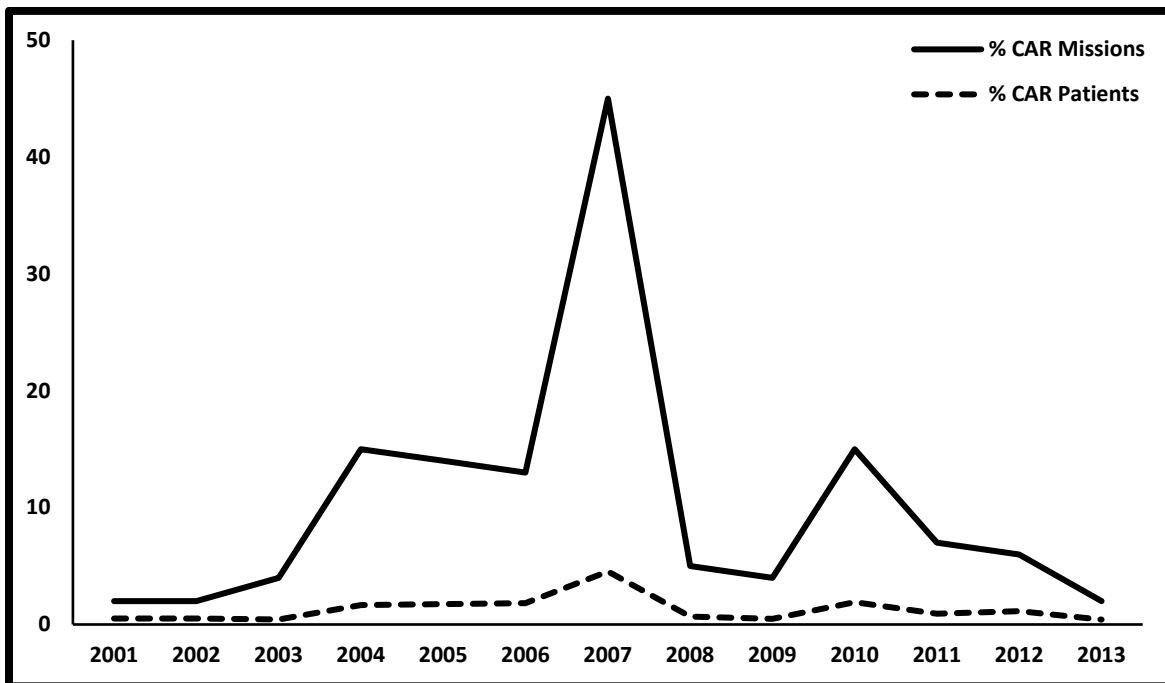
Note: Table derived from data presented by the American College of Surgeons Committee on Trauma. (ATLS, 2012; Cannon, 2018) % (percent), ml (milliliters).

5.5 Evidence Supporting the DO₂ Paradigm

This patient had bad DO₂ and had a bad result. This is one case report, one anecdote. Not definitive. Starting around 2005, with Operation Iraqi Freedom and Operation Enduring Freedom, patient data from several different military databases were collected and merged successfully, setting the precedent for many subsequent studies examining casualty epidemiology, treatment, and evacuation. (**Harmon, 2005**) Little came forth regarding either the TVFS or the DO₂ paradigm until the last several years when both indirect and direct evidence began to accumulate and establish the value of both.

Indirect evidence comes from several sources. In a 2-year retrospective and 1-year prospective analysis, Dewhurst et al looked at fixed-wing medical repatriation of civilian patients to the United Kingdom. Their high risk patients (aka “stabilized”) suffered significantly greater major interventions (7-11% versus 3%, $p < 0.01$) and major adverse events (9-12% versus 1%, $p < 0.01$) than their low risk patients (aka “stable”). The authors suggest flying high risk patients should not be undertaken without due consideration (e.g., TVFS employing the DO₂ paradigm) and appropriate clinical support (e.g., CCATT). (**Dewhurst, 2001**)

More interesting are subsequent observational studies spanning several different time frames during Operations Iraqi Freedom and Enduring Freedom. To better understand how the various findings apply to the TVFS and the DO₂ paradigm, it is important to factor into the mix CAR prescribing. Excepting 2007, when the authors (WPB and LWS) were successively deployed as TVFSs, the annual rate of CAR missions was 10.2% and the annual rate at which the TVFS prescribed a CAR was 1.4%. In 2007, those rates were 45.3% and 4.5%, respectively. (**Butler, 2020a**) See **Figure 32**. As is evident, this made for an unintended natural experiment.



Note: Graphic taken from US government technical report and not subject to copyright. (**Butler, 2018**) % (percent).

Figure 32. Annual Incidence of CAR Missions and Prescriptions

Three studies published examined time frames before, during, and after 2007. Each looked at the evacuation of patients under the care of CCATT teams. Two of the 3 studies included 65% trauma patients, the third 100%. The only inflight complication common to all three studies was hypotension. In the pre-2007 study, 22 of 133 patients (17%) suffered inflight hypotension; the 2007⁺ study had 29 of 656 (4.4%); and, the post-2007 study had 6 of 101 (6%). (Mason, 2011; Lairet, 2013; Minnick, 2013) Pre-2007 had a significantly higher incidence of inflight hypotension than either the 2007⁺ or post-2007 time frames (chi square, $p < 0.00001$ and $p = 0.013$, respectively); there was no significant difference between the 2007⁺ and post-2007 time frames. Admittedly, this analysis has severe statistical limitations, but it does point out the potential salutary effect of the DO₂ paradigm. See Table 17.

Table 17. Indirect Evidence Supporting DO₂ Paradigm --- Inflight

Indirect Evidence --- Inflight					
Time Frame	Study Time	Population	Hypotension	Normotension	Source
Pre-2007	Sep 2005 - Aug 2006	OIF, trauma (65%)	22 (17%)	111 (83%)	Mason, 2011
2007 ⁺	Jan 2007 - Jun 2008	OIF, OEF, trauma (65%)	29 (4%)	627 (96%)	Lairet, 2013
Post-2007	Mar 2009 - Mar 2010	OIF, OEF, trauma, fever	6 (7%)	95 (93%)	Minnick, 2013

Note: Table derived from published data. (Mason, 2011; Lairet, 2013; Minnick, 2013) OIF (Operation Iraqi Freedom), OEF (Operation Enduring Freedom).

Another pair of studies examined the effects of preflight prophylactic fasciotomy on combat casualties. One study looked at patients pre-2007 and the other 2007⁺. Both focused on the postflight rates of revision fasciotomy, amputation, and mortality. Interestingly, what was being evaluated was a prophylactic fasciotomy educational program. Simultaneously, TVFSs were more frequently validating patients for AE based on the DO₂ paradigm. What was found, in fact, was the number of preflight fasciotomies per casualty significantly rose while both postflight revision fasciotomy and mortality significantly dropped. No change was found in the rates of delayed fasciotomy, postflight muscle excision, or postflight amputation. Overall, the authors suggested the education program may well have prompted a greater number of fasciotomies and, perhaps, better quality fasciotomy; however, they could not exclude other care improvements (e.g., improved resuscitation) for the fall in mortality. (Ritenour, 2008; Kragh, 2013) Notably, the impact of optimized DO₂ (e.g., CAR imposition) cannot be excluded from either the drop in postflight revision fasciotomies or fall in mortality. See Table 18.

Table 18. Indirect Evidence Supporting DO₂ Paradigm --- Postflight

Indirect Evidence --- Postflight						
Time Frame	Casualties	Preflight Fasciotomy (per casualty)	Postflight Revision Fasciotomy	Postflight Amputations	Postflight Mortality	Source
Pre-2007 (Jan 2005 - Aug 2006)	336	1.9	15%	16%	8%	Ritenour, 2008
2007 ⁺ (Apr 2007 - Feb 2009)	268	4.6	8%	13%	3%	Kragh, 2013
		$p < 0.0001$	$p < 0.009$	$p > 0.05$	$p = 0.0125$	

Note: Table derived from published data. (Ritenour, 2008; Kragh, 2013))

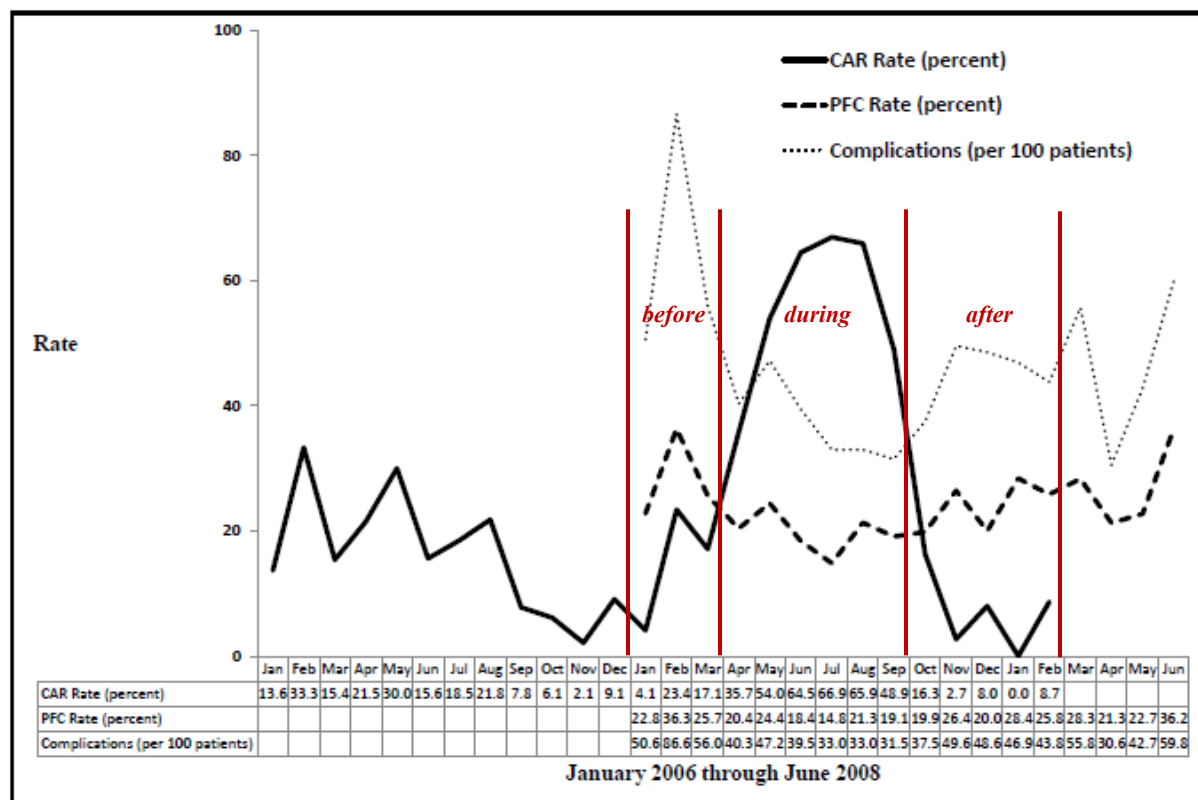
More directly looking studies focused on the modifiable factors within the purview of the TVFS. That is FiO_2 , hemoglobin, and cabin altitude. Earnest et al examined the impact of supplemental oxygen on infection outcome in a complex wounded/infected caprine AE model. They demonstrated significantly less *Pseudomonas* growth with supplemental oxygen. (Earnest, 2012). Luks et al, in a randomized double-blind trial at ~12,500 feet, demonstrated that sleeping in an oxygen enriched room (FiO_2 24% versus 13%) significantly improved periodic breathing with apneas, sleep quality, acute mountain sickness scores, and evening-to-morning arterial oxygen saturation. (Luks, 1998) Gerard et al performed a like experiment using a test room with controllable FiO_2 . Performance at a simulated altitude of 16,500 feet versus that with a 6% oxygen enrichment was studied. Quicker reaction times, improved hand-eye coordination, higher SaO_2 , and a more positive sense of well-being proved significant. (Gerard, 2000) Each of these studies, though not specific to DO_2 paradigm, lends some support to it.

Along the same line, Hannah and Rice demonstrated a hemoglobin cut-point of 8 g/dl looking at orthopedic postflight amputation revisions. Those patients with hemoglobin levels > 8 g/dl required significantly fewer revisions than those with < 8 g/dl hemoglobin (15% versus 46%, $p = 0.016$). Regression analytics revealed a significant dose-response effect. That is, as hemoglobin level rose, amputation revisions fell ($p = 0.001$). (Hannah, 2013) On the other hand, Mora et al's regression analytics with the 8 g/dl cut-point showed no difference in disposition or mortality of critically injured trauma patients. However, univariate analyses found a significantly greater inflight transfusion rate in those patients < 8 g/dl (23% versus 11%, $p = 0.0001$). No mention of other outcomes such as postflight procedures or complications was made; no mention of supplemental oxygen or CAR was made. (Mora, 2014) Similarly, Hamilton et al's regression analytics with a < 10 g/dl cut-point showed no difference in complications (sepsis, ventilator-associated pneumonia, ARDS) or mortality of critically injured burn patients. However, univariate analyses found a significantly greater number of ventilator days and higher mortality in those patients < 10 g/dl (15 versus 9 days, $p = 0.03$ and 21% versus 7%, $p = 0.04$, respectively). Interestingly, 6 of the 29 patients with <10 g/dl actually had hemoglobin < 8 g/dl, suggesting a potential over-influence on the univariate results. In addition, their *post hoc* analyses suggested an underpowered study, the requisite sample size being 475-1,900 patients, as opposed to the actual 140. And, no mention of other outcomes such as postflight procedures or complications was made; no mention of inflight transfusions, supplemental oxygen, or CAR was made. (Hamilton, 2015) Each of these studies, though not specific to DO_2 paradigm, lends some support to it.

Studies focused on the clinical impact of the TVFS employed CAR as a uniquely TVFS surrogate for application of the DO_2 paradigm. The CAR is an appropriate surrogate as it is the quintessential TVFS prescription and seldom prescribed by non-flight surgeon physicians.

Starting with an hypothesis-generating ecological study, data from TRAC²ES (CAR dataset) and LRMC Joint Theater Trauma Registry (Complications dataset), January 2007 through February 2008, were studied. The rate of CAR prescribing was significantly higher during the two authors' (WPB and LWS) deployments than before or after. See **Figure 28**. Postflight complications demonstrated the opposite relationship, higher postflight complication rates before and after the two author TVFSs' deployments. Formal correlation analysis detected a statistically significant inverse relationship. That is, as the rate of CAR prescribing rose, the rate of postflight complications dropped. This relationship was extant for both the rate of

patients with postflight complications and the number of postflight complications per 100 patients. (Butler, 2016) See Figure 33.



Note: Graphic taken from US government technical report and not subject to copyright. (Butler, 2020a) CAR (cabin altitude restriction), PFC (postflight complications).

Figure 33. Graphic Depiction of CAR Rates versus Postflight Complication Rates

Subsequently, a matched case-control study was performed comparing clinical outcomes of 50 CAR versus 50 Non-CAR patients. While no significant difference was detected for length of stay, number of ICU bed days, postflight transfusions, or discharge status, there was a significant difference in the number of postflight procedures performed at the debarkation site. Those transported with a CAR had fewer postflight procedures compared to those transported without a CAR, that is 5 versus 6 procedures, respectively. More specifically, CAR patients suffered significantly fewer major and minor procedures. (Fouts, 2017) See Table 19.

Table 19. Postflight Outcomes from the Matched Case-Control Study (Fouts, 2017)

Outcomes (as taken from TMDS)	CAR (n=50)	Non-CAR (n=50)	p-value
Length of Stay (days), M (SD)	3.70 (4.08) n=47	3.70 (2.54)	0.998 ^a
Number ICU Bed Days, M (SD)	2.34 (2.20) n=47	3.08 (2.63)	0.138 ^a
Postflight Blood Product Use (units), M (SD)	1.86 (9.50)	0.88 (3.73)	0.499 ^a
Patients Transfused, n (%)			
Yes	6 (12)	6 (12)	1.000 ^b
No	44 (88)	44 (88)	
Debarcation Site Postflight Procedures, M (SD)	4.98 (2.77)	6.08 (2.49)	0.032 ^{c,d}
Postflight Procedure Profile, n (%)			
Major Surgeries	57 (23)	95 (31)	0.047 ^{b,d}
Minor Surgeries	63 (25)	80 (26)	
Other Procedures	129 (52)	129 (43)	
	n=249	n=304	
Discharge Status, n (%)			
Home/Self-Care	8 (17)	6 (12)	0.342 ^b
Transfer to Short-Term Facility	38 (81)	43 (86)	
Death	1 (2.1)	1 (2)	
Unknown	3 (6.4)	0 (0)	

Note: ^aValues calculated using independent samples t-test. ^bValues were calculated using the chi-square test. ^cValues calculated using the Mann-Whitney U-test. ^dDenotes statistical significance. **Red** box denotes outcomes that appear to be both statistically and clinically different. Table taken from US government technical report and not subject to copyright. (Fouts, 2017) TMDS (Theater Medical Data System), M (mean), SD (standard deviation), % (percent).

Next, a dual case-control study was executed. The CAR and Complications datasets from the ecological study were merged, generating 1,114 patients eligible for study. These patients fell into three natural groups --- CAR patients, Non-CAR patients, and Non-CAR patients incidentally flown with a CAR --- and two natural comparisons --- CAR versus Non-CAR and Non-CAR flown with a CAR versus Non-CAR. Demographic characteristics and clinical parameters were similar between groups, not so, however, with injury severity indicators. Both direct and indirect markers of injury severity suggested that CAR patients were sicker than Non-CAR patients. At the same time, no such clear-cut dichotomy of severity could be detected between the Non-CAR flown with a CAR and Non-CAR patients.

Excepting the Non-CAR patients having significantly fewer postflight complications, clinical outcomes were essentially the same between CAR and Non-CAR patients; whereas, Non-CAR patients flown with a CAR demonstrated clearly superior outcomes over the Non-CAR patients. There were fewer ventilator days, fewer postflight procedures, and fewer postflight complications. Indeed, the Non-CAR flown with a CAR group had 17% better odds of having fewer patients with postflight procedures and 41% better odds of having fewer patients with postflight complications than the Non-CAR group. All told, it appeared that the CAR prescription normalized the sicker CAR patients into Non-CAR patients and brought the Non-CAR patients into a less morbid state. (Butler, 2018) See Table 20.

Table 20. Postflight Outcomes from the Dual Case-Control Study (Butler, 2018)

Significant Outcomes (N = 1114)						
Factor	CAR (n = 442)	Non-CAR (n = 436)	p-value	Non-CAR flown with a CAR (n = 236)	Non-CAR (n = 436)	p-value
Intensive Care Unit Days, ^a Median (Q)	1 (0,0,3,4)	0 (0,0,2,3)	0.010	0 (0,0,2,3)	0 (0,0,2,3)	<0.001
Ventilator Days, ^a Median (Q)	0 (0,0,2,3)	0 (0,0,1,3)	0.002	0 (0,0,0,1)	0 (0,0,1,3)	0.002
Length of Stay Days, ^a Median (Q)	3 (1,2,4,6)	3 (1,2,4,6)	0.287	3 (2,2,5,6)	3 (1,2,4,6)	<0.001
Injury Severity Score, ^a Median (Q) --- Clinical Injury Severity Group	14 (5,9,25,34) [moderate → severe]	13 (4,6,20,26) [moderate]	<0.001	9 (2,4,14,22) [moderate]	13 (4,6,20,26) [moderate]	<0.001
Number of Postflight Procedures, ^a Median (Q)	2 (0,0,4,6)	2 (0,0,4,6)	0.658	1 (0,0,3,5)	2 (0,0,4,6)	0.004
Patients w/out Postflight Procedures, ^b N (%)	93 (21%)	101 (23%)	0.448	76 (32%)	101 (23%)	0.011
Number of Postflight Complications, ^a Median (Q)	0 (0,0,1,2)	0 (0,0,1,2)	0.018	0 (0,0,0,1)	0 (0,0,1,2)	<0.001
Patients w/out Postflight Complications, ^b N (%)	265 (60%)	297 (68%)	0.012	192 (81%)	297 (68%)	<0.001
^a Mann-Whitney U-test. ^b Chi-square calculated.						

Note: ^aValues calculated using the independent samples Mann-Whitney U test. ^bValues calculated using the Chi-square statistic. Red boxes denote outcomes that appear to be both statistically and clinically different. Table taken from US government technical report and not subject to copyright. (Butler, 2018) CAR (cabin altitude restriction), Q (quartiles), N (number), % (percent).

Recently, Maddy et al explored CAR in CCATT patients with a moderate-severe TBI. Their regression analytics found no difference between CAR and Non-CAR patients in ventilator days, ICU days, hospital days, disposition, or mortality. Interestingly, there were significantly more CAR patients with penetrating head injuries, cranial/facial fractures, pneumocephalus, bone fragments/foreign bodies, and head surgeries. (Maddy, 2020) Such head injuries carry a seriously worse prognosis than blunt head injuries, implying that the CAR patients were sicker than the Non-CAR patients. (Kazim, 2011; Rowell, 2011) In addition, when it came to preflight and inflight interventions, CAR patients trended higher in 13 of 15 preflight and 6 of 12 inflight as opposed to 2 of 15 and 4 of 12, respectively, in the Non-CAR patients; all suggesting sicker CAR patients. Notably, the vast majority of these trending, not significant variables when subjected to *post hoc* analyses were underpowered. For example, the preflight intervention variable “craniectomy” had a power of 26% suggesting a requisite sample size in the neighborhood of 2,000 patients, as opposed to the actual 435. Another potential issue, CAR was defined as $\leq 5,000$ feet, ignoring all the CAR prescriptions between 5,001 and 8,000 feet. In one study, this amounted to ~43% of CARs prescribed. (Butler, 2017) And, there was no indication that Non-CAR patients flown on a CAR mission were excluded. Those limitations noted, this study, to some extent, supports the DO₂ paradigm and CAR prescribing in that the CAR patients appear sicker than the Non-CAR patients and yet have the same outcomes. It seems that the CAR, just like the dual case-control study, normalized the CAR patients into Non-CAR patients, for the better.

Lastly, in a pilot study, specifically scrutinizing the matched case-control study data, patients with *good* DO₂ consistently underwent fewer postflight procedures. In fact, preflight, *good* DO₂ patients had significantly fewer postflight procedures (effect size: Hedges’ $g = 0.78$, large effect) while, inflight, *good* DO₂ patients closely approached significance. (Butler, 2020b)

Here, *bad* DO₂ was considered the DO_{2crit} described by Lieberman et al, that is < 7.3 ml O₂/kg/min. (Lieberman, 2000)

In contrast, taking the *bad* DO₂ at an estimated DO_{2crit} < 8.0 ml O₂/kg/min, as derived from several DO₂ studies of the very sick (Shibutani, 1983; Komatsu, 1987; Ronco, 1993), patients with *good* DO₂, preflight and inflight, fared better with significantly fewer postflight procedures (preflight effect size: Hedges' g = 0.62, high medium effect; inflight effect size: Hedges' g = 0.79, large effect). (Butler, 2020b)

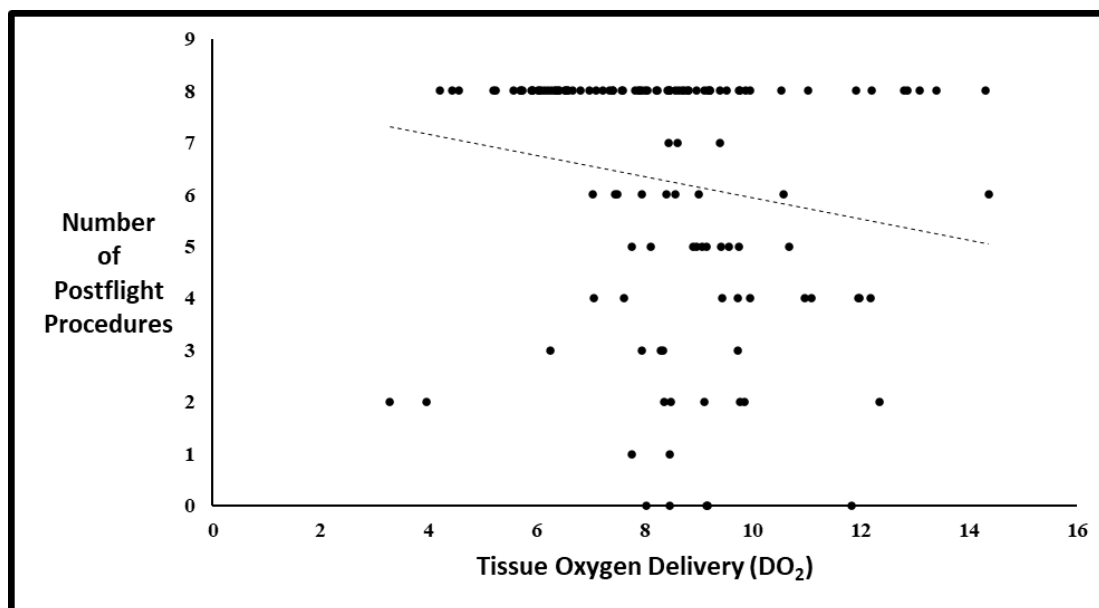
When combining the two phases of AE flight within the purview of the TVFS, preflight and inflight, *good* DO₂ patients suffered significantly fewer postflight procedures than the *bad* DO₂ patients (DO_{2crit} < 7.3 effect size: Hedges' g = 0.71, large effect; DO_{2crit} < 8.0 effect size: Hedges' g = 0.64, high medium effect). (Butler, 2020b) See Table 21.

Table 21. Postflight Outcomes from the Pilot DO₂ Study (Butler, 2020b)

"Bad" and "Good" DO₂ as Relates to AE Flight Status and Postflight Procedures				
AE Flight Status	Number of Postflight Procedures with Bad DO₂, M (SD)	Number of Postflight Procedures with Good DO₂, M (SD)	p-value	n
** Bad DO₂ < 7.3 ml O₂/kg/min & Good DO₂ > 7.3 ml O₂/kg/min **				
Preflight	7.58 (1.44) n = 12	5.74 (2.52) n = 46	0.019*	
Inflight	7.29 (1.86) n = 14	5.71 (2.39) n = 28	0.059	
Postflight	7.20 (1.93) n = 10	6.41 (2.40) n = 17	0.386	
TVFS Impact (Preflight & Inflight)	7.42 (1.65) n = 26	5.73 (2.58) n = 74	0.002*	
** Bad DO₂ < 8.0 ml O₂/kg/min & Good DO₂ > 8.0 ml O₂/kg/min **				
Preflight	7.11 (1.82) n = 19	5.64 (2.59) n = 39	0.031*	
Inflight DO₂	7.05 (2.06) n = 22	5.35 (2.31) n = 20	0.030*	
Postflight	7.23 (1.74) n = 13	6.21 (2.58) n = 14	0.245	
TVFS Impact (Preflight & Inflight)	7.07 (1.93) n = 41	5.54 (2.64) n = 59	0.002*	

Note: Values calculated using independent samples t-test (results replicated with Mann-Whitney U test). *Denotes statistical significance (bold). Red boxes denote outcomes that appear to be both statistically and clinically different. Table taken from US government technical report and not subject to copyright. (Butler, 2020b) AE (aeromedical evacuation), DO₂ (tissue oxygen delivery), M (mean), SD (standard deviation), O₂ (oxygen), ml (milliliters), kg (kilogram), min (minute), TVFS (Theater Validating Flight Surgeon).

Moreover, there appeared to be a dose-response relationship. In fact, a significant inverse correlation between DO_2 and postflight procedures ($R = -0.1786$, $p = 0.0454$) was demonstrated. In other words, as the DO_2 rose the number of postflight procedures fell. The applicable regression equation was: $y = -0.20x + 7.98$. But for the postflight procedure reporting ceiling (only 8 procedures could be recorded), this inverse relationship would almost certainly have been stronger. (Butler, 2020b) See Figure 34.



Note: See the well depicted recording ceiling of 8 postflight procedures. Also, the regression line well demonstrates the inverse dose-response relationship. Table taken from US government technical report and not subject to copyright. (Butler, 2020b) DO_2 (tissue oxygen delivery).

Figure 34. Dose-Response Relationship Between DO_2 and Postflight Procedures

Thus, it appears that there is ample evidence suggesting that an optimized *good* DO_2 promotes less postflight patient morbidity. As the intensivist in the ICU seeks to optimize DO_2 by most often manipulating cardiac output, not to mention FiO_2 and hemoglobin, the TVFS seeks the same employing supplemental oxygen, transfusion, and, uniquely, the CAR. (Lees, 2009; Lobo, 2013; Butler, 2020a) A DO_2 exceeding the $\text{DO}_{2\text{crit}}$ of $< 7.3 \text{ ml O}_2/\text{kg}/\text{min}$ offers up the best possible validation prescription for the stabilized, clinically volatile patient.

5.6 Cost of the DO_2 Paradigm

The prescriptions key to the DO_2 paradigm are supplemental oxygen, transfusion, and CAR. Generally speaking, supplemental oxygen and transfusion cost no different in the AE world than in the medical world. Not so much the CAR. Imposing a CAR often means that the most efficient cruising altitude (i.e., the operating altitude designed to be most cost-effective) cannot be flown. Because of the engineered cabin-altitude/cruising-altitude relationship, a CAR almost always demands a lower cruising altitude. As a consequence, conventional wisdom holds

that CAR has serious operational impact --- longer flight time, upped fuel consumption, higher likelihood of inflight refueling, increased cost of flight, greater turbulence exposure, and more physical stress on the aircraft. This view often led to an organizational resistance to CAR prescribing.

In 2007, one of the authors (LWS), requested a CAR mission impact assessment from Headquarters Air Mobility Command (AMC) Test and Evaluation Squadron (TES). With a C-17 mission from Balad AB (Iraq) to Ramstein AB (Germany), AMC/TES detected no mission impact for a flight flown with the cabin at sea level, 5,000 feet, or 10,000 feet. At the same time, with a C-17 mission from Bagram AB (Afghanistan) to Ramstein AB (Germany), they detected no mission impact for a flight flown with the cabin at 5,000 feet or 10,000 feet, but, with a flight flown at sea level, they detected minimal impact, that being “requires air refuel or fuel stop (due to lower cruise altitude).” (Fouts, 2017)

Later, Fouts et al, using a matched case-control methodology, demonstrated no statistically significant difference in either flight duration or fuel cost when comparing CAR versus Non-CAR flights, whether the flight was intratheater or intertheater and no matter what the aircraft type. That said, however, *post hoc* testing suggested these analyses underpowered to detect a significant difference. (Fouts, 2017)

Consequently, Operational Line of the Air Force flight data was matched with TRAC²ES data. A total of 8,191 missions were identified. Purging incomplete, inaccurate, missing, and estimated data resulted in a Flight Duration dataset (n = 5,561) and a Fuel Cost dataset (n = 2,601).

Flight Duration analyses revealed that CAR was universally associated with reduced flight times, ranging from ~1.8 to ~18.6 minutes. None were operationally significant (defined as 30 minutes) and all contradicted the conventional wisdom.

Fuel Cost analyses yielded mixed results. CAR flights were more expensive and operationally significant (defined as \$5,000) in the Balad Air Base (AB), Iraq to Ramstein AB, Germany C-17 route by ~\$5,500. CAR flights were more expensive, but operationally not significant for both the C-17 and KC-135 in the Bagram AB, Afghanistan to Ramstein AB, Germany route. And, CAR flights were less expensive in the Ramstein AB, Germany to Andrews Air Force Base (AFB), Maryland route by ~\$2,800. These findings offered no ready support for the conventional wisdom. (Butler, 2020c)

Thus, these findings, conjoined with both the clinical dollar savings and clinical human savings, effectively argue for the regular employment of CAR. As a result, there should be no embargo, or push back, from appropriate prescribing of CAR.

6.0 THE BRADFORD-HILL CRITERIA

In an address to the Section of Occupational Medicine of the Royal Society of Medicine in London on 14 January 1965, Sir Austin Bradford Hill defined nine criteria for determining if an environmental factor causes an occupational illness. (Abboud, 2017) In his speech, Hill asserted “None of my nine viewpoints can bring indisputable evidence for or against the cause-and-effect hypothesis and none can be required as a *sine qua non*.” This caveat followed a specific discussion of each of the nine criteria. Later, Hill’s address was published in the Proceedings of the Royal Society of Medicine. (Hill, 1965)

Today, these nine criteria are the gold standard for taking association to causation. In this particular discussion, the “environmental factor” to be considered will be the DO₂ paradigm and the “occupational illness” will be, among others, the AE patients’ postflight procedures and complications (aka adverse outcomes). As learned from previous Sections, the DO₂ paradigm is about tissue oxygen delivery and those influencing factors modifiable by the TVFS, that is FiO₂ (via supplemental oxygen), hemoglobin level (via transfusion), and cabin altitude (via CAR).

Each of the nine criteria will be stated, defined (as per Hill, 1965), and then discussed relative to the DO₂ paradigm.

1. Strength → This is defined as the strength of association, most commonly thought of as correlational association. The DO₂ paradigm, as characterized by CAR, was found to have an inverse relationship with adverse outcomes. As the rate of CAR prescribing rose, the rate of postflight complications dropped. Statistical analysis of this relationship revealed a Spearman rho of -0.666 ($p = 0.0009$) suggesting a fairly strong association. (Butler, 2016) In addition, the Non-CAR flown with a CAR group had 17% better odds of having fewer patients with postflight procedures and 41% better odds of having fewer patients with postflight complications than the Non-CAR group. (Butler, 2018) Although there are not a surplus of studies to choose from, those present suggest a strong association of the DO₂ paradigm with better postflight outcomes.
2. Consistency → This is defined as repeatedly observed association by different persons in different places and times using different data. Indirect studies, though admittedly weak evidence, suggest that the DO₂ paradigm may be associated with reduced inflight hypotension and may potentially be a factor in the reduced postflight revision fasciotomies and mortality seen in patients with prophylactic fasciotomy. (Mason, 2011; Lairet, 2013; Kragh, 2013; Minnick, 2013) Like suggestion can be found in studies looking at supplemental oxygen and hemoglobin. (Luks, 1998; Gerard, 2000; Earnest, 2012; Hannah, 2013; Mora, 2014; Hamilton, 2015) The more direct studies have shown a distinct benefit to the DO₂ paradigm, again as characterized by CAR. Fouts et al found that CAR was associated with significantly fewer postflight major and minor procedures. (Fouts, 2017) Butler et al found the sicker CAR patients’ outcomes similar to those of the less ill Non-CAR patients and, at the same time, found Non-CAR patients flown with a CAR suffered significantly fewer postflight procedures and complications than the Non-CAR patients. (Butler, 2018) And, ostensibly showing no benefit from CAR, Maddry et al actually present data that lends soft support for prescribing CAR. (Maddry, 2020) Thus, both the indirect and direct studies consistently suggest good outcomes from DO₂ paradigm. Although the studies overlap, to some extent, with

investigators, time frames, and locations, it cannot be helped as there are only a few researchers studying the impact of the TVFS.

3. Specificity → This is defined by the exclusiveness of the association. The DO₂ paradigm has only recently appeared in AE. In contrast to the ground-based ICU goal of optimized cardiac output, the TVFS employs the DO₂ paradigm uniquely with CAR. Liberal prescribing of CAR within the DO₂ paradigm began around 2007. The rate of postflight complications went from a high month of ~36% to a low month of ~15% ($p = 0.033$). **(Butler, 2016)** This suggests that inception of the DO₂ paradigm had a specific and rather immediate postflight salutary effect. The TVFS also wields two other influential prescriptions as part of the DO₂ paradigm. Supplemental oxygen and transfusion are less unique to the TVFS and more difficult to discern specificity of effect within the DO₂ paradigm.
4. Temporality → This is defined by the suspected cause dependably preceding the outcome. The DO₂ paradigm, as prescribed by the TVFS, is exclusively effected at patient validation, well before AE. The prescription itself is often implemented just prior to flight or inflight, never postflight. **(Borden Institute, 2004; Hurd, 2006; Butler, 2016; Butler, 2018)**
5. Biological Gradient → This is defined as a dose-response relationship between suspected cause and outcome. Hannah and Rice demonstrated a dose-response effect with the hemoglobin component of DO₂. As the hemoglobin level rose the rate of postflight amputation revision fell ($p = 0.001$). **(Hannah, 2013)** More to the point, *good* DO₂, that is > 7.3 ml O₂/kg/min, was associated with significantly fewer postflight procedures. As the DO₂ climbed, the number of postflight procedures dropped. Despite a recording ceiling for postflight procedures (i.e., 8), the dose-response effect proved significant ($R = -0.1786$, $p = 0.0454$). The applicable regression equation was $\text{Postflight Procedures} = 7.98 - (0.20 * \text{DO}_2)$. **(Butler, 2020b)**
6. Plausibility → This is defined by the suspected causation being biologically plausible. Based on the long history of DO₂ clinical importance in ground-based medical settings, it is likely DO₂ in AE settings would be equally important. In the AE setting, there are physiological stressors not found in ground-based medical settings. **(Blumen, 1995; Dufour, 2003; Hurd, 2006)** Several --- hypoxia, vibration, hypobaria --- have a direct and serious impact on DO₂. The DO₂ paradigm is specifically designed to counter those stressors. **(Butler, 2020a)**
7. Coherence → This is defined by a lack of conflict with the known facts and natural history surrounding the suspected cause and outcome. Any number of animal and human studies record the adverse impact of hypoxia and hypobaria. Many have been cited in this monograph. That said, there appears to be no conflict, either conceptually or within the outcome data, between the DO₂ paradigm and known AE natural history. **(Butler, 2020a; Butler, 2020b)**

8. Experiment → This is defined as evidence derived from empirical prospective controlled research. There is no such direct evidence with employment of the DO₂ paradigm; all evidence is retrospective. However, there are a couple of experimental studies lending veracity to the DO₂ paradigm. Earnest et al, in a complex infected caprine model, demonstrated supplemental oxygen abrogation of bacterial growth during simulated AE. (Earnest, 2012) Similarly, experiments with oxygen enriched rooms show significant benefit in healthy humans overnighting at mountain altitudes. (Luks, 1998; Gerard, 2000) And, during Vietnam, Henry et al, using preflight, inflight, and postflight arterial blood gases, found a seriously improved patient PaO₂ when a CAR was invoked. (Henry, 1973) Although none of these studies specifically employed the DO₂ paradigm as an experimental intervention, they did employ the supplemental oxygen and CAR components of the DO₂ paradigm treatment triad. Their results, in no way, conflict with what might be expected from an experiment focused on the DO₂ paradigm.
9. Analogy → This is defined as a comparison of two like settings, the one in question against a similar well-recognized setting. Accordingly, in an example offered by Hill, a drug not dissimilar from thalidomide is proffered for production. By analogy, a birth defects effect might be anticipated. (Hill, 1965) Looking at the present case, the DO₂ paradigm in AE is not unlike DO₂ applied in the ICU. As DO₂ is a well-accepted means of optimizing ICU patients for recovery, so, too, the DO₂ paradigm should be expected to optimize patients for AE. (Butler, 2016; Butler, 2018; Butler 2020a; Butler, 2010b)

Thus, it appears that the DO₂ paradigm meets the Bradford Hill criteria of causality. In other words, it appears that the DO₂ paradigm, as prescribed by the TVFS, results in a salutary benefit to the AE patient, yielding less postflight morbidity, specifically fewer postflight complications and procedures. See **Table 22**.

Table 22. The Bradford Hill Criteria of Causality as Applied to the DO₂ Paradigm

Bradford Hill Criteria			
Criterion	Criterion Status	Criterion Strength	Source(s)
Strength	Met	Strong	Butler, 2016; Butler, 2018
Consistency	Met	Limited	Luks, 1998; Gerard, 2000; Mason, 2011; Earnest, 2012; Hannah, 2013; Kragh, 2013; Lairet, 2013; Minnick, 2013; Mora, 2014; Hamilton, 2015; Fouts, 2017; Butler, 2018; Maddry, 2020
Specificity	Met	Weak	Butler, 2016
Temporality	Met	Strong	Borden Institute, 2004; Hurd, 2006; Butler, 2016; Butler, 2018
Biological Gradient	Met	Strong	Hannah, 2013; Butler, 2020b
Plausibility	Met	Strong	Blumen, 1995; Dufour, 2003; Hurd, 2006; Butler, 2020a
Coherence	Met	Strong	Butler, 2020a; Butler, 2020b
Experiment	Met	Limited	Henry, 1973; Luks, 1998; Gerard, 2000; Earnest, 2012
Analogy	Met	Strong	Hill, 1965; Butler, 2016; Butler, 2018; Butler 2020a; Butler 2020b

Note: Criterion Status is either *Met* or *Not Met*. Criterion Strength is *Strong*, *Limited*, *Weak*, or *None*.

7.0 FUTURE

Aeromedical evacuation has an evolving future. The KC-46A Pegasus is poised to join today's three primary AE aircraft (i.e., C-130, KC-135, and C-17). The aerial refueler is also specifically designed for both cargo and AE. The environmental controls (e.g., lighting), electrical power, and storage have been optimized with patients in mind. Only recently has its initial AE mission taken place; a 17-hour mission where 1 standard AE crew attended to 5 patients/2 attendees over 6 sorties with stops at 4 bases. This success serves notice that the KC-46A might well supplant the C-17 as the AE workhorse. (<https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104537/kc-46a-pegasus/> and <https://www.af.mil/News/Article-Display/Article/2276760/kc-46-completes-its-first-aeromedical-evacuation-mission/>)

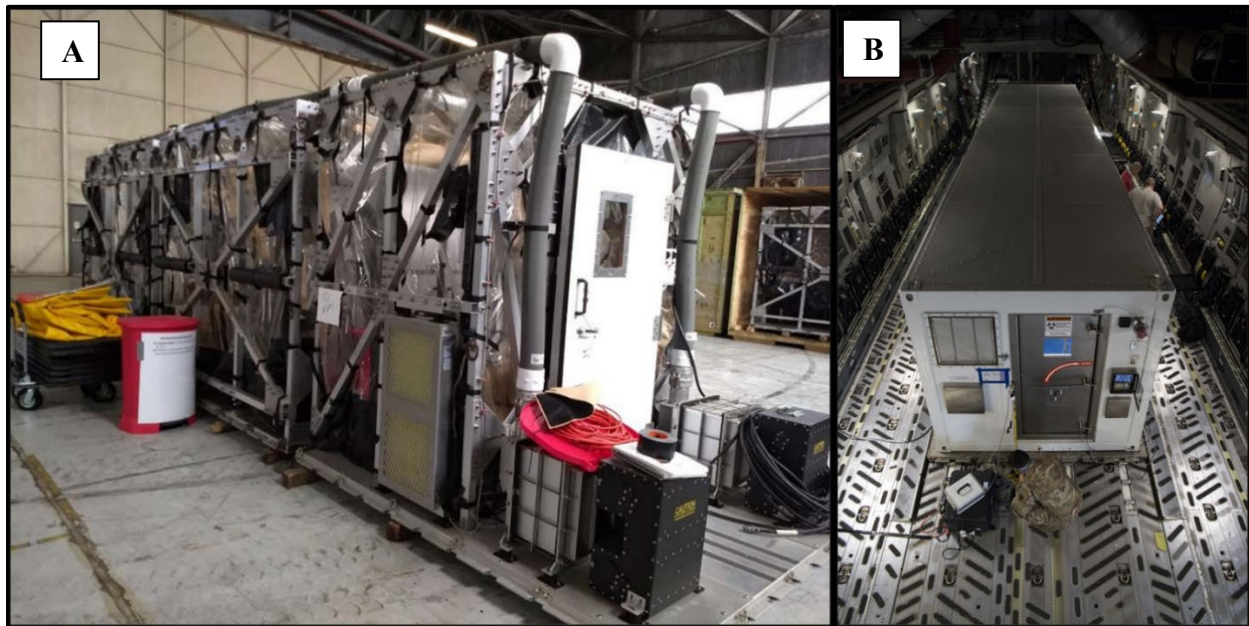
In addition, the USAF has transitioned from a strictly strategic AE model to a combined tactical and strategic AE model. The CCATT team approach has led to an abundance of specialized teams, among them the Acute Lung Rescue Team, the ECMO (extracorporeal membrane oxygenation) Team, the Tactical Critical Care Evacuation Team, the Tactical Critical Care Evacuation Team-Enhanced, the Mobile Field Surgical Team, and the Aeromedical Isolation Team. Depending on exigencies, these teams will form up and disband as needed and not needed.

Aeromedical evacuation of casualties with unmanned aerial vehicles or RPVs (remotely piloted vehicles) has garnered increasing attention. In fact, a NATO Science and Technology Organization (STO) research panel convened from 2009-2012 to consider just that. The conclusions from that panel suggested that CASEVAC from the battlefield, or point of injury, is the RPV's most likely short-term application; this being done in a "back haul" fashion following delivery of cargo. The panel also defined "safe ride" standards upon which to base such RPV-CASEVAC. Lastly, the panel declared that true MEDEVAC and, for that matter, AE were neither technologically feasible nor acceptable (primarily due to the lack of capable inflight medical equipment). That is, as of December 2012. (Rodig, 2012) In line with RPV tactical evacuation is the notion of autonomous medical systems. Recently, a NATO exploratory team has recommended a research panel be created to look into "Robotic & Autonomous Evacuation" (RASEVAC). Specific settings identified were urban, littoral, naval, and search and rescue. Although focused on evacuation aboard autonomous platforms, onboard medical personnel were not excluded. (TATRC, 2020)

Another potential future probably on the cusp of reality is modular AE. In other words, AE of patients in an enclosed self-contained clinical module that is placed upon and plugged into an aircraft. In this module, patient care will take place as if the patient is in a ground-based clinical setting (e.g., ward, ICU). Similar modular notions have been operational for many years, particularly in airport disaster planning. (Abelson, 1973; Star, 1980)

It is easy to imagine specialized modular units, such as ICU, surgical suite, and isolation-capable, not to mention modules pressurized to sea level. In fact, during the Ebola outbreak in September 2014, the United States Africa Command identified the need to transport such high consequence infectious disease (HCID) patients. By January 2015, the Transport Isolation System (TIS) was operational. It can accommodate 2 litter patients or 4 ambulatory patients. The TIS can fly on the C-130H, C-130J, and C-17. (<https://www.amc.af.mil/About-Us/Fact-Sheets/Display/Article/2132917/transport-isolation-system-tis/>) But, the TIS module is not designed to transport airborne virus patients, such as Covid-19. As a result, two other module systems are being considered by the USAF. The Portable Bio-Containment Module (PBCM),

designed for 4 patients, and the Negative Pressure Containment (NPC) module, designed for 30⁺ patients, are both in active evaluation by the Air Force Operational Test and Evaluation Center. In the near future, HCID patients will be moving via the TIS, PBCM, and/or the NPC, as appropriate. (<https://www.afotec.af.mil/News/Article-Display/Article/2158463/operational-testers-unite-in-solution-for-transporting-covid-19-patients/>) See **Figure 35**.



Note: A → Transport Isolation System (TIS); B → Portable Bio-Containment Module (PBCM) Photos taken by USAF and posted on Air Force Operational Test & Evaluation Center website. (<https://www.afotec.af.mil/News/Article-Display/Article/2158463/operational-testers-unite-in-solution-for-transporting-covid-19-patients/>)

Figure 35. USAF's Transport Isolation System and Portable Bio-Containment Module

Other countries have embraced the modular AE notion. The Danish Air Force has employed the modular concept with ambulance placement aboard C-130 aircraft as well as actual medical modules. (Lt Col Claus Lie, personal communication, 2014) See **Figure 36**. In like manner, an ICU-like module has been reported in use with the Japanese Air Self-Defense Force. (Yamaguchi, 2014) And, most recently, Knight Aerospace announced the sale of its Aeromedical Bio-Containment Module to Canada. The Knight module is capable of accommodating 4-16 patients plus medical personnel and can be loaded onto both the C-130 and C-17 aircraft. (<https://knightaerospace.com/general/knight-aerospace-to-support-the-royal-canadian-air-force-with-medical-module/>)



Note: Photos taken by and courtesy of Lt Col Claus Lie of the Danish Air Force.

Figure 36. Modular AE in the Danish Air Force (2014)

Clearly, AE is a medical field ripe with potential research areas and set perfectly for the innovative launch of specialized patient carriers. The medical module is but the start. Adapting medical modules for specific classes of medical malady (e.g., infectious disease) are in the future, even to the point of individualized patient module pods (“mod-pods”) for insertion into RPVs, not to mention remote, robotic monitoring and treatment aboard those very RPVs, the so-called RASEVAC. And, much farther afield are hibernation, cryptobiosis, and biostasis. While hibernation (months-long metabolic slowing following by self-reawakening, such as in bears) and cryptobiosis (metabolic stop/pause followed by self-revival, such as in the wood frog) are not really feasible at this time, biostasis (slowing of molecular processes) is under active pursuit. The Defense Advanced Research Projects Agency (DARPA) is seeking biostasis ways to extend the shelf life of bioproducts such as blood components, vaccines, antibodies, enzymes, pharmaceuticals, and to some extent, humans. Applying/prescribing some sort of biostasis intervention to an injured soldier might well lengthen the “golden hour” or might well isolate the patient from the stressors of an AE flight. Only time will tell what this line of research will produce. (<https://www.bbc.com/future/article/20180809-we-will-ever-be-able-to-freeze-time>)

Not conceptually dissimilar from biostasis, but certainly sooner available, pre-treatment of casualties to minimize the effects of inflight physiological stressors is on the horizon. A recent murine study looked at AE pretreatment with allopurinol, amitriptyline, adenosine-lidocaine-magnesium, or propranolol; the results were mixed. (Singer, 2020) Not dissimilar to oxygen prebreathe regimens for high altitude flight operations (e.g., U-2), hyperbaric oxygen breathing prior to diving has been discussed and even researched. Hyperbaric oxygen appears to depress decompression-induced inflammatory upregulation, inhibit microparticle release, and reduce bubble loads. (Camporesi, 2014; Thom, 2019) It is not too far a jump to imagine such patient preparation prior to AE. At the same time, there is research into the genetic basis for tolerating high altitude mountaineering hypoxia. Perhaps in the near future, identifying patients with the

insertion variant of the angiotensin-converting enzyme and those that can upregulate heat shock protein-70 and those that can upregulate hypoxia-inducible factor-1 might be a key ingredient to DO₂ optimization for AE. (**Brown, 2013; Berger, 2017**) Indeed, that well might become an instrumental piece in the TVFS validation algorithm. Needless to say and happily to say, the future medical practice of the TVFS is indeed exciting.

8.0 CONCLUSION

The purpose of this monograph was to bring together in one place the physiological basis for clinical validation of AE patients, creating a standard repository of information to facilitate both the training of and practice of the TVFS. The major physiological stressors --- acceleration/deceleration, humidity, hypothermia/hyperthermia, noise, vibration, hypobaria, and hypoxia --- have each been described along with the TVFS countermeasures. These discussions have all been couched within an overarching algorithm from which the TVFS can clinically validate a patient “good to go” for AE; in short, safe to fly.

The monograph also offers up the DO₂ paradigm as a means of approaching the complex physiology of critically ill and injured patients, those so called “stabilized” patients, that are now routinely flown, often within 24-48 hours of illness/injury. This DO₂ physiology was presented along with the various prescriptions available to the TVFS for optimizing DO₂ (i.e., supplemental oxygen, transfusion, and CAR). In addition, the beneficial impact of the DO₂ paradigm, more specifically the CAR prescription, on postflight patient morbidity was described. And, the conventional wisdom resisting liberal CAR prescribing was discussed and, to some degree, discredited.

The monograph then applied the Bradford Hill Criteria for causality to the epidemiological assertion: prescribing with the DO₂ paradigm reduces postflight patient morbidity. It was shown that all nine criteria were met, albeit some strongly met and others less strongly.

Lastly, future directions in AE were explored. Tackled here were RPV casualty evacuation, modular unit AE, medicinal and hyperbaric oxygen pretreatment, and even genetic modulation. Needless to say, AE offers up exciting future paths.

In summary, this monograph with its extensive reference list, accompanying toolkit, and graduated program of learning case series (20 cases) proffers to the Flight Surgeon and the TVFS not only an algorithm and paradigm for approaching a patient for AE, but also a means for logically and coherently applying today’s science to that prospective AE patient. As with any intervention in medicine, the information in this monograph should be employed with sound clinical judgment and compassion.

Throughout the monograph, the authors have presented hypotheses, conclusions, and recommendations based on studies performed and observations made over many decades. Needless to say, the data sets were often obtained with difficulty, given the nature of warfare and extant information-gathering tools. Thus, it is incumbent on future TVFS’ and those intent on ensuring the best “care in the air” that we continue to support policy and infrastructure that ensure AE-related medical data sets are not only optimized, but also preserved. The increasing ubiquity of electronic medical records makes it a “must” for planners to routinely include the means for easily recording the best information/data possible. In this way, the exigency of real-time data for clinical care as well as the almost real-time “Big Data” analytics for process improvement can be realized, making AE more nimble, more effective, and less morbid for our patients.

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APPENDIX A --- TVFS TOOLKIT

TABLE OF CONTENTS

Validation Overview

Checks & Balances -How the Four Physicians Interact to Evacuate a Patient.....	132
The TVFS's Clinical Validation Algorithm	132
The TVFS's Worksheet.....	133
Column Headings for the TVFS's Worksheet	133
Definitions for Column Headings Making Up the TVFS's Worksheet	134
Part 1. Prescribing Considerations for the TVFS	135
Part 2. Prescribing Considerations for the TVFS	136

GHOSTBaN Flight Stressors

Humidity & Temperature

Atmospheric Humidity and Temperature Response to Altitude.....	137
--	-----

Noise

Sound Level Distribution Across Frequency Bands for the C-130 and KC-135.....	138
Noise Attenuation Afforded by Ear Plugs and/or Ear Muffs.....	139

Vibration

Frequency Range for "Least" Human Vibration Tolerance.....	140
Physiologic Effects of Various Vibration Frequencies.....	141
Damping Effect of Cushions on Vibration	142

Trapped Air

Commercial Cabin Altitudes at a Cruising altitude of 35,000 Feet.....	143
Pressure-Volume-Diameter Relationships with Increasing Altitude.....	143
Trapped Air Volume at Sea Level	144
Trapped Air Pressure-Volume-Diameter Relationships	144
Trapped Air Resorption Gradients.....	145
Tissue-Trapped Air Resorption Times	146
Estimated Pneumothorax Size Employing the Rhea-Collins Method	147
Tension Pneumothorax Characteristics, Awake versus On Ventilator.....	148
TVFS Prescribing Approach for Patients with Pneumothorax.....	149
TVFS Prescribing Algorithm for Patients with Pneumomediastinum.....	150
Natural History of Postoperative Pneumoperitoneum Resorption	151
TVFS Prescribing Approach for Patients with Intra-Abdominal Air	152

Estimated Rise in IOP with Each 1,000 Feet of Cabin Altitude.....	153
TVFS Prescribing Approach for Patients with Pneumatoxis Oculi	154

Hypoxia & Oxygen

Table for Determining Sea Level Oxygen Equivalency at Altitude.....	155
Oxyhemoglobin Dissociation Curve.....	156
CCATT CPG --- ARDSNet Lung Protective Ventilator Strategy	156
Supplemental Oxyhemoglobin Dissociation Curve.....	157
Nomogram for Predicting Inflight PaO ₂	157
Pulmonary Shunt Ratio-Percent-Severity Depiction	158
PaO ₂ /FiO ₂ versus SpO ₂ /FiO ₂ Pulmonary Shunt Ratio Correlation	158

Hemorrhage & Hemoglobin

Classes of Hemorrhagic Shock	159
------------------------------------	-----

Tissue Oxygen Delivery (DO₂)

Hypobaria Impact on the Starling Intravascular-Extravascular Equilibrium	160
Balloon Analogy for Altitude-Mediated Tissue Edema (Starling Physiology).....	161
Notations from the DO ₂ Equations	162
Tables for Calculating DO ₂	163

Other Validation Tools

Clinical

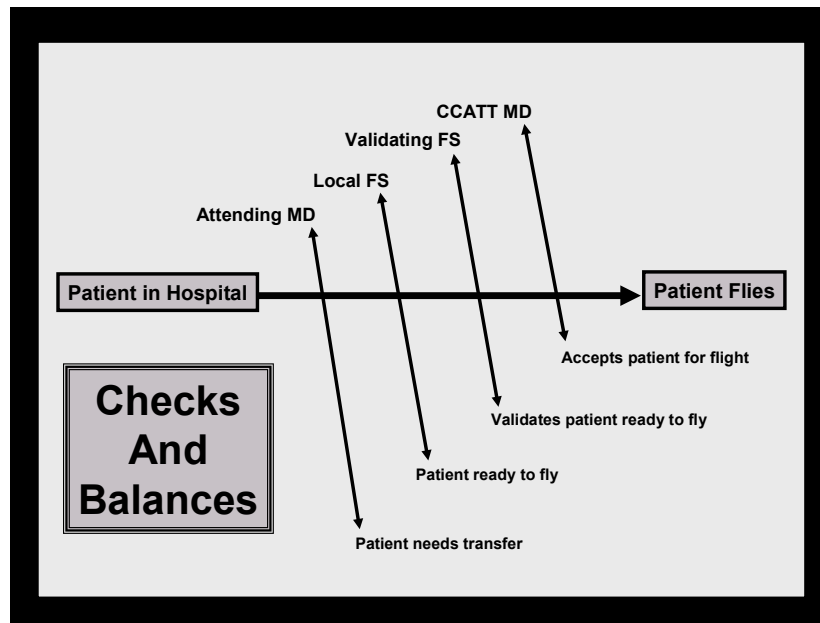
CCATT Decision Tree.....	167
AE Cardiac Tool	168
ROC (Rule Out Contagion) List	169
Approach to Psychiatric Patients	170
Approach to Patients with Hernias or Kidney Stones.....	170
Approach to Preventing Extremity Compartment Syndrome.....	170

Aircraft

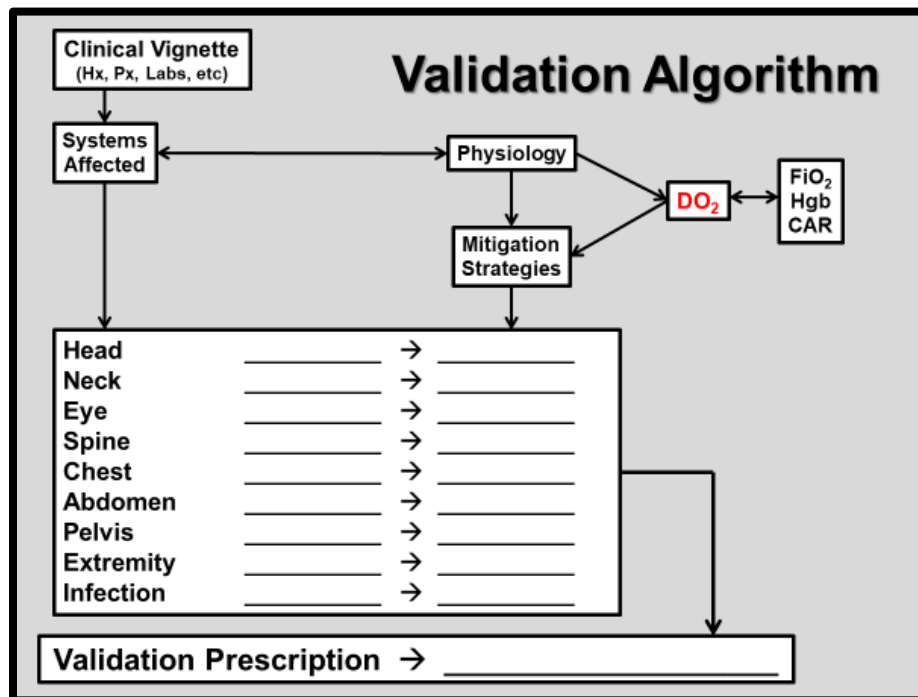
Litter Comparison	171
Patient Capacities of AE Aircraft	171
AE Aircraft Airflow Characteristics	172
C-17 Cruising-CAR Relationship.....	173
KC-135 Cruising-CAR Relationship	174
C-130 Cruising-CAR Relationship.....	175
Brief Overview of the Wound Vac in AE.....	176

VALIDATION OVERVIEW

Checks & Balances --- How the Four Physicians Interact to Evacuate a Patient



The TVFS's Clinical Validation Algorithm



Note: Hx (history), Px (physical), DO₂ (tissue oxygen delivery), FiO₂ (oxygen fraction of inspired air), Hgb (hemoglobin level [g/dl]), CAR (cabin altitude restriction).

TVFS's Worksheet

Occasionally, operational pace will result in many casualties often coupled with small or even large mass casualty events. This pace can create confusion and potential chaos within the validation process. Clinical exigencies can threaten to overwhelm the TVFS. One methodology for avoiding that was developed by the authors (WPB and LWS), referred to as the "Worksheet." It was an ExcelTM spreadsheet with columns for specific validating information and rows dedicated to specific patients. The *worksheet* proved highly effective, handling large numbers of casualties in an efficient and coherent fashion. It also proved effective in reporting validation status to both Medical and Line leadership. And, it proved, retrospectively, an unintentional and unexpected tool for characterizing the very active TVFSs' clinical practice. (Butler, 2017)

Column Headings for the TVFS's Worksheet

Column Headings for TVFS's Worksheet				
Patient Information	Clinical Picture	Labs	TVFS Prescriptions	Status
ID	Neuro-head	Hgb	TVFS-precedence	Validating in Progress
Status	Neuro-spine	PEEP	TVFS-classification	Validated
Grade	Face-Neck	FiO ₂ -delivery	TVFS-oxygen delivery	Validated s/p Information
Age	Extremity	% FiO ₂	TVFS-FiO ₂ (%)	DEATH
Gender	Chest	PaO ₂	Difference (%)	Cancelled
CCATT	Abdomen	SpO ₂	TVFS-CCATT	Validating Comments
Precedence	Pelvis		TVFS-RONs	
Classification	Burns		TVFS-Stops	
Injury	Cardiac		TVFS-HOB	
Theater	Other Systems (#)		TVFS-CAR	
Originating Facility	Other-1		TVFS-head first	
	Other-2		TVFS-c-collar	
	VIGNETTE		TVFS-spine precautions	
	Etiology		TVFS-owl/back	
	Characterization		TVFS-CT suction	
	Ongoing Information		TVFS-NG suction	
			TVFS-transfusion	
			TVFS-drain/ostomy care	
			TVFS-int1	
			TVFS-int2	
			TVFS-int3	
			TVFS-int4	
			TVFS-int5	
			TVFS-int6	

The definition for each heading is listed in the following table. Note that this *worksheet* is not "written in stone," being provided as only a starting point. It should be customized to best suit both the individual TVFS's and his/her validation needs.

Definitions for Column Headings Making Up the TVFS's Worksheet

Definitions for Column Headings Making Up the TVFS's Worksheet			
Patient Information		TVFS Prescriptions	
[per Patient Movement Request]		[as prescribed by TVFS]	
ID	identification	TVFS-precedence	determined by TVFS
Status	service (e.g., Army)	TVFS-classification	determined by TVFS
Grade	rank	TVFS-oxygen delivery	oxygen delivery device
Age	years	TVFS-FiO ₂ (%)	prescribed by TVFS
Gender	male:female	Difference (%)	FiO ₂ (prescribed in PMR) vs FiO ₂ prescribed by TVFS
CCATT	yes:no	TVFS-CCATT	Critical Care Air Transport Team --- yes:no
Precedence	sourced from facility	TVFS-RONs	Remain Overnight --- yes:no
Classification	sourced from facility	TVFS-Stops	yes:no (number of stops permitted)
Injury	Battle Injury:Disease, Non-Battle Injury (BI:DNBI)	TVFS-HOB	head of bed elevation --- yes:no // reason
Theater	operation	TVFS-CAR	cabin altitude restriction level (e.g., 5000 feet)
Orig Fac	originating facility	TVFS-head first	loaded on aircraft head-first --- yes:no
Clinical Picture		[per TVFS]	
[per Patient Movement Request]			
Neuro-head	head injury/illness	TVFS-c-collar	cervical collar --- yes:no
Neuro-spine	spine injury/illness	TVFS-spine precautions	spine protection --- yes:no
Face-Neck	face-neck injury/illness	TVFS-owl/back	rigid litter or backboard --- yes:no
Extremity	extremity injury/illness	TVFS-CT suction	chest tube suction --- yes:no
Chest	chest injury/illness	TVFS-NG suction	nasogastric tube suction --- yes:no
Abdomen	abdominal injury/illness	TVFS-transfusion	blood components evacuated with patient --- yes:no
Pelvis	pelvic injury/illness	TVFS-drain/ostomy care	surgical drain/ostomy care needed --- yes:no
Burns	burn injury	TVFS-int1	other prescription (<i>see the following table</i>)
Cardiac	cardiac injury/illness	TVFS-int2	other prescription (<i>see the following table</i>)
Other Systems (#)	number of unlisted systems	TVFS-int3	other prescription (<i>see the following table</i>)
Other-1	unlisted system (e.g., genitourinary)	TVFS-int4	other prescription (<i>see the following table</i>)
Other-2	unlisted system (e.g., endocrine)	TVFS-int5	other prescription (<i>see the following table</i>)
VIGNETTE	clinical history as needed	TVFS-int6	other prescription (<i>see the following table</i>)
Etiology	etiology of malady	Status	
Characterization	description of malady	[per TVFS]	
Ongoing Information	information updates	Validating in Progress	yes:no
Labs		Validated	yes:no
[per Patient Movement Request]		Validated s/p Information	validated after information gathered --- yes:no
Hgb	hemoglobin level	DEATH	yes:no // preflight:inflight:postflight
PEEP	positive end-expiratory pressure (cmH ₂ O)	Cancelled	yes:no
FiO ₂ -delivery	oxygen delivery device	Validating Comments	information needed for validation
FiO ₂ (%)	oxygen fraction of inspired air (prescribed in PMR)		
PaO ₂	arterial oxygen partial pressure		
SpO ₂ (%)	hemoglobin saturation		

The authors have embedded these two tables and a sample *worksheet* to help streamline the process of building an operational *worksheet*. See below.



Worksheet.xlsx

Part 1. Prescribing Considerations for the TVFS

Prescribing Considerations for the TVFS in Aeromedical Evacuation --- Part 1			
Inflight Stressors	Physiological Effects	Clinical Effects	Countermeasures
Gravity	acceleration-deceleration	hemodynamic flow	head-first load, feet-first load, head of bed elevation, prohibit traction weights, consider Stryker™ or vacuum spine board, long steady take-off, gentle climb out, long slow landing
Humidity	reduced humidity	dehydration	rehydration (oral, intravenous), humidified breathing gases
Temperature	thermal instability	hypothermia, hyperthermia	<u>Hypo</u> : upped aircraft heat, blankets (reflective, heated), warmed IV fluids, warmed ventilator air; <u>Hyper</u> : upped aircraft cooling, upped airflow, cool misting (ground)
Noise	temporary threshold shift	temporary hearing loss	earplugs, earmuffs
Vibration	vibration	increased pain intensified pressure points upped metabolic activity tissue edema	damping with cushions (preferably air bladder or jelly/gel)*, seat/litter isolation (hammock-like), centered fuselage loading away from engines, aircraft routing
Barometric Pressure	pressure-volume-diameter changes	trapped gas expansion	
	-- <i>pneumocephalus</i>	-- headache, confusion, nausea (tension pneumocephalus)	supplemental O ₂ , head-first load, HOB elevation, avoid Valsalva, long slow take-off & landing, CAR
	-- <i>pneumothorax</i>	-- chest pain, dyspnea (tension pneumothorax)	needle/chest tube, Heimlich valve/suction water seal, lung protective ventilation, supplemental O ₂ , CAR
	-- <i>pneumomediastinum</i>	-- chest pain, dyspnea, neck pain (subq air) ("malignant" pneumomediastinum)	bedrest, avoid Valsalva, supplemental O ₂ , lung protective ventilation, CAR
	-- <i>pneumopericardium</i>	-- chest pain, shifting tympany, muffled heart (pericardial tamponade)	bedrest, avoid Valsalva, supplemental O ₂ , lung protective ventilation, needle/tube drain suction water seal, CAR
	-- <i>pneumoperitoneum</i>	-- distention, tympany, oliguria (abdominal compartment syndrome)	NGT, supine, bedrest, supplemental O ₂ , CAR
	-- <i>pneumatox oculi</i>	-- peri-orbital/orbital emphysema -- damaged/disrupted globe (impaired vision, expelled globe content) -- retinal reattachment bubble (pathologic IOP, impaired retinal perfusion)	avoid Valsalva/lifting, supplemental O ₂ , humidity, CAR recline w/ HOB elevated, patch & shield, contralateral pinhole patch, supplemental O ₂ , slow take-off/landing, CAR < 20% bubble, recline w/ HOB elevated, CAR (> 10%), slow take-off/landing, 2,000 ⁺ foot descent w/ sxms; supplemental O ₂ as needed for retina (of questionable resorption benefit) baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg} should be < 50 mmHg
	-- <i>miscellaneous (equipment)</i>	ET (or tracheostomy) cuffs: <i>tracheal pressure necrosis</i> bladder catheter balloon: <i>balloon rupture</i> closed system drains: <i>air and/or drain fluids into wound</i> ostomies: <i>ostomy dislodgement</i> air splints: <i>tourniquet-like effect</i> epidural catheter: <i>back pain</i>	air exchange with ascent/descent; air replacement w/ saline air replacement w/ saline venting drain on ascent/descent "burping" or "pinholing" appliance air exchange with ascent/descent; substitute plaster splint analgesics via AE nursing staff
	venous gas emboli effect altered tissue dynamics	evolved, infused (tissue edema effect)	CAR
	-- <i>inflammatory upregulation</i> -- <i>Starling dysequilibrium</i>	leaky vessels, tissue edema leaky vessels, tissue edema	CAR CAR
	drop in DO₂	ischemia	CAR, transfusion, supplemental O ₂
Oxygen	hypoxia	ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>injured bone & soft tissue</i>	tissue ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>on supplemental oxygen</i>	hypoxia & ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>immediate postop extubation</i> drop in DO₂	transient pulmonary shunt & hypoxia ischemia	postpone validation at least 4-6 hours CAR, transfusion, supplemental O ₂

Note: * Denotes the concern for Boyle's Law effects with air bladder cushions (altitude-induced expansion with asymmetry). Hypo (hypothermia), IV (intravenous), Hyper (hyperthermia), O₂ (oxygen), w/ (with), HOB (head of bed), CAR (cabin altitude restriction), NGT (nasogastric tube), IOP (intraocular pressure), mmHg (millimeters of mercury pressure), ET (endotracheal tube), AE (aeromedical evacuation), DO₂ (tissue oxygen delivery), postop (postoperative), CCATT (Critical Care Air Transport Team), GI (gastrointestinal), ENT (Ear, Nose, & Throat = Otolaryngologic), OSL™ (oversize litter), lb (pound), DCS (decompression sickness), RON (remain overnight).

Part 2. Prescribing Considerations for the TVFS

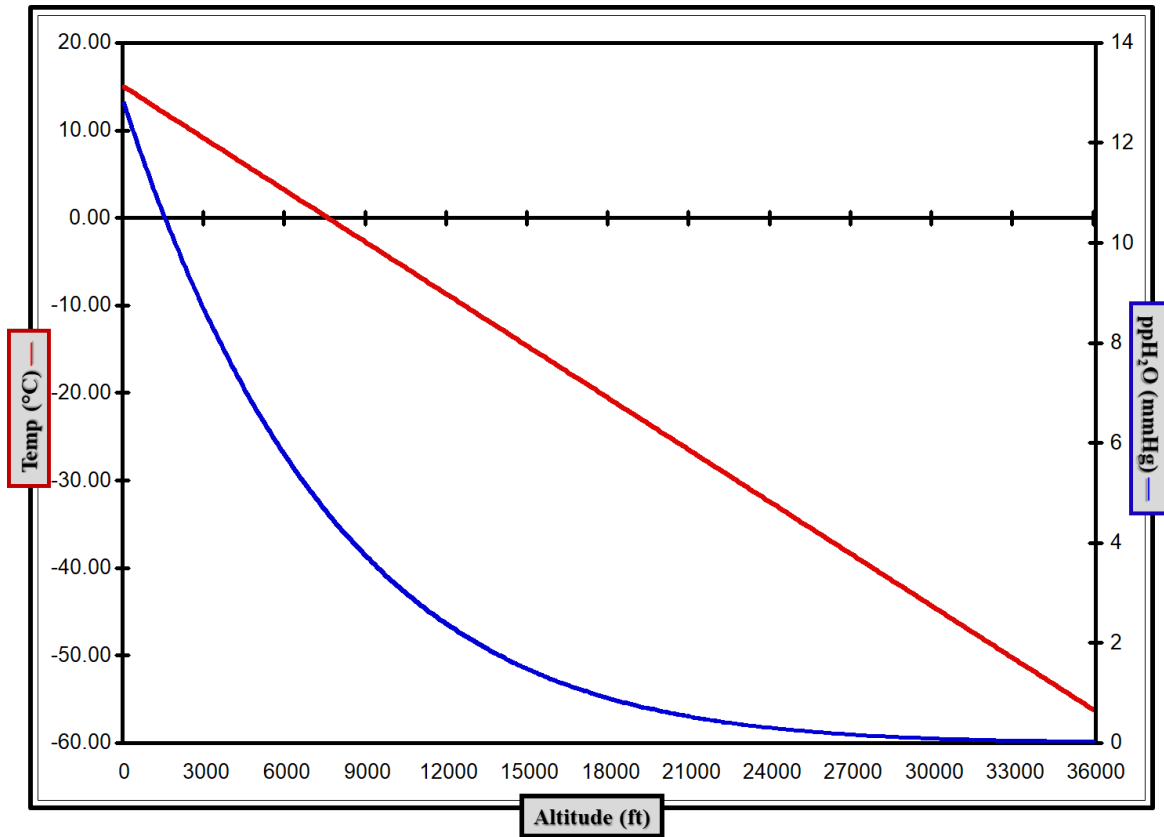
Prescribing Considerations for the TVFS in Aeromedical Evacuation --- Part 2		
Prescriptive Category	Prescription	Clinical Setting
Medical Adjuncts	cardiac monitor; suction; pulse oximeter medical attendant (tech, nurse, doctor) CCATT	Cardiac, Pulmonary, Critical Care Cardiac, Psychiatric Critical Care, Cardiac, Pulmonary
Medical Interventions	protect airway (nasotracheal/orotracheal intubation) nasogastric tube supplemental O ₂ ; positive end-expiratory pressure sedation/physical restraints in flight deep vein thrombosis prophylaxis blood components (transfusion) medications extended ground stabilizing (fluids, vasopressors, blood, tertiary survey) equalization maneuvers (Valsalva, Toynbee, Frenzel, etc)	Critical Care, Immediately Post-Operation Critical Care, Abdominal Surgery (GI, splenectomy) Critical Care, Pulmonary, Trauma, Burns Psychiatric All Settings Trauma, Anemia All Settings Trauma, Critical Care
Middle Ear Adjuncts	Afrin TM and neosynephrine myringotomy	All Settings All Settings All Settings
Patient Paraphernalia	endotracheal (or tracheostomy) tube cuffs - cuff inflation w/ water chest tube - suction or Heimlich valve (no clamping of tubing) Jackson-Pratt TM drain - open on ascent and descent Hemovac TM drain - open on ascent and descent colostomy bag - decompress on ascent ("pinhole", "burp") bladder catheter - balloon inflation w/ water bivalve casts; control air splints cushions (litter, head, heel) blankets	Trauma, Pulmonary Trauma, Pulmonary Orthopedic, ENT, Thoracic, Abdominal Surgery Orthopedic, ENT, Thoracic, Abdominal Surgery Abdominal Surgery All Settings Orthopedic Neurologic, Orthopedic, Critical Care All Settings
Positioning Interventions	head first loading litter at aircraft airflow outlet valves head of bed elevation headrest to elevate and protect head seizure precautions spine precautions cervical spine collar OSL TM litter (regular litter = 250 lb; oversize litter = 400 lb) Stryker TM frame; vacuum spine board	Neurologic, Ophthalmologic Infectious Neurologic, Ophthalmologic, ENT, Pulmonary, Cardiac Neurologic, Ophthalmologic, ENT Neurologic Neurologic Neurologic (cervical spine injury) Orthopedic (pelvic injury), Neurologic (spine injury) Neurologic (spine injury)
Aircraft Manipulations	cabin altitude restriction full use of runway length modify rate of climb and descent (long, slow landings; long steady climbs) cabin airflow patterns aerial refueling no RONs (remain overnight); no stops	Trapped Gas, DO ₂ optimizing, Pulmonary, DCS Neurologic, Pulmonary, Cardiac Neurologic, Pulmonary, Cardiac Infectious Cabin Altitude Restriction, Extended AE Flight Critical Care, Cardiac, Pulmonary

Note: * Denotes the concern for Boyle's Law effects with air bladder cushions (altitude-induced expansion with asymmetry). Hypo (hypothermia), IV (intravenous), Hyper (hyperthermia), O₂ (oxygen), w/ (with), HOB (head of bed), CAR (cabin altitude restriction), NGT (nasogastric tube), IOP (intraocular pressure), mmHg (millimeters of mercury pressure), ET (endotracheal tube), AE (aeromedical evacuation), DO₂ (tissue oxygen delivery), postop (postoperative), CCATT (Critical Care Air Transport Team), GI (gastrointestinal), ENT (Ear, Nose, & Throat = Otolaryngologic), OSLTM (oversize litter), lb (pound), DCS (decompression sickness), RON (remain overnight).

GHOSTBaN FLIGHT STRESSORS

Humidity & Temperature

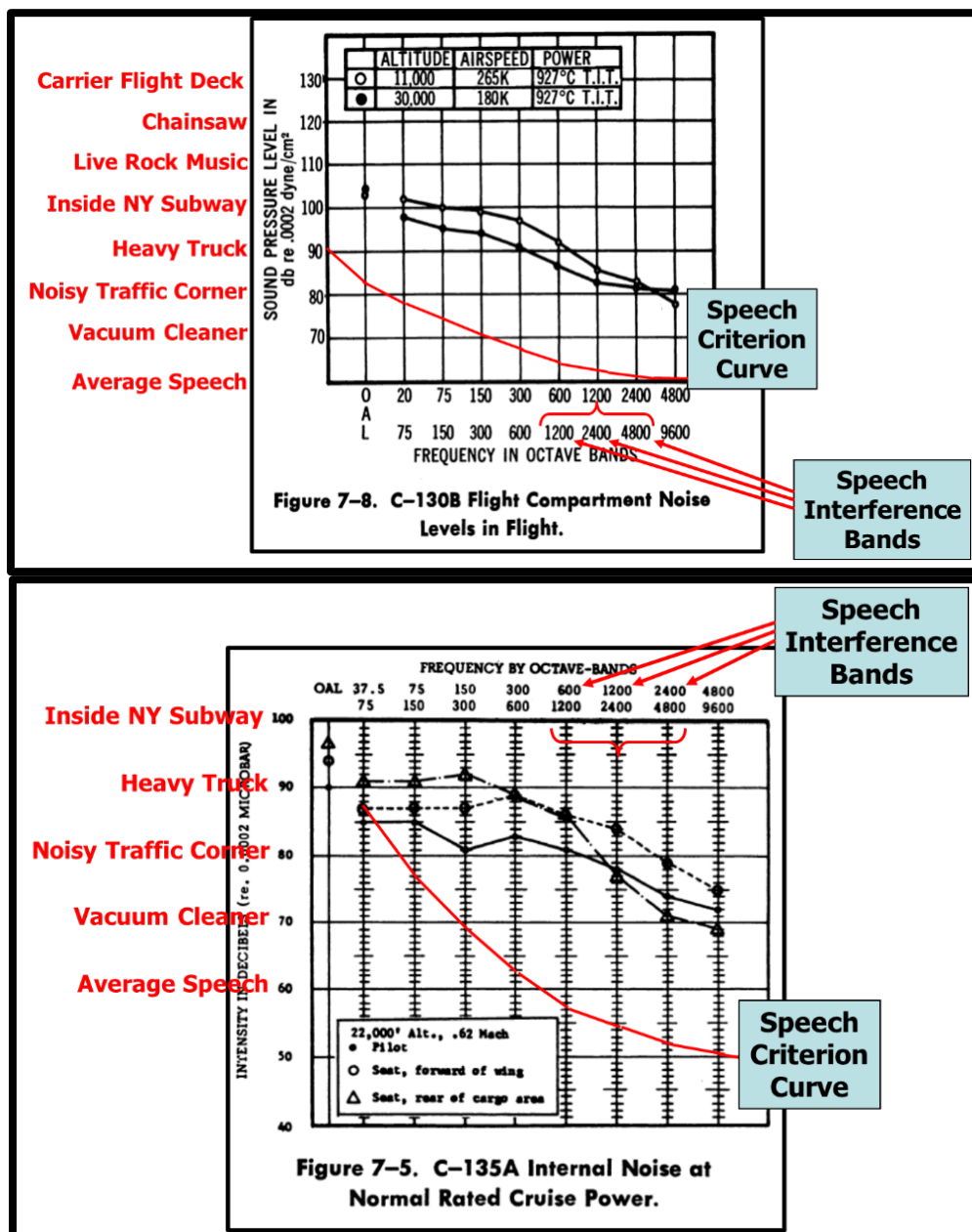
Atmospheric Humidity and Temperature Response to Altitude



Note: Graphic created by and courtesy of Lt Col Daniel Cole (USAFR, MC, FS). Temp (temperature), C (Centigrade), ppH₂O (partial pressure of water), mmHg (millimeters of mercury pressure), ft (feet).

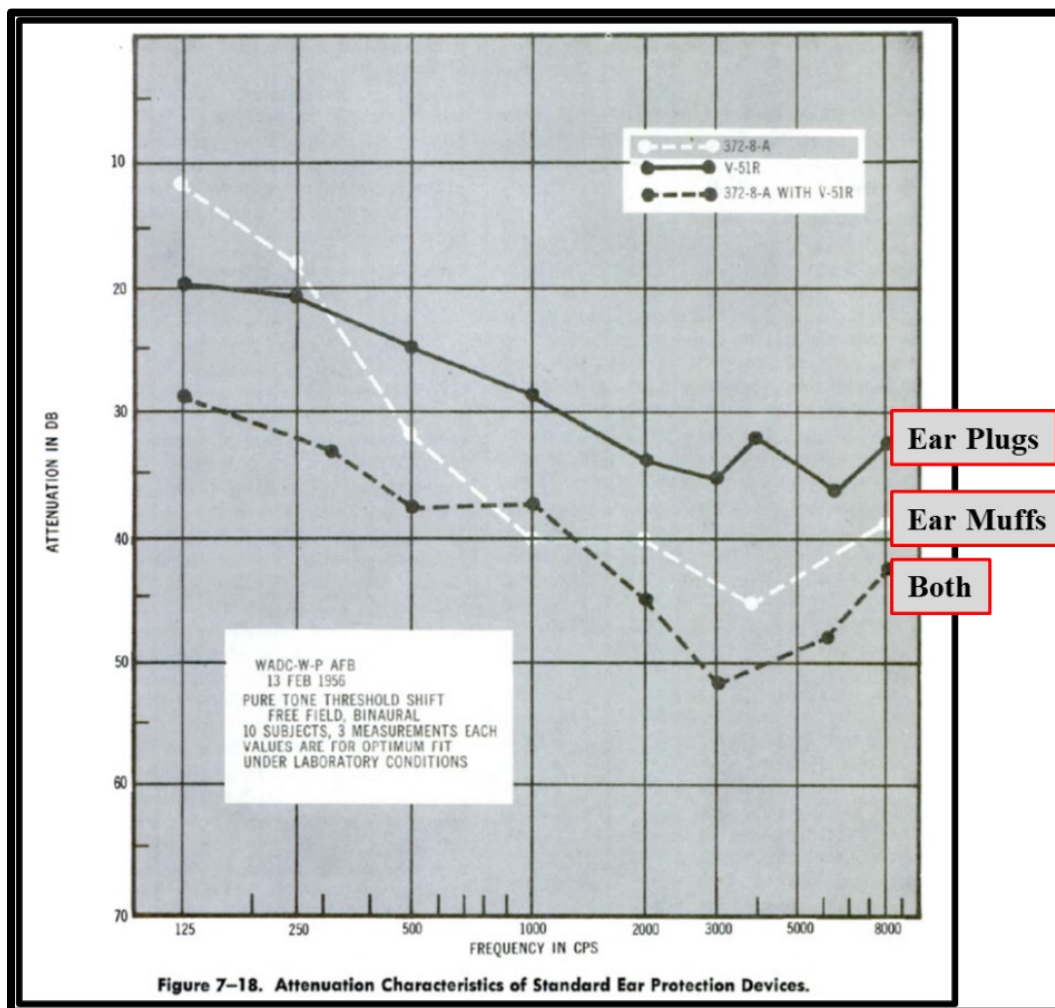
Noise

Sound Level Distribution Across Frequency Bands for the C-130 and KC-135



Note: Graphics taken from AFP 161-18 (1968), pages 7-7 and 7-8. Speech Interference Bands and Speech Criterion Curve created by and courtesy of Lt Col Daniel Cole (USAFR, MC, FS). The Speech Criterion Curves (aka sound/speech perception thresholds) are drawn based on depictions found in the literature. (Fletcher, 1933; Quam, 2012; Blamey, 2015) US government product not subject to copyright.

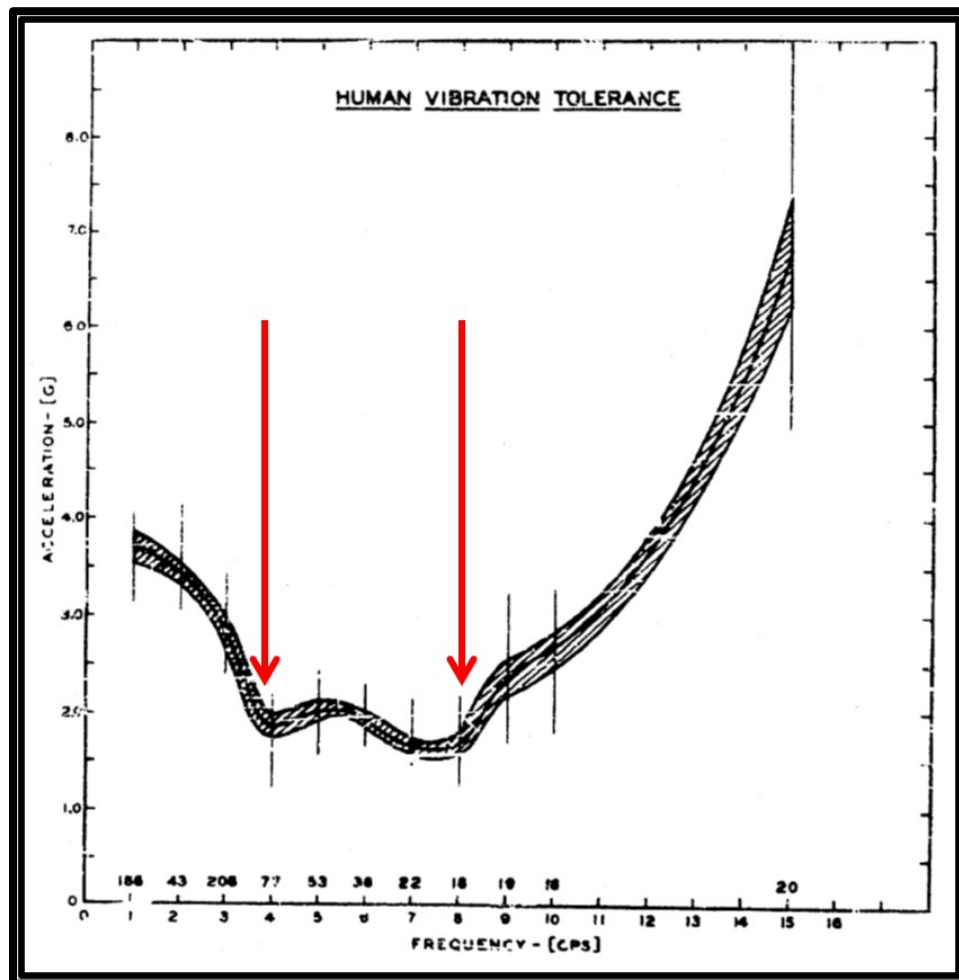
Noise Attenuation Afforded by Ear Plugs and/or Ear Muffs



Note: Graphic taken from AFP 161-18 (1968), page 7-13. US government product not subject to copyright. DB (decibels), CPS (cycles per second).

Vibration

Frequency Range for “Least” Human Vibration Tolerance



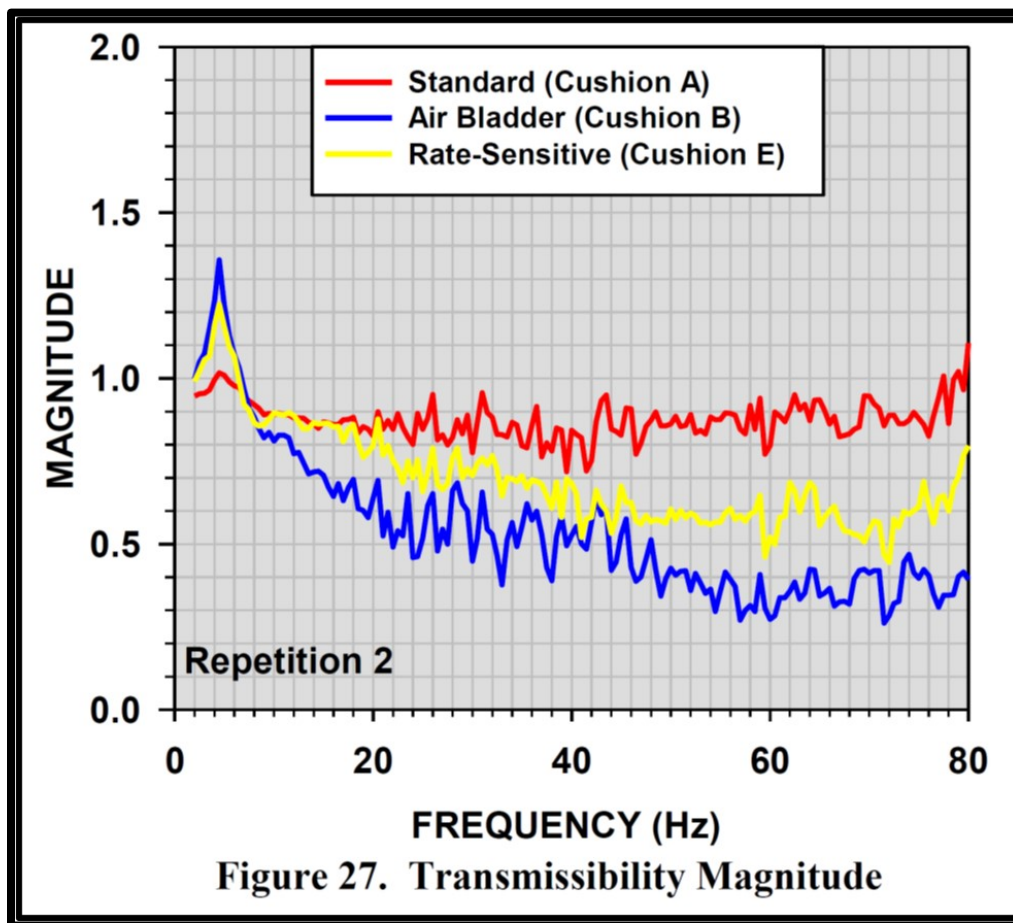
Note: Graphic taken from Ziegenruecker & Magid, July 1959, Aeromedical Report 59-391 (DTIC 227341), page 7. US government product not subject to copyright. CPS (cycles per second).

Physiological Effects of Various Vibration Frequencies

Vibration Impact on the Human Body					
Body Region		Symptoms	Frequency (resonant)	Comment	Reference
Eye	Eye	impaired vision impaired vision	40Hz	resonant frequency	AFP 161-18, 1968
	Eye		60-90 Hz	resonant frequency	Hopcroft, 2005
Head-Neck			10-25 Hz	blurring	Hopcroft, 2005
			20-40 Hz; 60-90 Hz	blurring	Stott, 2016
	Head	"lump" in throat	30 Hz	resonant frequency	Hopcroft, 2005
	Head		> 10 Hz	resonant frequency (<u>supine</u>)	Stott, 2016
	Head		12-15 Hz	resonant frequency (seated)	Stott, 2016
	-- Head sensations		13-20 Hz	dull, aching; congested feeling	Magid, 1960
	-- Pharynx	12-16 Hz		Magid, 1960	
	-- Jaw	6-8 Hz		Magid, 1960	
-- Phonation	impaired speech	13-20 Hz	thoracoabdomino-mechanical dysjunction; laryngeal transmission	Magid, 1960	
Maximum Tolerance		Head Pain	4-10 Hz	dull, aching pain	Magid, 1960
Thorax		chest motion interference	10-12 Hz	resonant frequency	Hopcroft, 2005
	Thorax		3-8 Hz	resonant frequency	Carchietti, 2013
	Heart & Lungs		4-5 Hz	resonant frequency (seated)	Stott, 2017
	-- Upper Trunk		8 Hz	resonant frequency (<u>supine</u>)	
	-- Respiration	4-8 Hz		Magid, 1960; Hopcroft, 2005	
	-- Dyspnea	1-4 Hz	chest motion impaired	Magid, 1960	
	-- Pain	5-9 Hz		Magid, 1960	
	-- Valsalva Maneuver	performed reflex-like	4.5-10 Hz		Magid, 1960
Maximum Tolerance		Chest Pain Dyspnea	3-9 Hz 1-4 Hz	precordial/substernal/across chest chest motion impaired	Magid, 1960 Magid, 1960
Abdomen		abdominal contraction pain	4-8 Hz	resonant frequency	Hopcroft, 2005
	Abdomen		8 Hz	resonant frequency (<u>supine</u>)	Stott, 2016
	Abdomen		5-10 Hz	resonant frequency	Carchietti, 2013
	Organs		4.5-9 Hz	maximum voluntary contraction	Magid, 1960
Maximum Tolerance		Abdominal Pain	4.5-10 Hz	umbilical/RUQ umbilical/RUQ pain	Magid, 1960 Magid, 1960
Pelvis		urge to micturate	10-18 Hz	severe urge	Magid, 1960
		urge to defecate	10.5-16 Hz	severe urge	Magid, 1960
		back pain	8-12 Hz	lumbosacral	Magid, 1960
	Maximum Tolerance		Testicular Pain	7-10 Hz	colicky/groin centric
Musculo-skeletal		altered muscle tone	4-5 Hz	resonant frequency (seated)	Stott, 2016
			8 Hz	resonant frequency (<u>supine</u>)	Stott, 2016
			13-20 Hz	involuntary tightening (lower extremities, back neck, head)	Magid, 1960
		reflex contraction edema	20-100 Hz 30-50 Hz	Tonic Vibration Reflex leg edema	Stott, 2016 Mittermayr, 2003
Maximum Tolerance					
General Discomfort		ill-defined discomfort	4.5-8 Hz		Magid, 1959
Maximum Tolerance		ill-defined discomfort	1-10 Hz	muscles, joints, thorax, abdomen	Magid, 1960
Anxiety					
-- Motion Sickness			< 0.5-1.0 Hz		Hopcroft, 2005; Stott, 2016
Maximum Tolerance			3-10 Hz		Magid, 1960
Physiologic		injury interface friction muscle contraction clot fluidization	26-54 Hz	helicopter vibration	Carchietti, 2013
			10-50 Hz	upped venous return	Carchietti, 2013
			50-100 Hz	physicochemical deconstruction	Carchietti, 2013
	-- Muscle Activity	muscle contraction	10-50 Hz	whole body vibration exercise	Cardinale, 2005; Carchietti, 2013
	-- Metabolic Rate	increased	20-50 Hz	akin to gentle exercise	Stott, 2016
					Cardinale, 2005; Cardinale, 2006; Yazar-Fisher, 2014; Stott, 2016; Wollersheim, 2017
-- Respiratory Rate	hyperventilation	variable	mild drop in P _a CO ₂	Stott, 2016	
-- Tonic Vibration Reflex	muscle contraction	20-100 Hz		Cardinale, 2006; Stott, 2016	

Note: RUQ (right upper quadrant), Hz (Hertz, cycles per second), PaCO₂ (arterial partial pressure of carbon dioxide).

Damping Effect of Cushions on Vibration



Note: Graphic taken from Wright et al, January 2010, AFRL-RH-WP-TR-2010-0083, page 36. US government product not subject to copyright. Hz (Hertz, cycles per second).

Trapped Gas

Commercial Cabin Altitudes at a Cruising Altitude of 35,000 Feet

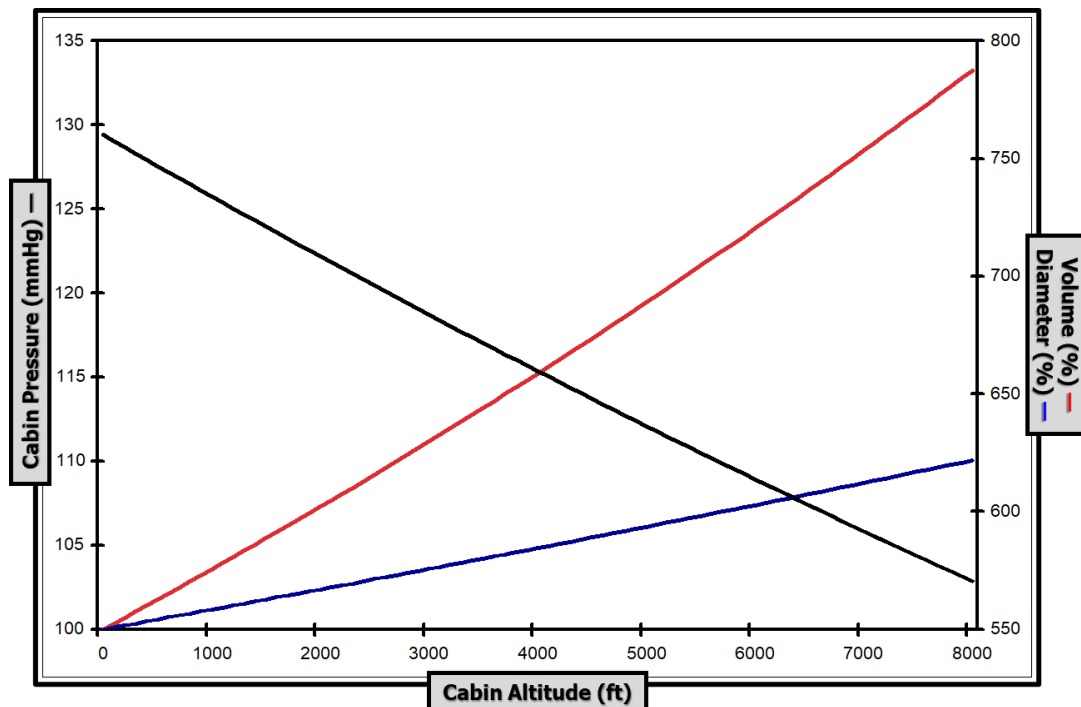
Aircraft Type	Differential Pressure (PSI)†	Cabin Altitude (ft)
Boeing 727	8.6	5,400
Boeing 757	8.6	5,400
Boeing 767	8.6	5,400
Boeing 747	8.9	4,700
Boeing 737	7.45	8,000
DC8	8.77	5,000
DC9	7.76	7,300
DC10	8.6	5,400
A-300	8.25	6,100
A-320	8.3	6,000
L-1011	8.4	5,800
BAC-111	7.5	7,900
Concord	10.7	1,000

* Cabin altitude is the design specification at a flight altitude of 35,000 feet. Cabin altitude varies with flight altitude. Reprinted with permission from reference 9.

†1 psi = 51.7 mmHg. Differential pressures were supplied by the manufacturer or the Federal Aviation Administration.

Note: Reprinted with permission. (Kokame, 1994) psi (pounds per square inch), ft (feet).

Pressure-Volume-Diameter Relationships with Increasing Altitude



Note: Graphic created by and courtesy of Lt Col Daniel Cole. (USAFR, MC, FS). mmHg (millimeters mercury pressure), % (percent), ft (feet).

Trapped Air Volume at Sea Level

Trapped Air Volume at Sea Level		
Measured Diameter (cm)	Radius (cm)	Volume (ml)
1.0	0.5	0.5
2.0	1.0	4.2
3.0	1.5	14.1
4.0	2.0	33.4
5.0	2.5	65.3
6.0	3.0	112.8
7.0	3.5	179.1
8.0	4.0	267.3
9.0	4.5	380.6
10.0	5.0	522.0
11.0	5.5	694.8
12.0	6.0	902.1

Note: Table derived with ideal application of $V = 4/3 \pi r^3$.
cm (centimeters), ml (milliliters).

Trapped Air Pressure-Volume-Diameter Relationships

Pressure-Volume-Diameter Relationships			
Altitude (feet)	Pressure (mmHg)	Volume Change (%)	Diameter Change (%)
10000	523	45.3	13.3
9000	543	40.0	11.8
8000	565	34.5	10.4
7000	587	29.5	9
6000	609	24.8	7.7
5000	632	20.3	6.3
4000	656	15.9	5
3000	681	11.6	3.7
2000	707	7.5	2.4
1000	733	3.7	1.2
500	746	1.9	0.6
Sea Level	760	0	0
33	1520	-50	-21
66	2280	-67	-31
99	3040	-75	-37
132	3800	-80	-41
165	4560	-83	-45

Note: Table derived with ideal application of Boyle's Law ($P_1 * V_1 = P_2 * V_2$) and $V = 4/3 \pi r^3$.
mmHg (millimeters mercury pressure), % (percent).

Trapped Air Resorption Gradients

Trapped Air Resorption					
Gases	Trapped Air Pressures (mm Hg)	Breathing Air (mm Hg)			
		Arterial Pressures (mmHg)	Venous Pressures (mmHg)	Tissue Pressures (mmHg)	Trapped Gas Moves Into
Oxygen (O ₂)	158	95	40	30	arterial/venous/tissue
Nitrogen (N ₂)	596	573	573	573	arterial/venous/tissue
Water Vapor (H ₂ O)	5.7	47	47	47	equilibrium
Carbon Dioxide (CO ₂)	0.3	40	46	46	equilibrium
	760			696	
Gases	Trapped Air Pressures (mm Hg)	Breathing 100% Oxygen (mm Hg)			
		Arterial Pressures (mmHg)	Venous Pressures (mmHg)	Tissue Pressures (mmHg)	Trapped Gas Moves Into
Oxygen (O ₂)	158	636	54	30	venous/tissue
Nitrogen (N ₂)	596	0	0	573	arterial/venous/tissue
Water Vapor (H ₂ O)	5.7	47	47	47	equilibrium
Carbon Dioxide (CO ₂)	0.3	40	46	46	equilibrium
	760			696	

Note: Table derived from data presented by Addis, Chadha and Cohn, Ivezic et al, and Edmonds et al. (**Addis, 1965; Chadha, 1983; Ivezic, 2006; Edmonds, 2016**). mmHg (millimeters mercury pressure).

Tissue-Trapped-Air Resorption Times

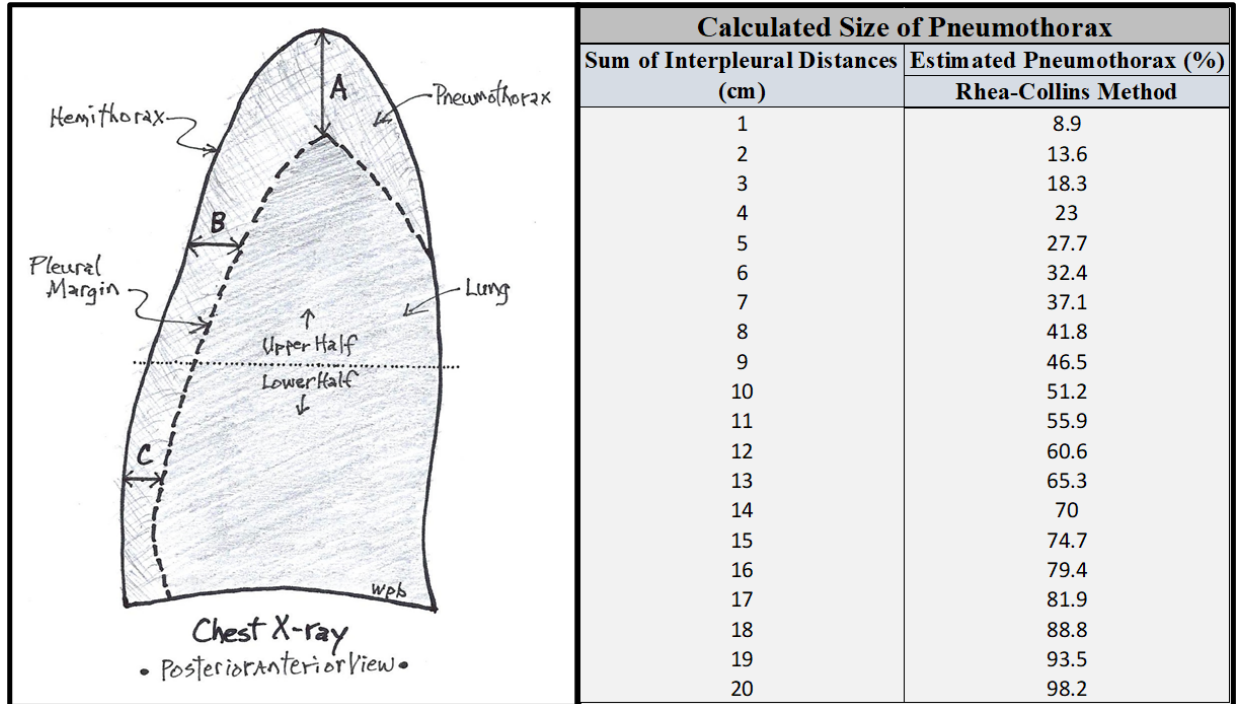
Tissue-Trapped-Air Resorption Times			
Tissue	Time (days)	Comment	Reference
Pneumocephalus			
--- subarachnoid	1	pneumoencephalogram 20-120 ml [avg = ~30 ml]	Tondreau, 1985
--- subarachnoid	1	pneumoencephalogram	Davidoff, 1951
--- intraventricular	2-3	pneumoencephalogram "few days"	Dandy, 1919
--- intraventricular/subdural	1 2 3	50% air resorbed 67% air resorbed 75% air resorbed	Davidoff, 1951
--- unspecified	7	85% of cases	Goldman, 1986; Chan, 2000; Tran, 2010; Javan, 2011
--- unspecified	7-14	85% of cases	Dabdoub, 2015
--- unspecified	14-21	< 2 ml may persist 1-2 wks	Ani, 2016
--- unspecified	21	up to 25% of cases persist 3 wks	Donovan, 2008
--- unspecified	21	post-surgery air may persist 3 wks	Willson, 2014
--- oxygen treated (68%) [24 hrs O ₂]	reduced	65% drop vs 31% in 24 hrs 1.4 ml/hr w/ O ₂ vs 0.7 ml/hr	Gore, 2008 (PCT)
--- oxygen treated (100%) [3 hrs O ₂]	reduced	81% drop vs 68% in 24 hrs 3.6 ml/hr w/ O ₂ vs 2.9 ml/hr	Hong, 2015 (PRCT)
Pneumothorax			
--- room air (bedrest)	---	1.25%/day*	Kircher, 1954
--- room air (outpatient)	---	1.8%/day***	Flint, 1984
--- room air (outpatient)	---	2.2%/day**	Kelly, 2006b
--- oxygen treated (50-60%) [continuous O ₂]	2 3-4	minimal pneumothorax ~ 25% pneumothorax	Panjwani, 2017
--- oxygen treated (bedrest) [2-4 L/min, continuous O ₂]	---	4.3%/day** [Room Air = 2.1%/day]	Park, 2017
--- oxygen treated (100%) [rebreather, continuous O ₂]	3	4.2%/day* [range = 1.5%/day-8.3%/day]	Chadha, 1983
Pneumomediastinum			
--- room air (bedrest)	2	3x faster with O ₂	Putukian, 2004
--- room air (bedrest)	1-7	pneumomediastinum in Israeli pilots	Grossman, 2005
--- room air (bedrest)	2-4		Morgan, 2007; Szymanski, 2010
--- oxygen treated (bedrest)	---	6x faster with O ₂	Kouritas, 2015
Pneumopericardium			
--- room air (bedrest)	3	case report	Hamp, 2015
--- room air (outpatient)	7	case report	Sherrier, 2020
--- room air (bedrest)	8	case report	Mishra, 2016
--- oxygen treated (40-50%)	2	case report	Levin, 1996
Pneumoperitoneum			
--- room air (laparotomy) [children: 2 days to 8 years old] [x-rays]	1	19/19 (100%) cleared	Hope, 1958
--- room air (herniorrhaphy) [children: 8 wks to 8 years old] [x-rays]	2	9/12 (75%) cleared [10-110 ml air injected at closure]	
--- room air (appendectomy) [children: 4-16 years old] [x-rays]	5	46/46 (100%) cleared [60 ml air injected at closure] hrs to resorption = 69.72 + 3.96*(age - 11.52)	Svartholm, 1969
--- room air (laparotomy) [CT scans]	3 6	13% cleared (max 5.8 ml) 50% cleared (max 3.1 ml)	Earls, 1993
--- room air (laparotomy) [CT scans]	1-3 4-7 8-18	53% cleared (mean = 7.5 ml) 69% cleared (mean = 4.0 ml) 70% cleared (mean = 1.2 ml)	
--- room air (laparotomy) [CT scans]	0-3 0-5 6-15 ≥ 16	0% cleared (mean = 29 ml) 19% cleared (mean = 22 ml) 59% cleared (mean = 5 ml) 90% cleared (mean = 7 ml)	Malgras, 2017
Pneumatoxis oculi			
--- perfluoromethane (CF ₄)	---	t _{1/2} = 1 days ---- human = up 3-5x	Lincoff, 1984 [New Zealand red rabbit model]
--- perfluoroethane (C ₂ F ₆)	---	t _{1/2} = 2 days ---- human = up 3-5x	
--- perfluoropropane (C ₃ F ₈)	---	t _{1/2} = 6 days ---- human = up 3-5x	
--- perfluoro- <i>n</i> -butane (C ₄ F ₁₀)	---	t _{1/2} = 12 days ---- human = up 3-5x	
--- room air	7	17% bubble (1 ml)	Ivan, 2003
--- xenon (Xe)	1-2	17% bubble (1 ml)	
--- sulfur hexafluoride (SF ₆)	10-14	17% bubble (1 ml)	
--- perfluorocarbon gases (C _n F _n)	10-65	17% bubble (1 ml)	Alvarez, 2003
--- sulfur hexafluoride (SF ₆)	14	AsMA Guideline (time to < 30% bubble)	
--- perfluoropropane (C ₃ F ₈)	42	AsMA Guideline (time to < 30% bubble)	
--- sulfur hexafluoride (SF ₆)	13-24	18 ± 2.9 days (30% bubble)	Kontos, 2017; Kancierz, 2018
--- hexafluoroethane (C ₂ F ₆)	28-44	34.5 ± 3.3 days (20% bubble)	
--- perfluoropropane (C ₃ F ₈)	59-79	67.7 ± 5.5 days (15% bubble)	
--- perfluoroethane [100% O ₂ treated]		albino rabbit model no effect on resorption or volume	Lincoff, 1989b

Note: *Denotes area-based two-rectangle estimate of pneumothorax size (**Kircher, 1954**); **Denotes volume-based estimate of pneumothorax size (**Collins, 1995**); ***Denotes an undefined technique for estimating pneumothorax size.

Note: In detecting pneumothoraces, as compared to the gold standard chest CT scan, the supine chest x-ray (50% sensitivity) is less sensitive than the upright chest x-ray (92% sensitivity) is less sensitive than the ultrasound (92-100% sensitivity). (**Ball, 2009a**)

Note: avg (average), % (percent), ml (milliliter), wk (week), hr (hour), w/ (with), O₂ (oxygen), PCT (prospective controlled trial), PRCT (prospective randomized controlled trial), L (liter), min (minute), CT (computed tomography), t_{1/2} (half-life).

Estimated Pneumothorax Size Employing the Rhea-Collins Method



Note: Adapted from data and methods presented in Rhea et al, Collins et al, and Kelly et al. (**Rhea, 1982; Collins, 1995; Kelly, 2006a**) Regression equation correlating plain chest x-ray with CT volumetrics is $Y = 4.2 + [4.7 * (A+B+C)]$ ($r = 0.98, p < 0.0001$). (**Collins, 1995**) Drawing by and courtesy of the author (WPB). cm (centimeters), % (percent).

A = maximum interpleural distance at lung apex;

B = interpleural distance at midpoint of upper half of lung;

C = interpleural distance at midpoint of lower half of lung.

Tension Pneumothorax Characteristics, Awake versus On Ventilator

Tension Pneumothorax Characteristics		
Characteristic	Awake	On Ventilator
Etiology		
-- Trauma	~20%	~14%
-- Barotrauma	~4%	~52%
-- CVP Catheter	~2%	~17%
Clinical Setting		
-- Emergency Department	~52%	~11%
-- ICU	~5%	~26%
-- Operating Room	~4%	~47%
Symptoms		
-- Pleuritic Chest Pain	~52%	---
-- Dyspnea	~38%	---
-- Shortness of Breath	~31%	---
-- Agitation	+++	---
Physical Findings		
-- Tracheal Deviation	~18%	~2%
-- Subcutaneous Emphysema	~11%	~31%
-- Hyper-resonance	~27%	~8%
Vital Signs		
-- Tachycardia	~43%	~31%
-- Hypotension	~16%	~66%
--- Development	Progressive	Rapid
-- Hypoxia	~40%	~87%
--- SpO ₂ Drop	Progressive	Immediate
-- PaO ₂ /FiO ₂ < 300	~77%	~96%
-- Upped Ventilation Pressure	---	+++
Time Course	Progressive	Rapid
Respiratory Arrest	~10%	---
Cardiac Arrest	---	~30%

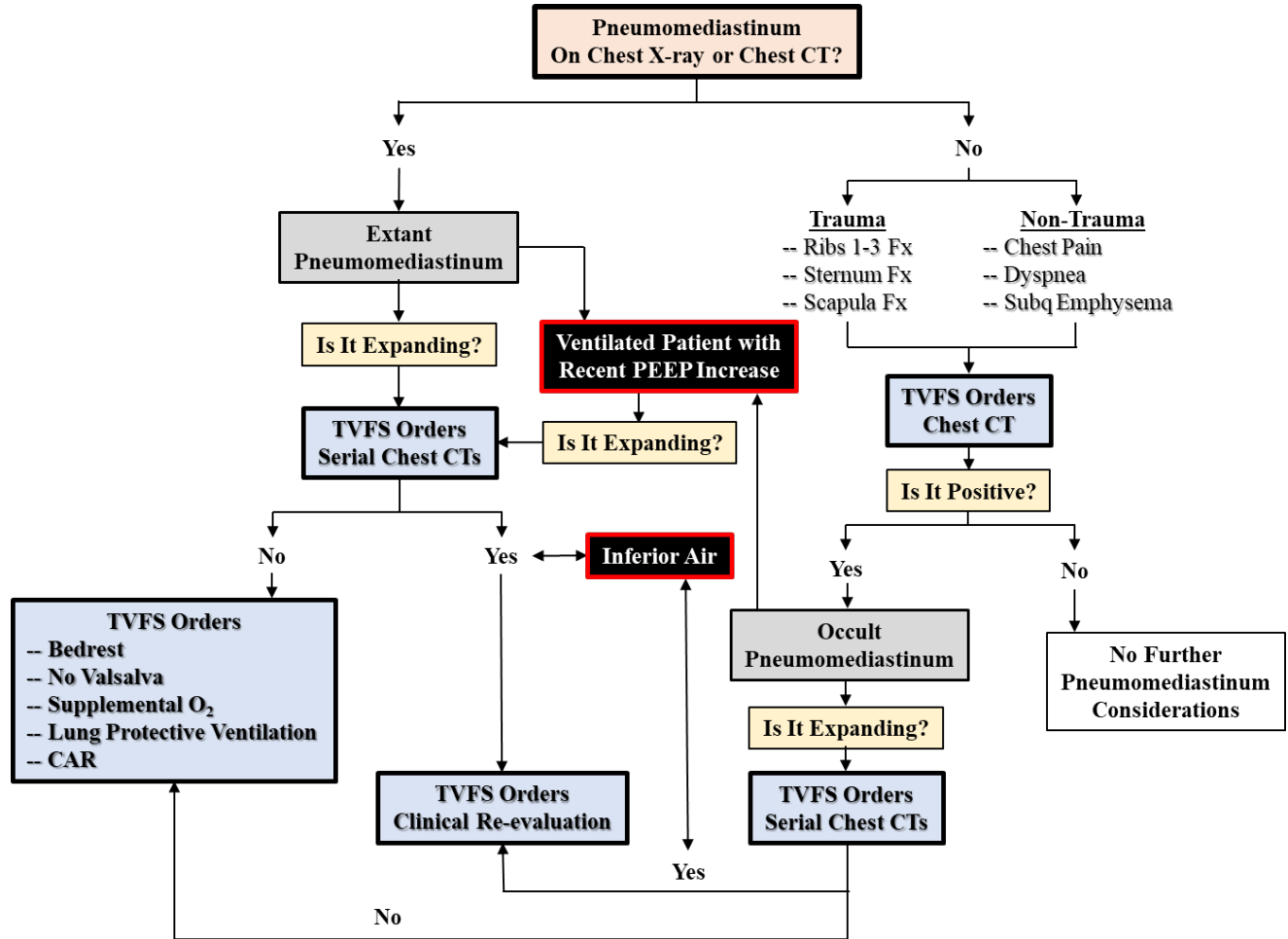
Note: Table derived from data presented by Roberts et al and Leigh-Smith & Harris; percentages approximate the authors' findings. (Leigh-Smith, 2005; Roberts, 2015) The table depicts how much more at risk of rapid death a ventilated patient with a tension pneumothorax is compared to an awake patient. CVP (Central Venous Pressure), ICU (Intensive Care Unit), SpO₂ (pulse oximetry peripheral hemoglobin saturation), PaO₂ (arterial partial pressure of oxygen), FiO₂ (fraction of oxygen in inspired air).

TVFS Prescribing Approach for Patients with Pneumothorax

Pneumothorax Prescribing Considerations					
Pneumothorax	Awake		Percent	On Ventilator	
	Factors	TVFS Prescription		TVFS Prescription	Factors
Potential Pneumothorax (no pneumothorax on CXR)	rib fracture pulmonary contusion chest wall contusion subcutaneous emphysema	chest CT scan	-- not detected --	chest CT scan	rib fracture pulmonary contusion chest wall contusion subcutaneous emphysema
Occult/Extant Pneumothorax	no respiratory distress origin altitude maintained	-- consider no needle or chest tube -- supplemental O ₂ -- CAR	< 15-20%	-- chest tube to suction water seal -- lung protective ventilation -- supplemental O ₂ -- CAR	tension pneumothorax threat -- high tidal volume -- high levels of PEEP -- insertion of CVP line
		-- in-place needle or chest tube -- Heimlich valve or suction water seal -- supplemental O ₂ -- CAR	> 15-20%	-- chest tube to suction water seal -- lung protective ventilation -- supplemental O ₂ -- CAR	
Post Chest Tube Removal	after 24 hours small stable residual	-- consider supplemental O ₂ -- consider CAR		should not fly	within 24 hours ventilated
	1-3 weeks	no intervention		see Occult/Extant Pneumothorax	extubated & awake after 24 hours stable residual
				no intervention	1-3 weeks

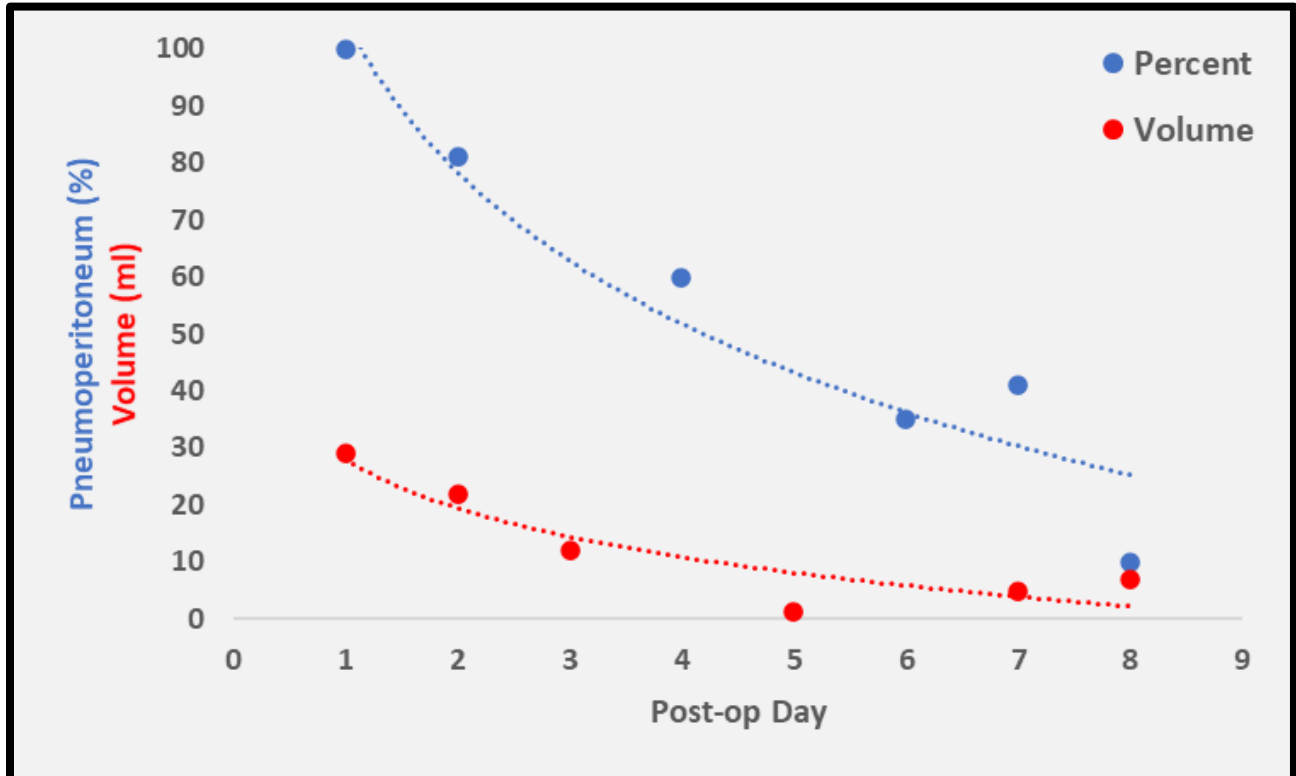
Note: CXR (chest x-ray); CT (computed tomography), O₂ (oxygen), CAR (cabin altitude restriction), % (percent), PEEP (positive end-expiratory pressure), CVP (central venous pressure).

TVFS Prescribing Algorithm for Patients with Pneumomediastinum



Note: Subq (subcutaneous), PEEP (positive end-expiratory pressure), TVFS (Theater Validating Flight Surgeon), CT (computed tomography scan), O₂ (oxygen), CAR (cabin altitude restriction).

Natural History of Postoperative Pneumoperitoneum Resorption



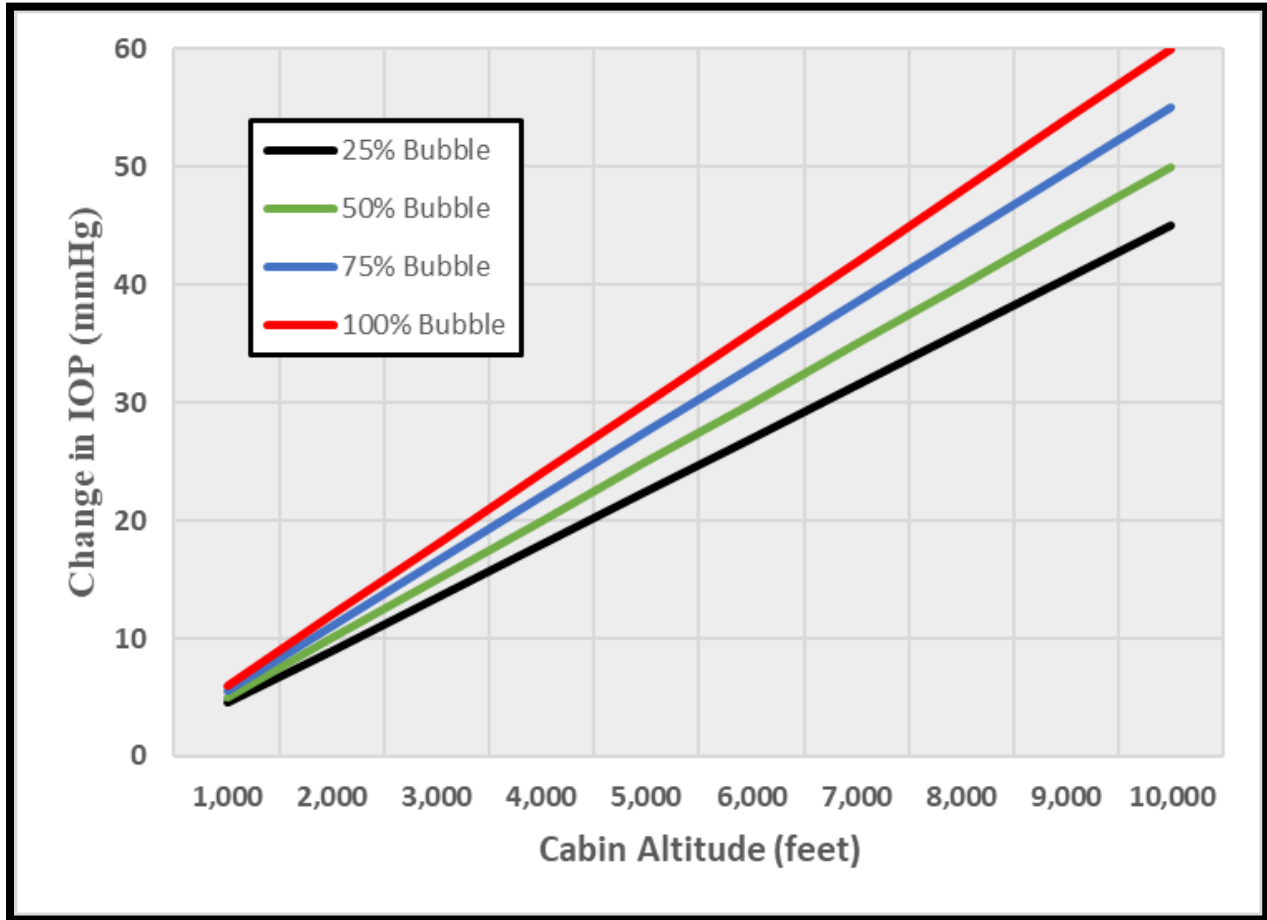
Note: Progressive decline in percent and volume pneumoperitoneum as determined by CT scan. The overall graphic was derived from data presented by Malgras et al. (Malgras, 2017) % (percent), ml (milliliters).

TVFS Prescribing Approach for Patients with Intra-Abdominal Air

Intra-Abdominal Air Prescribing Considerations		
Intraluminal	Prescriptions	Extraluminal
Uncomplicated Normal	nothing specific	Uncomplicated Surgery
	nothing specific	Surgery with Drains (minimal air)
Splenectomy (large air, impaired, no suction)	NGT to suction CAR	
	supplemental O ₂ , CAR	Surgery with Drains (large air)
Anastomoses (peri-anastomotic air)	NGT to suction supplemental O ₂ , CAR	
	supplemental O ₂ supplemental O ₂ , CAR, supine, bedrest	Pneumoperitoneum (minimal air) IAH risk.....(large air)
Ileus (minimal air) (large air).....IAH risk	supplemental O ₂ , CAR NGT to suction, supplemental O ₂ , CAR, supine, bedrest	
Sepsis, Ascites (abdominal edema).....IAH risk	NGT to suction, supplemental O ₂ , CAR, supine, bedrest	Major Trauma/Burns IAH risk...(abdominal edema)
Intra-abdominal Hypertension (ACS risk)	NGT to suction, supplemental O ₂ , CAR, supine, bedrest	Intra-abdominal Hypertension (ACS risk)

Note: NGT (nasogastric tube), O₂ (oxygen), CAR (cabin altitude restriction), IAH (intra-abdominal hypertension), ACS (abdominal compartment syndrome).

Estimated Rise in IOP with Each 1,000 Feet of Cabin Altitude



Note: Graphic derived and extrapolated from experimental animal (New Zealand white rabbit) data as presented by Fromow-Guerra et al. Pressure conversions, rabbit to human, were by the Friedenwald methodology. The inserted intraocular bubbles (SF₆) were 25%, 50%, and 100% intraocular volume; human-converted IOPs rose approximately 4.5, 5.0, and 6.0 mmHg per 1,000 feet cabin altitude, respectively. The pressure differences between bubbles were not significant. (Fromow-Guerra, 2016) IOP (intraocular pressure), mmHg (millimeters mercury pressure), % (percent).

TVFS Prescribing Approach for Patients with Pneumatosis Oculi

Pneumatosis Oculi Prescribing Considerations	
Conditon	Prescriptions
Peri-orbital/Orbital Emphysema	
--- open communicating soft tissues	nothing specific
--- closed soft tissues	delayed validation; supplemental O ₂ , humidification, decongestants, no Valsalva/lifting, CAR
Penetrating Trauma	
--- open globe	nothing specific
--- closed globe	CAR, slow take-off/landing, recline w/ HOB elevated, supplemental O ₂ , antibiotics, bilateral patching estimated IOP < 50 mmHg per (baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg})
Inserted Gas	
--- general guidance	delayed validation until bubble at least < 30%
--- bubble < 20%	upright posture, CAR, aircrew counseled, sxms prompt cabin drop ≥ 2,000 feet; supplemental O ₂ as needed for retina (of questionable resorption benefit) estimated IOP < 50 mmHg per (baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg})
--- bubble ≤ 10%	upright posture, aircrew counseled, sxms prompt cabin drop ≥ 2,000 feet, estimate IOP to invoke "no CAR"; supplemental O ₂ as needed for retina (of questionable resorption benefit) estimated IOP < 50 mmHg per (baseline IOP + {[cabin altitude/1,000] x 4-6 mmHg})

Note: O₂ (oxygen), CAR (cabin altitude restriction), HOB (head of bed), IOP (intraocular pressure), mmHg (millimeters mercury pressure), % (percent).

HYPOXIA & OXYGEN

Table for Determining Sea Level Oxygen Equivalency at Altitude

$$P_{iO_2} = F_{iO_2} * (P_{\text{ground level}} - P_{H_2O}), \quad (1)$$

where P_{iO_2} is the inspired oxygen partial pressure, F_{iO_2} is the oxygen fraction, $P_{\text{ground level}}$ is the barometric pressure at ground level and P_{H_2O} is the partial pressure of water vapor. Water vapor must be considered since the body humidifies all inspired air/gas. Inserting appropriate values permits calculation of ground level (in this case, sea level) inspired oxygen partial pressure.

$$P_{iO_2} = 0.21 * (760 \text{ mmHg} - 47 \text{ mmHg}) = \sim 150 \text{ mmHg} \quad (2)$$

To determine the ground level equivalent fraction of oxygen at any given altitude (P_{altitude}), the following expression is applied:

$$F_{iO_2} * (P_{\text{ground level}} - P_{H_2O}) = \text{Required } F_{iO_2} * (P_{\text{altitude}} - P_{H_2O}) \quad (3)$$

Rearranging the expression:

$$\text{Required } F_{iO_2} = [F_{iO_2} * (P_{\text{ground level}} - 47 \text{ mmHg})] / (P_{\text{altitude}} - 47 \text{ mmHg}) \quad (4)$$

Study an example. A patient to be evacuated is breathing 60% oxygen. The AE mission is flown with a cabin altitude of 8,000 feet and ground level is at sea level. Calculating with appropriate values produces:

$$\text{Required } F_{iO_2} = [F_{iO_2} * (P_{\text{ground level}} - 47 \text{ mmHg})] / (P_{\text{altitude}} - 47 \text{ mmHg}), \quad (1)$$

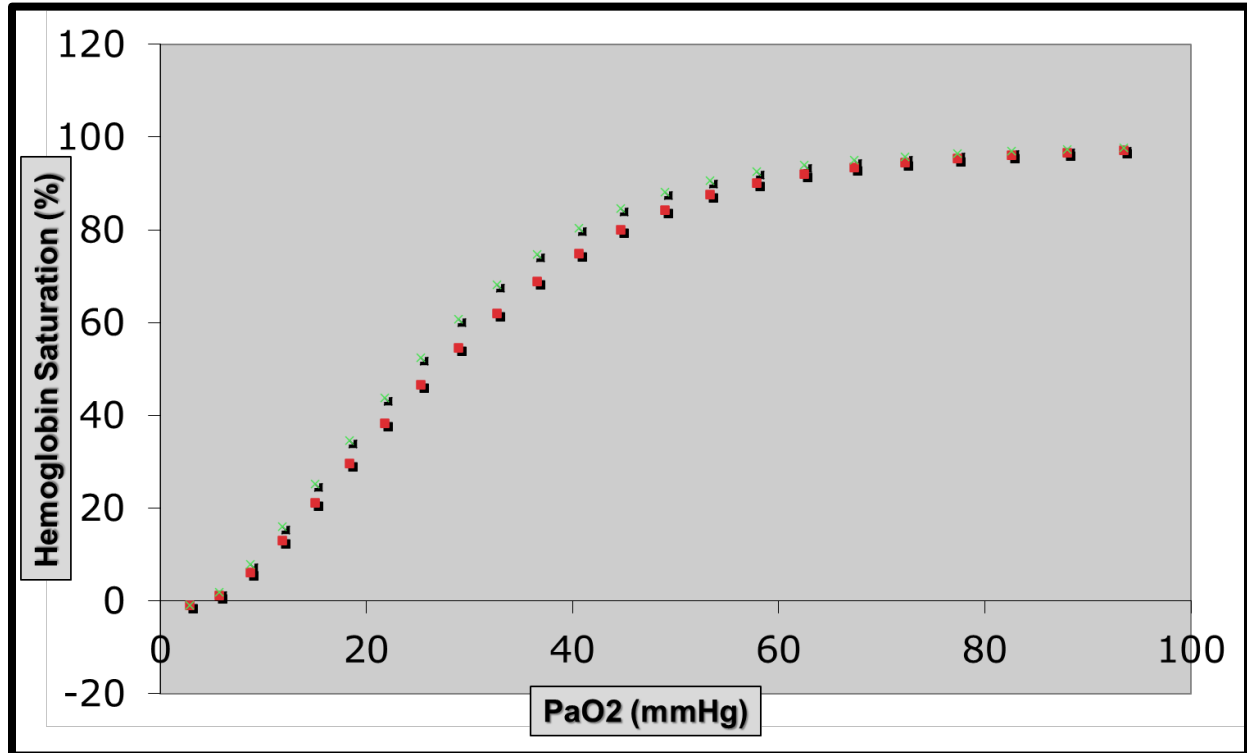
$$\text{Required } F_{iO_2} = [0.60 * (760 \text{ mmHg} - 47 \text{ mmHg})] / (565 \text{ mmHg} - 47 \text{ mmHg}), \quad (2)$$

$$\text{Required } F_{iO_2} = [0.60 * (713 \text{ mmHg})] / (518 \text{ mmHg}) = \mathbf{0.83 \text{ (or 83\%)}} \quad (3)$$

Altitude (Ft)	Atmospheric Pressure (mmHg)	Oxygen 21% (mmHg)	Oxygen Requirements to Maintain Sea Level Equivalency**																		
10000	522	110		32	38	45	53	60	68	75	83	90	98								
9000	543	114		30	36	43	50	58	65	72	79	86	93								
8000	565	119		29	34	41	48	55	62	69	76	83	89	96							
7000	587	123		28	33	40	46	53	59	66	73	79	86	92	99						
6000	609	128		27	32	38	44	51	57	63	70	76	82	89	95	101					
5000	633	133		26	30	37	43	49	55	61	67	73	79	85	91	97					
4000	656	138		25	29	35	41	47	53	59	64	70	76	82	88	94	100				
3000	681	143		24	28	34	39	45	51	56	62	67	73	79	84	90	96				
2000	707	148		23	27	32	38	43	49	54	59	65	70	76	81	86	92	97			
1000	733	154		22	26	31	36	42	47	52	57	62	68	73	78	83	88	94	99		
0	760	160	PiO ₂	150	178	214	250	285	321	357	392	428	463	499	535	570	606	642	677	713	
			FiO ₂	0.21	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	
		O ₂ Source	RA	Nasal Cannula (1-6 L/min)						Non-Rebreathing Mask (7-15 L/min)											
				Simple Mask (5-8 L/min)						Partial Rebreathing Mask with Bag (7-15 L/min)											
				**Pertinent Formula:						$PiO_2 = FiO_2 \times (P_{\text{sea level}} - P_{H_2O})$ $\text{Required } FiO_2 = [FiO_2 \times (P_{\text{sea level}} - 47 \text{ mmHg})] / (P_{\text{altitude}} - 47 \text{ mmHg})$											

Note: Table employs formulae described by McLaughlin et al and oxygen delivery device capabilities described in the Air Force Instruction. (McLaughlin, 2003; AFI 48-307 Vol 1, 2017) Although this table is determined for sea level equivalency, another could be easily created with any desired ground level equivalency. Rule of Thumb: Nasal Cannula (~4% per L/min); Simple Mask (~6% per L/min); Non-Rebreathing Mask (~4-6% per L/min). Ft (feet), mmHg (millimeters mercury pressure), % (percent), P_{iO_2} (partial pressure of inspired air), F_{iO_2} (oxygen fraction of inspired air), O₂ (oxygen), RA (room air), L (liter), min (minute), P (pressure).

Oxyhemoglobin Dissociation Curve



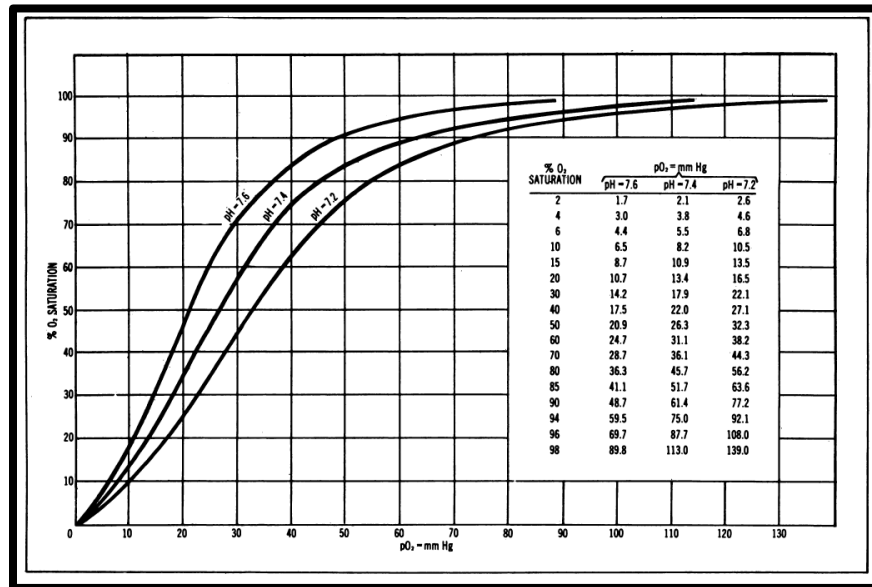
Note: Graphic created by and courtesy of Lt Col Daniel Cole. (USAFR, MC, FS) Physiological equations derived by Kelman were employed. (Kelman, 1966a; Kelman, 1966b) The Red Squares represent the Kelman equation; the Green Xs represent the Kelman equation corrected for pH and patient temperature. % (percent), mmHg (millimeters mercury pressure).

CCATT CPG - ARDSNet Lung Protective Ventilator Strategy

PEEP Titration Table - ARDSNet ARMA Trial																	
PEEP	5	5	8	8	10	10	10	12	14	14	14	16	18	18	20	22	24
Fio2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	1	1	1	1
<-----Move across table to keep SaO ₂ 92 – 96 %----->																	
Patients falling in shaded area are not necessarily too sick for flight but risks and benefits should be considered as described in the CPG.																	

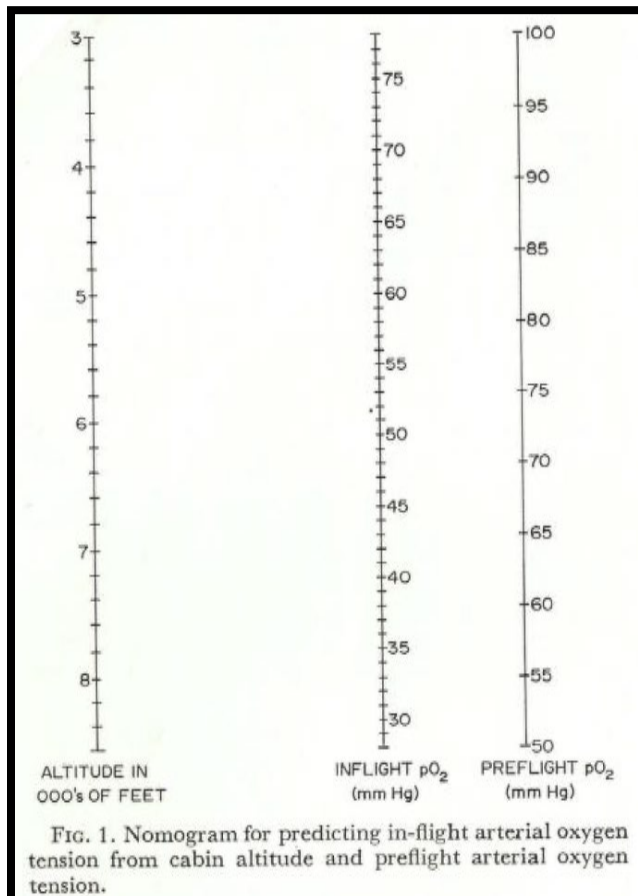
Note: Graphic taken from the Joint Trauma System *CCAT Mechanical Ventilation Clinical Practice Guideline*, a US government publication not subject to copyright. (JTS, 2013) CCAT[T] (Critical Care Air Transport [Team]), PEEP (positive end-expiratory pressure), ARDSNet (Acute Respiratory Distress Syndrome Network), ARMA (ARDS Respiratory Management Arm), FiO₂ (oxygen fraction of inspired air), SaO₂ (arterial hemoglobin oxygen saturation (%)), CPG (clinical practice guideline).

Supplemental Oxyhemoglobin Dissociation Curve



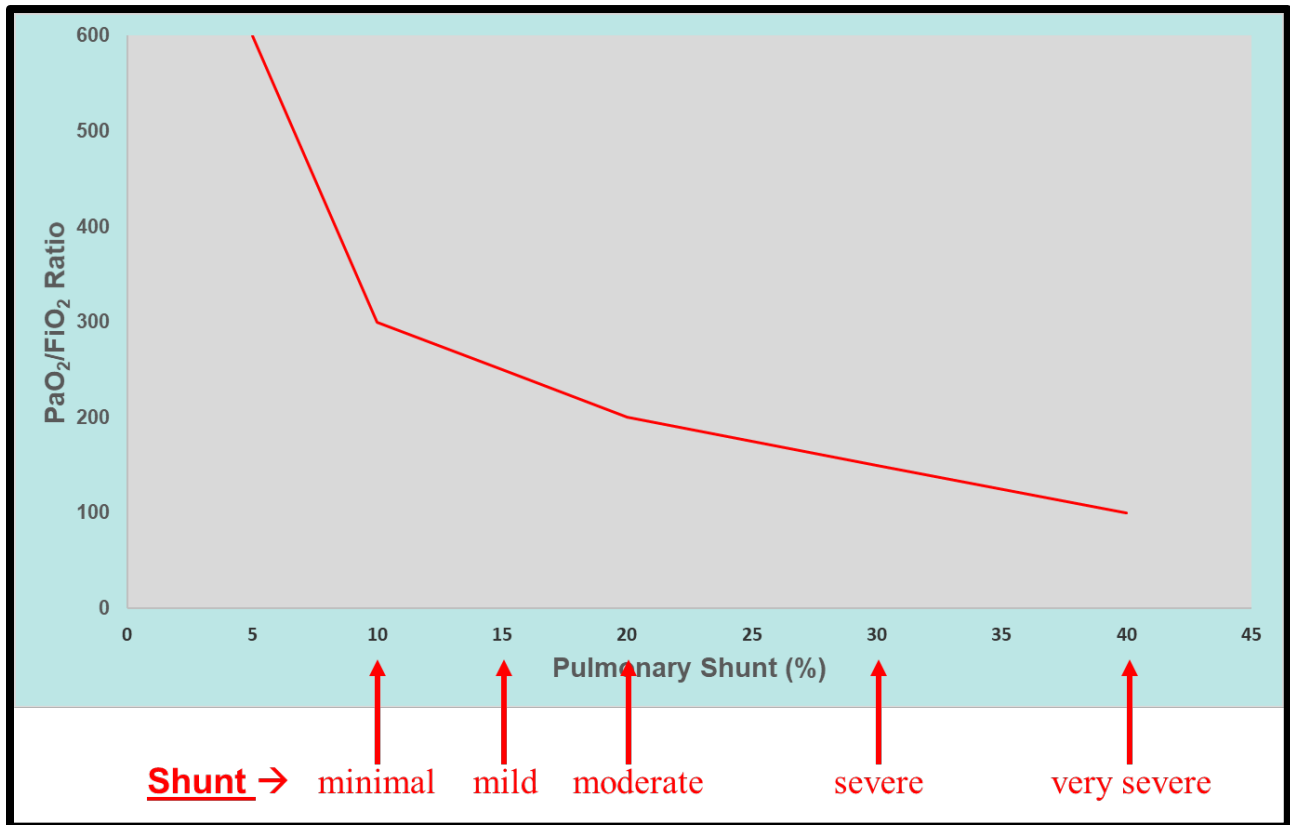
Note: Graphic taken from Aerospace Medicine, Flight Surgeon's Guide, 27 December 1968, Figure 2-4, page 2-14. US government publication not subject to copyright.

Nomogram for Predicting Inflight PaO₂



Note: Reprinted with permission from the Journal of the American College of Surgeons, formerly Surgery Gynecology & Obstetrics. (Henry, 1973)

Pulmonary Shunt Ratio-Percent-Severity Depiction



Note: Graphic created using data presented in Tintinalli's Emergency Medicine. (Glass, 2020) PaO₂ (arterial oxygen partial pressure), FiO₂ (oxygen fraction of inspired air), % (percent).

PaO₂/FiO₂ versus SpO₂/FiO₂ Pulmonary Shunt Ratio Correlation

PaO ₂ /FiO ₂ Ratio versus SpO ₂ /FiO ₂ Ratio Correlation		
PaO ₂ /FiO ₂ Ratio	SpO ₂ /FiO ₂ Ratio	Clinical Setting
< 400	< 400-512	Acute Lung Injury Acute Respiratory Distress Syndrome
< 300	< 316-357	
< 200	< 214-232	
< 100	< 67-148	

Note: Table developed from calculations based on regression equation ($S/F = 64 + (0.84 * P/F)$) and data presented various articles. (Pandharipande, 2006; Rice, 2007; Pandharipande, 2009) S (SpO₂), F (FiO₂), P (PaO₂), PaO₂ (arterial oxygen partial pressure), FiO₂ (oxygen fraction of inspired air).

HEMMORRHAGE & HEMOGLOBIN

Classes of Hemorrhagic Shock

Total Blood Volume	5,000 ml				Total Blood Volume
Blood Loss	≤ 15%	15-30%	30-40%	> 40%	
Blood Pressure	normal	normal	decreased	decreased	
Heart Rate	< 100	100-120	120-140	> 140	
Respiratory Rate	14-20	20-30	30-40	>35	
SHOCK	Class I	Class II	Class III	Class IV	
Blood Loss				> 2,000 ml	
				1,500-2,000 ml	
				750-1,500 ml	
				≤ 750 ml	

Note: Table derived from data presented by the American College of Surgeons Committee on Trauma. (ATLS, 2012; Cannon, 2018) % (percent), ml (milliliters).

TISSUE OXYGEN DELIVERY (DO₂)

Hypobaria Impact on the Starling Intravascular-Extravascular Equilibrium

--- Starling Fluid Flux Equation ---

$$J_v = K_f * [(P_C - P_T) - (\pi_C - \pi_T)], \quad \text{where}$$

J_v is the driving force for fluid movement

($J_v > 0 \rightarrow$ denotes filtration into the interstitial space;

$J_v < 0$ denotes resorption into the vascular space),

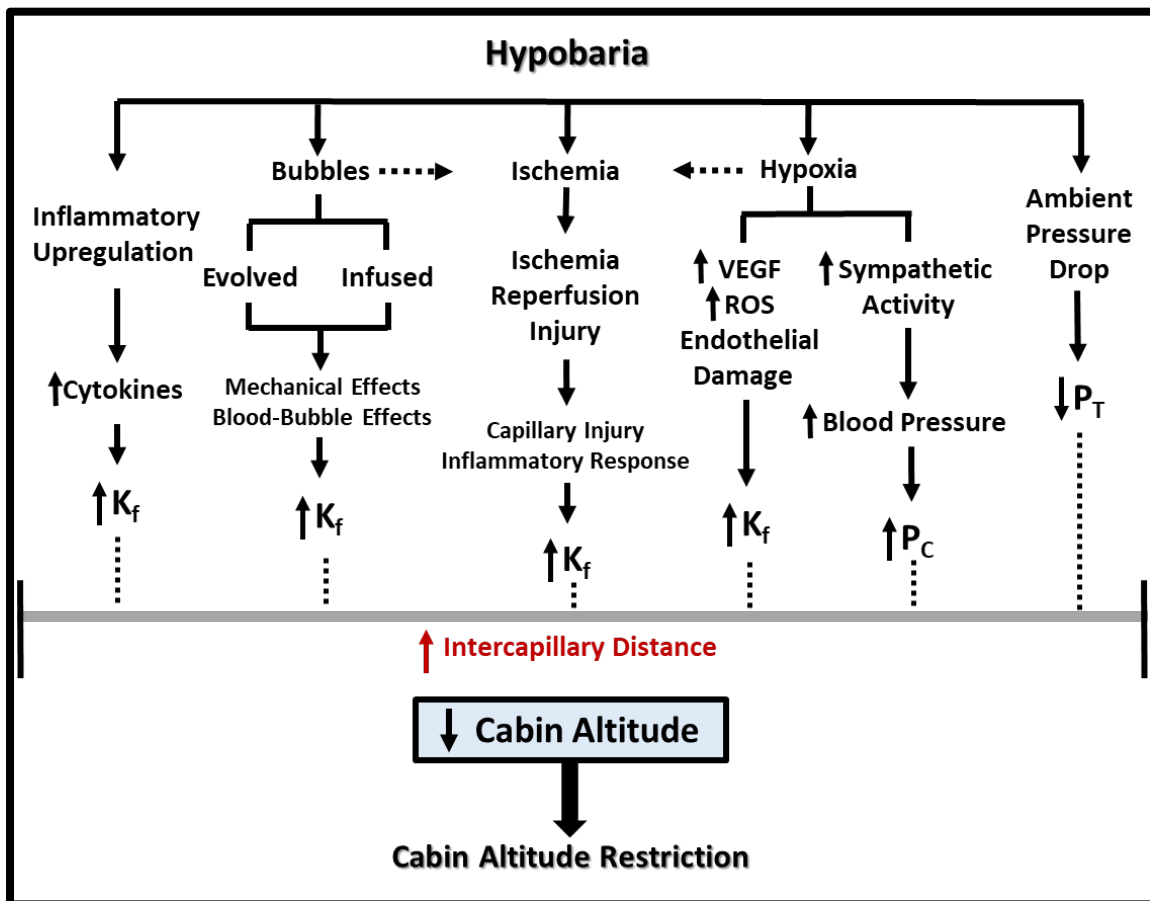
K_f is the capillary permeability factor,

P_C is the capillary hydrostatic pressure,

P_T is the interstitial tissue hydrostatic pressure,

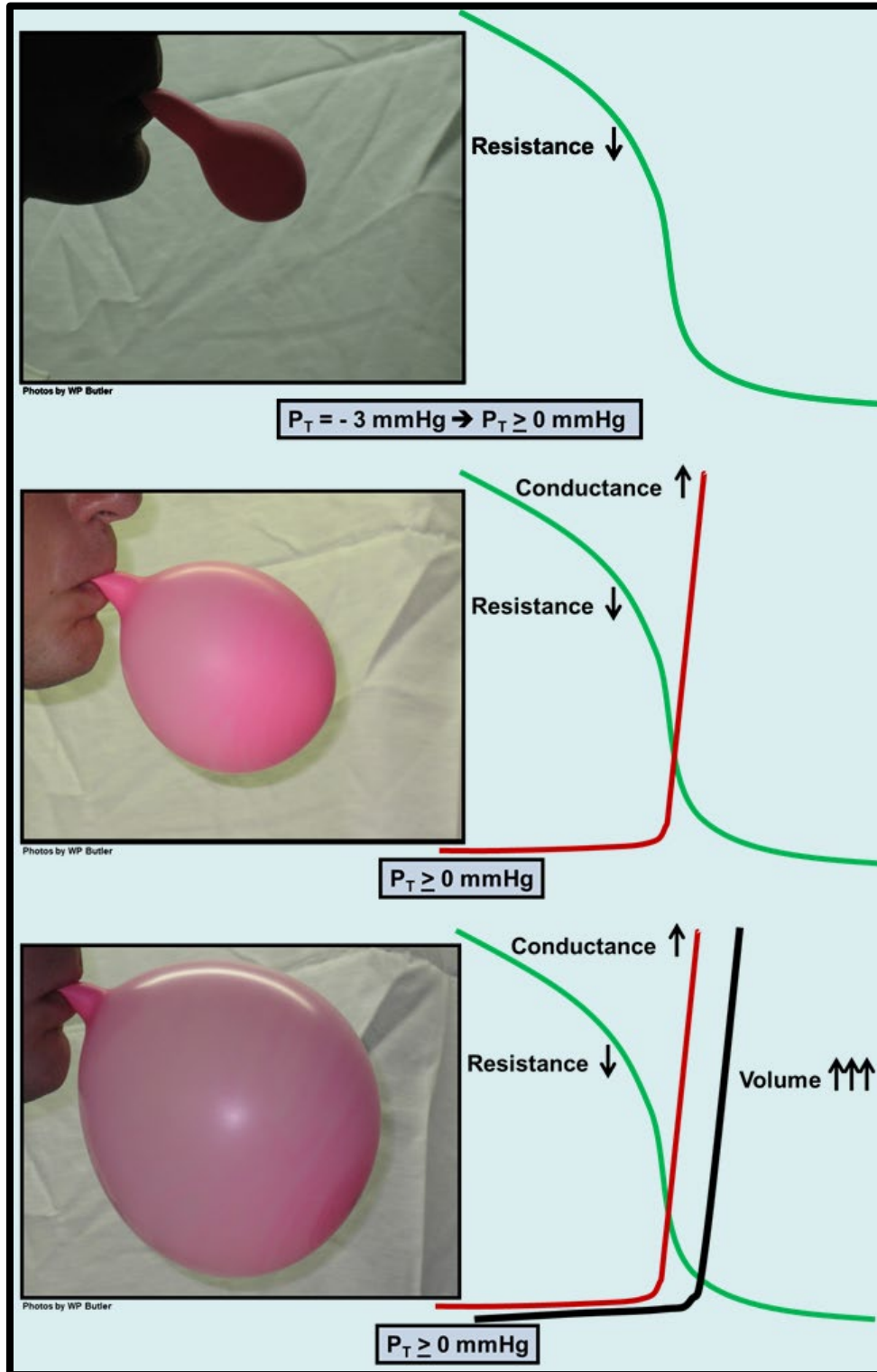
π_C is the capillary osmotic pressure, and

π_T is the interstitial tissue osmotic pressure. (Costanzo, 2011)



Note: K_f (capillary permeability), P_C (capillary hydrostatic pressure), P_T (interstitial tissue hydrostatic pressure), VEGF (vascular endothelial growth factor), ROS (reactive oxygen species).

Balloon Analogy for Altitude-Mediated Tissue Edema (Starling Physiology)



Note: Photographs taken by and courtesy of author (WPB). Curves depict concepts and data previously published. (Guyton, 1966; Guyton, 1968; Klatzo, 1987; Krasney, 1994) P_T (interstitial tissue hydrostatic pressure), mmHg (millimeters mercury pressure).

Notations from the DO₂ Equations

$$\text{Alveolar Gas Equation (Constanzo, 2014)} \rightarrow \quad (1)$$

$$P_{AO_2} = [(P_B - P_{H_2O}) * FiO_2] - PaCO_2/RQ$$

P_{AO_2} : alveolar oxygen partial pressure (mmHg)
 P_B : ambient barometric pressure (mmHg)
 P_{H_2O} : water vapor partial pressure (generally considered 47 mmHg)
 FiO_2 : oxygen fraction of inspired air
 $PaCO_2$: arterial carbon dioxide partial pressure (mmHg)
 RQ : respiratory quotient (CO_2 eliminated/ O_2 consumed)

$$\text{Arterial Oxygen Content Equation (Constanzo, 2014)} \rightarrow \quad (2)$$

$$CaO_2 = (SaO_2 * HgbCC * Hgb) + (0.0031 * PaO_2)$$

CaO_2 : arterial oxygen content (ml O_2 /dl)
 SaO_2 : arterial hemoglobin oxygen saturation (%)
 $HgbCC$: hemoglobin carrying capacity (1.34 ml O_2 /g)
 Hgb : hemoglobin level (g/dl)
 PaO_2 : arterial oxygen partial pressure (mmHg)

$$\text{Tissue Oxygen Delivery Equation (Constanzo, 2014)} \rightarrow \quad (3)$$

$$DO_2 = (CaO_2 * CO)/Wt$$

DO_2 : tissue oxygen delivery (ml O_2 /kg/min)
 CaO_2 : arterial oxygen content (ml O_2 /dl)
 CO : cardiac output (heart rate x stroke volume, ml/min)
 Wt : weight (kg)

$$\text{Kelman's Oxygen Dissociation Curve Model (Kelman, 1966a; Kelman, 1966b)} \rightarrow \quad (4)$$

$$SaO_2 = [100 * (a_1x + a_2x^2 + a_3x^3 + x^4)] / (a_4 + a_5x + a_6x^2 + a_7x^3 + x^4)$$

SaO_2 : arterial hemoglobin oxygen saturation (%)
 x : oxygen tension (aka arterial oxygen partial pressure, mmHg)
 a_1 : -8.5322289×10^3
 a_2 : 2.1214010×10^3
 a_3 : -6.7073989×10^1
 a_4 : 9.3596087×10^5
 a_5 : -3.1346258×10^4
 a_6 : 2.3961674×10^3
 a_7 : -6.7104406×10^1

Tables for Calculating DO₂

Assumptions

1. DO_{2crit} < 7.3 ml O₂/kg/min
2. Cardiac Output (CO)
 - a. Normal = 55 dl/min
 - b. Abnormal = 45 dl/min
3. Alveolar-Arterial O₂ Difference
 - a. (age/4) + 4 = 9 mmHg
4. Young, healthy person
 - a. ~20 years old
 - b. ~80 kg weight

Effects of Lowered Hemoglobin on Tissue Oxygen Delivery											
Hgb (g/dl)	% O ₂ Delivered	Altitude (Ft)	Atmospheric Pressure (mmHg)	Moist (37°C) O ₂ (mmHg)	RQ	Alveolar O ₂ (mmHg) w/ typical PCO ₂ 40 mmHg	Arterial O ₂ (mmHg) w/ A-a = 8	O ₂ %Sat (from dissociation curve)	CaO ₂	DO ₂ w/ nl CO	DO ₂ w/ abn CO
15.0	21%	0	760	150	0.85	103	95	0.98	20.0	13.7	11.2
15.0	21%	1000	733	144	0.85	97	89	0.97	19.8	13.6	11.1
15.0	21%	2000	707	139	0.86	92	84	0.96	19.6	13.4	11.0
15.0	21%	3000	681	133	0.86	87	79	0.95	19.3	13.3	10.9
15.0	21%	4000	656	128	0.87	82	74	0.95	19.3	13.3	10.9
15.0	21%	5000	633	123	0.87	77	69	0.93	18.9	13.0	10.6
15.0	21%	6000	609	118	0.88	73	65	0.91	18.5	12.7	10.4
15.0	21%	7000	587	113	0.88	68	60	0.90	18.3	12.6	10.3
15.0	21%	8000	565	109	0.89	64	56	0.86	17.5	12.0	9.8
15.0	21%	9000	543	104	0.89	59	51	0.83	16.8	11.6	9.5
15.0	21%	10000	522	100	0.90	55	47	0.79	16.0	11.0	9.0
15.0	50%	0	760	357	0.85	309	301	0.99	20.8	14.3	11.7
15.0	50%	1000	733	343	0.85	296	288	0.99	20.8	14.3	11.7
15.0	50%	2000	707	330	0.86	283	275	0.99	20.8	14.3	11.7
15.0	50%	3000	681	317	0.86	270	262	0.99	20.7	14.2	11.7
15.0	50%	4000	656	305	0.87	259	251	0.99	20.7	14.2	11.6
15.0	50%	5000	633	293	0.87	247	239	0.99	20.6	14.2	11.6
15.0	50%	6000	609	281	0.88	236	228	0.99	20.6	14.2	11.6
15.0	50%	7000	587	270	0.88	225	217	0.99	20.6	14.1	11.6
15.0	50%	8000	565	259	0.89	214	206	0.99	20.5	14.1	11.6
15.0	50%	9000	543	248	0.89	203	195	0.99	20.5	14.1	11.5
15.0	50%	10000	522	238	0.90	193	185	0.99	20.5	14.1	11.5
15.0	100%	0	760	713	0.85	666	658	0.99	21.9	15.1	12.3
15.0	100%	1000	733	688	0.85	639	631	0.99	21.9	15.0	12.3
15.0	100%	2000	707	660	0.86	613	605	0.99	21.8	15.0	12.2
15.0	100%	3000	681	634	0.86	587	579	0.99	21.7	14.9	12.2
15.0	100%	4000	656	609	0.87	563	555	0.99	21.6	14.9	12.2
15.0	100%	5000	633	586	0.87	540	532	0.99	21.5	14.8	12.1
15.0	100%	6000	609	562	0.88	517	509	0.99	21.5	14.8	12.1
15.0	100%	7000	587	540	0.88	495	487	0.99	21.4	14.7	12.0
15.0	100%	8000	565	518	0.89	473	465	0.99	21.3	14.7	12.0
15.0	100%	9000	543	496	0.89	451	443	0.99	21.3	14.6	12.0
15.0	100%	10000	522	475	0.90	431	423	0.99	21.2	14.6	11.9

Effects of Lowered Hemoglobin on Tissue Oxygen Delivery											
Hgb (g/dl)	% O ₂ Delivered	Altitude (Ft)	Atmospheric Pressure (mmHg)	Moist (37°C) O ₂ (mmHg)	RQ	Alveolar O ₂ (mmHg) w/ typical PCO ₂ 40 mmHg	Arterial O ₂ (mmHg) w/ A-a = 8	O ₂ %Sat (from dissociation curve)	CaO ₂	DO ₂ w/ nl CO	DO ₂ w/ abn CO
10.0	21%	0	760	150	0.85	103	95	0.98	13.4	9.2	7.6
10.0	21%	1000	733	144	0.85	97	89	0.97	13.3	9.1	7.5
10.0	21%	2000	707	139	0.86	92	84	0.96	13.1	9.0	7.4
10.0	21%	3000	681	133	0.86	87	79	0.95	13.0	8.9	7.3
10.0	21%	4000	656	128	0.87	82	74	0.95	13.0	8.9	7.3
10.0	21%	5000	633	123	0.87	77	69	0.93	12.7	8.7	7.1
10.0	21%	6000	609	118	0.88	73	65	0.91	12.4	8.5	7.0
10.0	21%	7000	587	113	0.88	68	60	0.90	12.2	8.4	6.9
10.0	21%	8000	565	109	0.89	64	56	0.86	11.7	8.0	6.6
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10.0	100%	2000	707	660	0.86	613	605	0.99	15.1	10.4	8.5
10.0	100%	3000	681	634	0.86	587	579	0.99	15.1	10.4	8.5
10.0	100%	4000	656	609	0.87	563	555	0.99	15.0	10.3	8.4
10.0	100%	5000	633	586	0.87	540	532	0.99	14.9	10.3	8.4
10.0	100%	6000	609	562	0.88	517	509	0.99	14.8	10.2	8.3
10.0	100%	7000	587	540	0.88	495	487	0.99	14.8	10.2	8.3
10.0	100%	8000	565	518	0.89	473	465	0.99	14.7	10.1	8.3
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10.0	100%	10000	522	475	0.90	431	423	0.99	14.6	10.0	8.2

Assumptions

1. $DO_{2crit} < 7.3$ ml O₂/kg/min
2. Cardiac Output (CO)
 - a. Normal = 55 dl/min
 - b. Abnormal = 45 dl/min
3. Alveolar-Arterial O₂ Difference
 - a. $(age/4) + 4 = 9$ mmHg
4. Young, healthy person
 - a. ~20 years old
 - b. ~80 kg weight

Hgb (g/dl)	% O ₂ Delivered	Altitude (Ft)	Atmospheric Pressure (mmHg)	Moist (37°C) O ₂ (mmHg)	RQ	Alveolar O ₂ (mmHg) w/ typical PCO ₂ 40 mmHg	Arterial O ₂ (mmHg) w/ A-a = 8	O ₂ %Sat (from dissociation curve)	CaO ₂	DO ₂ w/ nl CO	DO ₂ w/ abn CO
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9.0	21%	1000	733	144	0.85	97	89	0.97	12.0	8.2	6.7
9.0	21%	2000	707	139	0.86	92	84	0.96	11.8	8.1	6.7
9.0	21%	3000	681	133	0.86	87	79	0.95	11.7	8.0	6.6
9.0	21%	4000	656	128	0.87	82	74	0.95	11.7	8.0	6.6
9.0	21%	5000	633	123	0.87	77	69	0.93	11.4	7.9	6.4
9.0	21%	6000	609	118	0.88	73	65	0.91	11.2	7.7	6.3
9.0	21%	7000	587	113	0.88	68	60	0.90	11.0	7.6	6.2
9.0	21%	8000	565	109	0.89	64	56	0.88	10.5	7.2	5.9
9.0	21%	9000	543	104	0.89	59	51	0.83	10.2	7.0	5.7
9.0	21%	10000	522	100	0.90	55	47	0.79	9.7	6.7	5.4
9.0	50%	0	760	357	0.85	309	301	0.99	12.9	8.9	7.2
9.0	50%	1000	733	343	0.85	296	288	0.99	12.8	8.8	7.2
9.0	50%	2000	707	330	0.86	283	275	0.99	12.8	8.8	7.2
9.0	50%	3000	681	317	0.86	270	262	0.99	12.8	8.8	7.2
9.0	50%	4000	656	305	0.87	259	251	0.99	12.7	8.7	7.2
9.0	50%	5000	633	293	0.87	247	239	0.99	12.7	8.7	7.1
9.0	50%	6000	609	281	0.88	236	228	0.99	12.6	8.7	7.1
9.0	50%	7000	587	270	0.88	225	217	0.99	12.6	8.7	7.1
9.0	50%	8000	565	259	0.89	214	206	0.99	12.6	8.6	7.1
9.0	50%	9000	543	248	0.89	203	195	0.99	12.5	8.6	7.1
9.0	50%	10000	522	238	0.90	193	185	0.99	12.5	8.6	7.0
9.0	100%	0	760	713	0.85	666	658	0.99	14.0	9.6	7.9
9.0	100%	1000	733	688	0.85	639	631	0.99	13.9	9.6	7.8
9.0	100%	2000	707	660	0.86	613	605	0.99	13.8	9.5	7.8
9.0	100%	3000	681	634	0.86	587	579	0.99	13.7	9.4	7.7
9.0	100%	4000	656	609	0.87	563	555	0.99	13.7	9.4	7.7
9.0	100%	5000	633	586	0.87	540	532	0.99	13.6	9.3	7.6
9.0	100%	6000	609	562	0.88	517	509	0.99	13.5	9.3	7.6
9.0	100%	7000	587	540	0.88	495	487	0.99	13.4	9.2	7.6
9.0	100%	8000	565	518	0.89	473	465	0.99	13.4	9.2	7.5
9.0	100%	9000	543	496	0.89	451	443	0.99	13.3	9.2	7.5
9.0	100%	10000	522	475	0.90	431	423	0.99	13.2	9.1	7.5

Hgb (g/dl)	% O ₂ Delivered	Altitude (Ft)	Atmospheric Pressure (mmHg)	Moist (37°C) O ₂ (mmHg)	RQ	Alveolar O ₂ (mmHg) w/ typical PCO ₂ 40 mmHg	Arterial O ₂ (mmHg) w/ A-a = 8	O ₂ %Sat (from dissociation curve)	CaO ₂	DO ₂ w/ nl CO	DO ₂ w/ abn CO
8.5	21%	0	760	150	0.85	103	95	0.98	11.5	7.9	6.4
8.5	21%	1000	733	144	0.85	97	89	0.97	11.3	7.8	6.4
8.5	21%	2000	707	139	0.86	92	84	0.96	11.2	7.7	6.3
8.5	21%	3000	681	133	0.86	87	79	0.95	11.1	7.6	6.2
8.5	21%	4000	656	128	0.87	82	74	0.95	11.0	7.6	6.2
8.5	21%	5000	633	123	0.87	77	69	0.93	10.8	7.4	6.1
8.5	21%	6000	609	118	0.88	73	65	0.91	10.6	7.3	5.9
8.5	21%	7000	587	113	0.88	68	60	0.90	10.4	7.2	5.9
8.5	21%	8000	565	109	0.89	64	56	0.88	10.0	6.9	5.6
8.5	21%	9000	543	104	0.89	59	51	0.83	9.6	6.6	5.4
8.5	21%	10000	522	100	0.90	55	47	0.79	9.1	6.3	5.1
8.5	50%	0	760	357	0.85	309	301	0.99	12.2	8.4	6.9
8.5	50%	1000	733	343	0.85	296	288	0.99	12.2	8.4	6.8
8.5	50%	2000	707	330	0.86	283	275	0.99	12.1	8.3	6.8
8.5	50%	3000	681	317	0.86	270	262	0.99	12.1	8.3	6.8
8.5	50%	4000	656	305	0.87	259	251	0.99	12.1	8.3	6.8
8.5	50%	5000	633	293	0.87	247	239	0.99	12.0	8.3	6.8
8.5	50%	6000	609	281	0.88	236	228	0.99	12.0	8.2	6.7
8.5	50%	7000	587	270	0.88	225	217	0.99	11.9	8.2	6.7
8.5	50%	8000	565	259	0.89	214	206	0.99	11.9	8.2	6.7
8.5	50%	9000	543	248	0.89	203	195	0.99	11.9	8.2	6.7
8.5	50%	10000	522	238	0.90	193	185	0.99	11.8	8.1	6.7
8.5	100%	0	760	713	0.85	666	658	0.99	13.3	9.2	7.5
8.5	100%	1000	733	688	0.85	639	631	0.99	13.2	9.1	7.4
8.5	100%	2000	707	660	0.86	613	605	0.99	13.2	9.0	7.4
8.5	100%	3000	681	634	0.86	587	579	0.99	13.1	9.0	7.4
8.5	100%	4000	656	609	0.87	563	555	0.99	13.0	8.9	7.3
8.5	100%	5000	633	586	0.87	540	532	0.99	12.9	8.9	7.3
8.5	100%	6000	609	562	0.88	517	509	0.99	12.9	8.8	7.2
8.5	100%	7000	587	540	0.88	495	487	0.99	12.8	8.8	7.2
8.5	100%	8000	565	518	0.89	473	465	0.99	12.7	8.7	7.2
8.5	100%	9000	543	496	0.89	451	443	0.99	12.6	8.7	7.1
8.5	100%	10000	522	475	0.90	431	423	0.99	12.6	8.7	7.1

Assumptions

1. $DO_{2git} < 7.3$ ml O₂/kg/min
2. Cardiac Output (CO)
 - a. Normal = 55 dl/min
 - b. Abnormal = 45 dl/min
3. Alveolar-Arterial O₂ Difference
 - a. $(age/4) + 4 = 9$ mmHg
4. Young, healthy person
 - a. ~20 years old
 - b. ~80 kg weight

Hgb (g/dl)	% O ₂ Delivered	Altitude (Ft)	Atmospheric Pressure (mmHg)	Moist (37°C) O ₂ (mmHg)	RQ	Alveolar O ₂ (mmHg) w/ typical PCO ₂ 40 mmHg	Arterial O ₂ (mmHg) w/ A-a = 8	O ₂ %Sat (from dissociation curve)	CaO ₂	DO ₂ w/ nl CO	DO ₂ w/ abn CO
8.0	21%	0	760	150	0.85	103	95	0.98	10.8	7.4	8.1
8.0	21%	1000	733	144	0.85	97	89	0.97	10.7	7.3	6.0
8.0	21%	2000	707	139	0.86	92	84	0.96	10.6	7.3	5.9
8.0	21%	3000	681	133	0.86	87	79	0.95	10.4	7.2	5.9
8.0	21%	4000	656	128	0.87	82	74	0.95	10.4	7.2	5.9
8.0	21%	5000	633	123	0.87	77	69	0.93	10.2	7.0	5.7
8.0	21%	6000	609	118	0.88	73	65	0.91	10.0	6.8	5.6
8.0	21%	7000	587	113	0.88	68	60	0.90	9.8	6.8	5.5
8.0	21%	8000	565	109	0.89	64	56	0.86	9.4	6.5	5.3
8.0	21%	9000	543	104	0.89	59	51	0.83	9.1	6.2	5.1
8.0	21%	10000	522	100	0.90	55	47	0.79	8.6	5.9	4.8
8.0	50%	0	760	357	0.85	309	301	0.99	11.5	7.9	6.5
8.0	50%	1000	733	343	0.85	296	288	0.99	11.5	7.9	6.5
8.0	50%	2000	707	330	0.86	283	275	0.99	11.5	7.9	6.5
8.0	50%	3000	681	317	0.86	270	262	0.99	11.4	7.9	6.4
8.0	50%	4000	656	305	0.87	259	251	0.99	11.4	7.8	6.4
8.0	50%	5000	633	293	0.87	247	239	0.99	11.4	7.8	6.4
8.0	50%	6000	609	281	0.88	236	228	0.99	11.3	7.8	6.4
8.0	50%	7000	587	270	0.88	225	217	0.99	11.3	7.8	6.3
8.0	50%	8000	565	259	0.89	214	206	0.99	11.3	7.7	6.3
8.0	50%	9000	543	248	0.89	203	195	0.99	11.2	7.7	6.3
8.0	50%	10000	522	238	0.90	193	185	0.99	11.2	7.7	6.3
8.0	100%	0	760	713	0.85	666	658	0.99	12.7	8.7	7.1
8.0	100%	1000	733	688	0.85	639	631	0.99	12.6	8.6	7.1
8.0	100%	2000	707	660	0.86	613	605	0.99	12.5	8.6	7.0
8.0	100%	3000	681	634	0.86	587	579	0.99	12.4	8.5	7.0
8.0	100%	4000	656	609	0.87	563	555	0.99	12.3	8.5	6.9
8.0	100%	5000	633	586	0.87	540	532	0.99	12.3	8.4	6.9
8.0	100%	6000	609	562	0.88	517	509	0.99	12.2	8.4	6.9
8.0	100%	7000	587	540	0.88	495	487	0.99	12.1	8.3	6.8
8.0	100%	8000	565	518	0.89	473	465	0.99	12.1	8.3	6.8
8.0	100%	9000	543	496	0.89	451	443	0.99	12.0	8.2	6.7
8.0	100%	10000	522	475	0.90	431	423	0.99	11.9	8.2	6.7

Hgb (g/dl)	% O ₂ Delivered	Altitude (Ft)	Atmospheric Pressure (mmHg)	Moist (37°C) O ₂ (mmHg)	RQ	Alveolar O ₂ (mmHg) w/ typical PCO ₂ 40 mmHg	Arterial O ₂ (mmHg) w/ A-a = 8	O ₂ %Sat (from dissociation curve)	CaO ₂	DO ₂ w/ nl CO	DO ₂ w/ abn CO
7.5	21%	0	760	150	0.85	103	95	0.98	10.1	7.0	5.7
7.5	21%	1000	733	144	0.85	97	89	0.97	10.0	6.9	5.6
7.5	21%	2000	707	139	0.86	92	84	0.96	9.9	6.8	5.6
7.5	21%	3000	681	133	0.86	87	79	0.95	9.8	6.7	5.5
7.5	21%	4000	656	128	0.87	82	74	0.95	9.8	6.7	5.5
7.5	21%	5000	633	123	0.87	77	69	0.93	9.6	6.6	5.4
7.5	21%	6000	609	118	0.88	73	65	0.91	9.3	6.4	5.3
7.5	21%	7000	587	113	0.88	68	60	0.90	9.2	6.3	5.2
7.5	21%	8000	565	109	0.89	64	56	0.86	8.8	6.1	5.0
7.5	21%	9000	543	104	0.89	59	51	0.83	8.5	5.8	4.8
7.5	21%	10000	522	100	0.90	55	47	0.79	8.1	5.6	4.5
7.5	50%	0	760	357	0.85	309	301	0.99	10.9	7.5	6.1
7.5	50%	1000	733	343	0.85	296	288	0.99	10.8	7.5	6.1
7.5	50%	2000	707	330	0.86	283	275	0.99	10.8	7.4	6.1
7.5	50%	3000	681	317	0.86	270	262	0.99	10.8	7.4	6.1
7.5	50%	4000	656	305	0.87	259	251	0.99	10.7	7.4	6.0
7.5	50%	5000	633	293	0.87	247	239	0.99	10.7	7.3	6.0
7.5	50%	6000	609	281	0.88	236	228	0.99	10.7	7.3	6.0
7.5	50%	7000	587	270	0.88	225	217	0.99	10.6	7.3	6.0
7.5	50%	8000	565	259	0.89	214	206	0.99	10.6	7.3	6.0
7.5	50%	9000	543	248	0.89	203	195	0.99	10.6	7.3	5.9
7.5	50%	10000	522	238	0.90	193	185	0.99	10.5	7.2	5.9
7.5	100%	0	760	713	0.85	666	658	0.99	12.0	8.2	6.7
7.5	100%	1000	733	688	0.85	639	631	0.99	11.9	8.2	6.7
7.5	100%	2000	707	660	0.86	613	605	0.99	11.8	8.1	6.7
7.5	100%	3000	681	634	0.86	587	579	0.99	11.7	8.1	6.6
7.5	100%	4000	656	609	0.87	563	555	0.99	11.7	8.0	6.6
7.5	100%	5000	633	586	0.87	540	532	0.99	11.6	8.0	6.5
7.5	100%	6000	609	562	0.88	517	509	0.99	11.5	7.9	6.5
7.5	100%	7000	587	540	0.88	495	487	0.99	11.5	7.9	6.4
7.5	100%	8000	565	518	0.89	473	465	0.99	11.4	7.8	6.4
7.5	100%	9000	543	496	0.89	451	443	0.99	11.3	7.8	6.4
7.5	100%	10000	522	475	0.90	431	423	0.99	11.3	7.7	6.3

Assumptions

1. $DO_{2crit} < 7.3$ ml O₂/kg/min
2. Cardiac Output (CO)
 - a. Normal = 55 dl/min
 - b. Abnormal = 45 dl/min
3. Alveolar-Arterial O₂ Difference
 - a. $(age/4) + 4 = 9$ mmHg
4. Young, healthy person
 - a. ~20 years old
 - b. ~80 kg weight

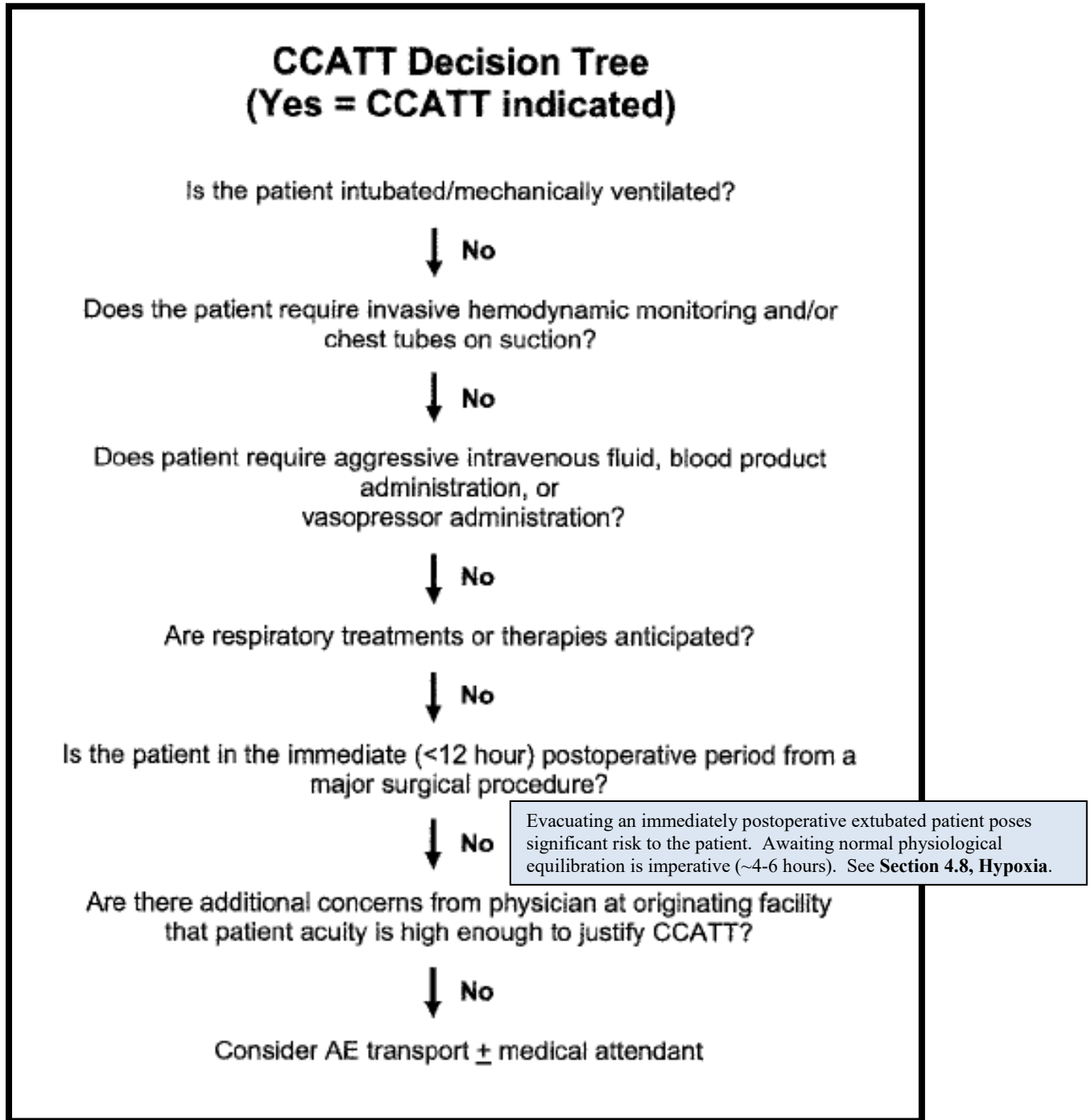
Effects of Lowered Hemoglobin on Tissue Oxygen Delivery											
Hgb (g/dl)	% O ₂ Delivered	Altitude (Ft)	Atmospheric Pressure (mmHg)	Moist (37°C) O ₂ (mmHg)	RQ	Alveolar O ₂ (mmHg) w/ typical PCO ₂ 40 mmHg	Arterial O ₂ (mmHg) w/ A-a = 8	O ₂ %Sat (from dissociation curve)	CaO ₂	DO ₂ w/ nl CO	DO ₂ w/ abn CO
7.0	21%	0	760	150	0.85	103	95	0.98	9.5	6.5	5.3
7.0	21%	1000	733	144	0.85	97	89	0.97	9.4	6.4	5.3
7.0	21%	2000	707	139	0.86	92	84	0.96	9.3	6.4	5.2
7.0	21%	3000	681	133	0.86	87	79	0.95	9.2	6.3	5.1
7.0	21%	4000	656	128	0.87	82	74	0.95	9.1	6.3	5.1
7.0	21%	5000	633	123	0.87	77	69	0.93	8.9	6.1	5.0
7.0	21%	6000	609	118	0.88	73	65	0.91	8.7	6.0	4.9
7.0	21%	7000	587	113	0.88	68	60	0.90	8.6	5.9	4.9
7.0	21%	8000	565	109	0.89	64	56	0.86	8.2	5.7	4.8
7.0	21%	9000	543	104	0.89	59	51	0.83	7.9	5.5	4.5
7.0	21%	10000	522	100	0.90	55	47	0.79	7.6	5.2	4.3
7.0	50%	0	760	357	0.85	309	301	0.99	10.2	7.0	5.7
7.0	50%	1000	733	343	0.85	296	288	0.99	10.2	7.0	5.7
7.0	50%	2000	707	330	0.86	283	275	0.99	10.1	7.0	5.7
7.0	50%	3000	681	317	0.86	270	262	0.99	10.1	6.9	5.7
7.0	50%	4000	656	305	0.87	259	251	0.99	10.1	6.9	5.7
7.0	50%	5000	633	293	0.87	247	239	0.99	10.0	6.9	5.6
7.0	50%	6000	609	281	0.88	236	228	0.99	10.0	6.9	5.6
7.0	50%	7000	587	270	0.88	225	217	0.99	10.0	6.8	5.6
7.0	50%	8000	565	259	0.89	214	206	0.99	9.9	6.8	5.6
7.0	50%	9000	543	248	0.89	203	195	0.99	9.9	6.8	5.6
7.0	50%	10000	522	238	0.90	193	185	0.99	9.9	6.8	5.5
7.0	100%	0	760	713	0.85	666	658	0.99	11.3	7.8	6.4
7.0	100%	1000	733	686	0.85	639	631	0.99	11.2	7.7	6.3
7.0	100%	2000	707	660	0.86	613	605	0.99	11.2	7.7	6.3
7.0	100%	3000	681	634	0.86	587	579	0.99	11.1	7.6	6.2
7.0	100%	4000	656	609	0.87	563	555	0.99	11.0	7.6	6.2
7.0	100%	5000	633	586	0.87	540	532	0.99	10.9	7.5	6.2
7.0	100%	6000	609	562	0.88	517	509	0.99	10.9	7.5	6.1
7.0	100%	7000	587	540	0.88	495	487	0.99	10.8	7.4	6.1
7.0	100%	8000	565	518	0.89	473	465	0.99	10.7	7.4	6.0
7.0	100%	9000	543	496	0.89	451	443	0.99	10.7	7.3	6.0
7.0	100%	10000	522	475	0.90	431	423	0.99	10.6	7.3	6.0

Effects of Lowered Hemoglobin on Tissue Oxygen Delivery											
Hgb (g/dl)	% O ₂ Delivered	Altitude (Ft)	Atmospheric Pressure (mmHg)	Moist (37°C) O ₂ (mmHg)	RQ	Alveolar O ₂ (mmHg) w/ typical PCO ₂ 40 mmHg	Arterial O ₂ (mmHg) w/ A-a = 8	O ₂ %Sat (from dissociation curve)	CaO ₂	DO ₂ w/ nl CO	DO ₂ w/ abn CO
6.5	21%	0	760	150	0.85	103	95	0.98	8.8	6.1	5.0
6.5	21%	1000	733	144	0.85	97	89	0.97	8.7	6.0	4.9
6.5	21%	2000	707	139	0.86	92	84	0.96	8.6	5.9	4.9
6.5	21%	3000	681	133	0.86	87	79	0.95	8.5	5.9	4.8
6.5	21%	4000	656	128	0.87	82	74	0.95	8.5	5.8	4.8
6.5	21%	5000	633	123	0.87	77	69	0.93	8.3	5.7	4.7
6.5	21%	6000	609	118	0.88	73	65	0.91	8.1	5.6	4.6
6.5	21%	7000	587	113	0.88	68	60	0.90	8.0	5.5	4.5
6.5	21%	8000	565	109	0.89	64	56	0.86	7.7	5.3	4.3
6.5	21%	9000	543	104	0.89	59	51	0.83	7.4	5.1	4.2
6.5	21%	10000	522	100	0.90	55	47	0.79	7.0	4.8	4.0
6.5	50%	0	760	357	0.85	309	301	0.99	9.6	6.6	5.4
6.5	50%	1000	733	343	0.85	296	288	0.99	9.5	6.5	5.4
6.5	50%	2000	707	330	0.86	283	275	0.99	9.5	6.5	5.3
6.5	50%	3000	681	317	0.86	270	262	0.99	9.4	6.5	5.3
6.5	50%	4000	656	305	0.87	259	251	0.99	9.4	6.5	5.3
6.5	50%	5000	633	293	0.87	247	239	0.99	9.4	6.4	5.3
6.5	50%	6000	609	281	0.88	236	228	0.99	9.3	6.4	5.2
6.5	50%	7000	587	270	0.88	225	217	0.99	9.3	6.4	5.2
6.5	50%	8000	565	259	0.89	214	206	0.99	9.3	6.4	5.2
6.5	50%	9000	543	248	0.89	203	195	0.99	9.2	6.3	5.2
6.5	50%	10000	522	238	0.90	193	185	0.99	9.2	6.3	5.2
6.5	100%	0	760	713	0.85	666	658	0.99	10.7	7.3	6.0
6.5	100%	1000	733	686	0.85	639	631	0.99	10.6	7.3	6.0
6.5	100%	2000	707	660	0.86	613	605	0.99	10.5	7.2	5.9
6.5	100%	3000	681	634	0.86	587	579	0.99	10.4	7.2	5.9
6.5	100%	4000	656	609	0.87	563	555	0.99	10.3	7.1	5.8
6.5	100%	5000	633	586	0.87	540	532	0.99	10.3	7.1	5.8
6.5	100%	6000	609	562	0.88	517	509	0.99	10.2	7.0	5.7
6.5	100%	7000	587	540	0.88	495	487	0.99	10.1	7.0	5.7
6.5	100%	8000	565	518	0.89	473	465	0.99	10.1	6.9	5.7
6.5	100%	9000	543	496	0.89	451	443	0.99	10.0	6.9	5.6
6.5	100%	10000	522	475	0.90	431	423	0.99	9.9	6.8	5.6

OTHER VALIDATION TOOLS

Clinical

CCATT Decision Tree



Note: Decision Tree proffered by Global Patient Movement Requirements Center to TVFSS. US government product not subject to copyright. Consult the office of the Air Mobility Command Surgeon General most up-to-date and detailed information.

AE Cardiac Tool

Approach to the Cardiac Patient and AE		Usual AE Requirements
Acute Coronary Syndrome / Myocardial Infarction		
Low Risk	Low CAD pretest probability (<10%) Less than 3 of the following: active smoker, hypertension, hypercholesterolemia, family history of premature CAD Negative cardiac markers (troponin, etc.) No pathologic ECG changes	AE crew
Intermediate Risk	Intermediate CAD pretest probability (10-90%) No High Risk likelihood features Diabetes Mellitus Negative cardiac markers (troponin, etc.) Fixed Q waves Abnormal ST segments or T waves Extracardiac vascular disease	Recommend/Consider: Cardiac Monitor Medical Attendant CCATT MAY be considered
High Risk	High CAD pretest probability > 90% Pathologic ECG changes of ischemia Hemodynamic instability Pulmonary edema (SaO2<92% on room air) Known history of coronary disease EF < 50% (if able to test) Sustained VT	At the least: Cardiac Monitor Medical Attendant CCATT SHOULD be considered
Valvular Disease		
Low Risk	Asymptomatic No dysrhythmia EF > 50% (if able to test) No evidence CHF/Pulmonary edema	AE Crew
Intermediate Risk	Exertional symptoms only, no rest symptoms (syncope, chest pain, dyspnea)	ACLS Medical Attendant Cardiac Monitor
High Risk	Symptoms at rest (syncope, chest pain, dyspnea) Any signs of CHF or pulmonary edema Requirement for IV pressors/diuretics/rate controllers	CCATT

Dysrhythmias	
Low Risk	Stable, rate controlled, asymptomatic SVT, A-flb, A-flutter WPW pattern on ECG (delta wave, short PR) 1st degree AVB, 2nd degree AVB (Wenckebach/Mobitz I) Pre-existing BBBs, asymptomatic
Intermediate Risk	Recurrent PSVT requiring IV meds EF < 50% (if able to test) Newly dx SVT, atrial flutter, rate controlled with PO medications or cardioversion within 48 hours Newly identified asymptomatic BBB, w/out evidence of MI
High Risk	Wide complex tachycardia CHF or pulmonary edema Symptomatic bradycardia Heart blocks requiring rate control/pacing

CAD Pre-test probability**	
Estimating the Pretest Probability of Coronary Artery Disease	
Step 1: Categorize the nature of the chest pain symptoms	
Coronary symptoms can be reliably characterized by using three clinical questions:	
1. Is the chest pain substernal?	
2. Are the symptoms precipitated by exertion?	
3. Is there prompt relief within 10 minutes with rest or nitroglycerin?	
Typical (classical) angina: all 3 present	
Atypical angina: any 2 present	
Nonanginal chest pain: 0-1 present	
Step 2: Estimate the pretest probability of coronary artery disease based on age.	
Low Probability (<10%)	
• Asymptomatic men and women of all ages	
• Women < 50 years with atypical chest pain	
Intermediate Probability (10%-90%)	
• Men of all ages with atypical angina	
• Women ≥ 50 years with atypical angina	
• Women 30-50 years with typical angina	
High Probability	
• Men ≥ 40 years with typical angina	
• Women ≥ 50 years with typical angina	
**Content from MxSAP 14, Cardiovascular Medicine	

Note: Developed by author (LWS) from earlier less user-friendly version by author (WPB).

ROC (Rule Out Contagion) List

THE "ROC" LIST

RULE-OUT CLINICAL INDICATORS LIST (HIGHLY COMMUNICABLE DISEASES)

The following indicators, if present on an AE patient movement request (PMR), are suggestive of a communicable disease. Illnesses in such patients could pose a disease threat to health care givers, aircrews, casual contacts and receiving communities.

POSITIVE HISTORY OF EXPOSURE

- ♦ Any history of exposure to sewage, body fluids, animals prior to illness?
- ♦ Any report of insect bites?
- ♦ SARS risk?

PLUS ANY OF THE FOLLOWING FOUR CLINICAL CATEGORIES:

FEVER? (Oral temperature greater or equal to 102.0F or 38.9C)

ABNORMAL BLEEDING?

- Any bleeding from gums or nosebleeds?
Any report of petechiae on the palate, throat or on mouth exam?
Are the patient's eyes "bloodshot" in appearance (conjunctival injection)?
- Any report of bloody stools or vomitus?

ADENOPATHY?

- Any report of tender or painful lymph nodes?
- Any report of lymph nodes with a "bruised" or darkened appearance?
- Any report of "matted lymph nodes", "goose-egg" size lymph nodes, or lymph nodes draining pus?

RAPID RESPIRATORY DECLINE, RASHES/SKIN CHANGES, UNUSUAL DETERIORATION?

- Did progression to severe symptoms and illness occur rapidly, over a period of less than 3 days, once the patient began to feel ill?
- Any report of "pox" or "pox-like" skin rash/lesion?
Any report of petechiae or purpura on the skin?
- Any report of a positive "Tourniquet Test"? (NB: inflating a BP cuff on an extremity performs this test. It is considered positive if small hemorrhages – "petechiae" – appear on the skin of the extremity distal to the cuff. This is a very good indicator of the vasculitis associated with hemorrhagic fever.)
Any report of icterus (yellow eyes, skin, or tongue)?
- Any report of cough AND fever in conjunction with any of the following...
 - Rapid disease progression, or
 - Petechiae, purpura, or
 - Lymphadenopathy as described herein.

*****NOTE: A "YES" TO CLINICAL FINDINGS SHOULD PROMPT IMMEDIATE TELEPHONE CONSULT WITH THE THEATRE FLIGHT SURGEON. EXPOSURE HISTORY ALONE DOES NOT NECESSARILY REQUIRE CONSULTATION.*****

Note: Checklist proffered by Global Patient Movement Requirements Center to TVFSs. US government product not subject to copyright.

Approach to Psychiatric Patients

Approach to Psychiatric Patients			
AE Classification	AE Definition	Contract for Safety	Requirements
1A	severe litter patient	No	sedated prior to flight restraints medical attendant
1B	intermediate litter patient	No	sedation or stand-by sedation stand-by restraints non-medical attendant
1C	cooperative walking patient	Yes	stand-by sedation no restraints non-medical attendant optional

Approach to Patients with Hernias or Kidney Stones

Approach to Patients with Hernias or Kidney Stones			
Diagnosis	Complicating Factor	Clinical Picture	Precedence
Inguinal Hernia	uncomplicated	inguinal bulge	Routine
	incarcerated	pain, not reducible, no bowel in hernia	Priority
	strangulated	pain, fever, not reducible, bowel in hernia	Urgent
Kidney Stone	uncomplicated stone	pain, no fever, mild hematuria	Routine
	above plus: hydroureter and/or hydronephrosis	pain, low grade fever, moderate hematuria	Priority
	above plus: impending or frank sepsis	pain, fever, tachycardia, elevated WBC, hematuria	Urgent

Approach to Preventing Extremity Compartment Syndrome

Approach to Preventing Extremity Compartment Syndrome		
Injured Extremity	TVFS Prescription	
	Supplemental Oxygen	Cabin Altitude Restriction
No Fasciotomy	Yes	Yes
Fasciotomy	Yes	Maybe

Note: "Maybe" must take into account extent of damage, extent of fasciotomy, and vascular integrity.

Aircraft

Litter Comparison

Litter Comparison	
Regular Litter	Overweight/Oversize Litter
vibration	vibration
pressure points	pressure points
patient < 250 pounds	patient < 450 pounds
non-rigid	rigid
oscillation	no oscillation
on stanchion	floor load
takes SMEED	no SMEED
convenient nursing	less convenient nursing
may wrap pelvic fracture	does not wrap pelvic fracture

Note: Consult the office of the Air Mobility Command Surgeon General for the most up-to-date and detailed information.

Aircraft Patient Capacities

Aircraft Patient Capacities			
Aircraft	Litters (stanchion)	Litters (floor load)	Ambulatory
C-130	72	15	44
C-17	36	60	102
KC-135	15	8	31

Note: Consult AFI 48-307, Volume 1, En Route Care and Aeromedical Evacuation Medical Operations for the most up-to-date and detailed information.

AE Aircraft Airflow Characteristics

Table A14.1. Aircraft Airflow.				A
Aircraft Type	Air Flow Direction	Ambient Air Intake and Exchange Rate (minutes)	Post-Mission Time Required to Obtain 99.9% Removal Efficiency*	
C-130	Top to bottom/aft to forward. NOTE 2	4 (Sea level) - 8 (FL35)	1 Hr	
C-17	Aft to forward	16-30	3.5 hrs.	
C-21	Aft to forward	2.2	15 minutes	
KC-135	Top to bottom	4-5 NOTE 3	35 minutes	
KC-10	Top to bottom/forward to aft	7.5	1 hr.	

Airframe Performance Overview					B
Testing Rank	Airframe	Cockpit Safety (IN FLIGHT)	Cockpit Safety (Loading & Unloading)	Medical Staff Rest Capabilities	
1st	KC10	Very High	High	Very High	
2nd	KC46	Very High	Low	Very High	
3rd	C5	High	Low	High	
4th	KC135	Very High	Low	Low	
5th	C17	Medium	Not Tested	Low	
6th	C130J	Low	Low	Very Low	

Note: **A** → Table taken from AFI 48-307 Vol 1, 9 January 2017, page 241. US government product not subject to copyright. **B** → Table courtesy Lieutenant Colonel Christopher Cieurzo, Chief, Patient Movement Operations Division, TRANSCOM. US government product not subject to copyright. Hr(s) (hour[s]), FL350 (Flight Level 350 (35,000 feet)).

C-17 Cruising-CAR Relationship

TO 1C-17A-1

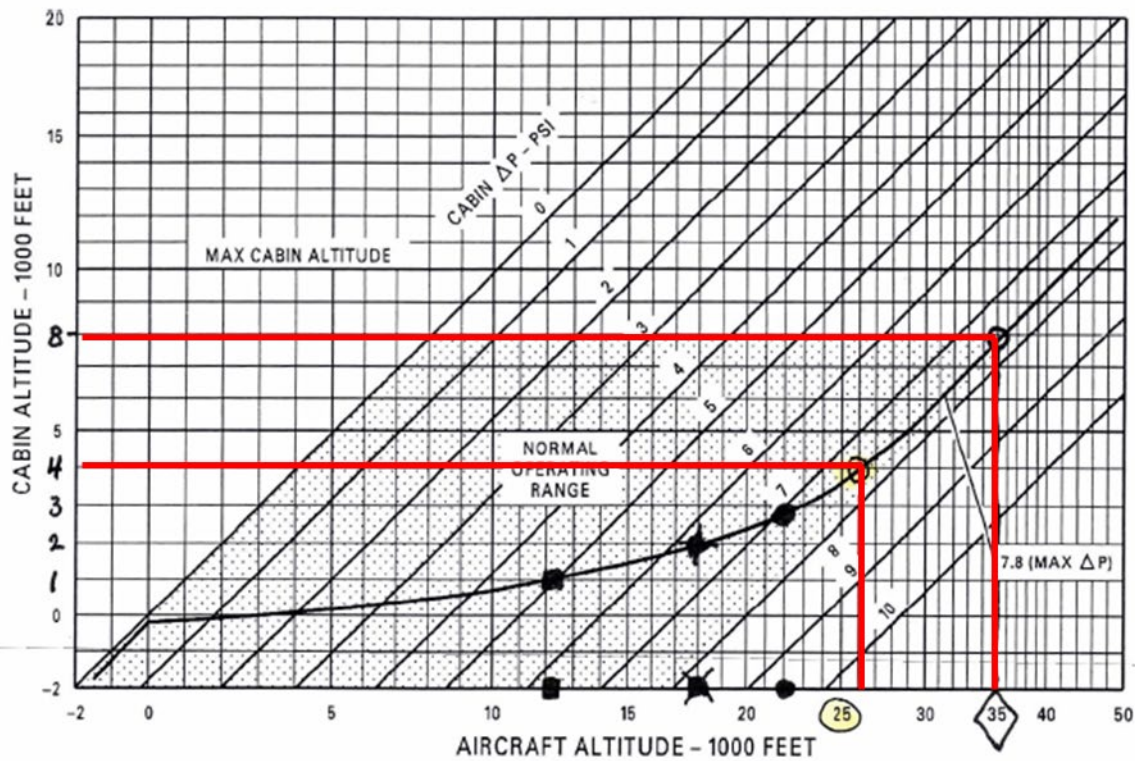
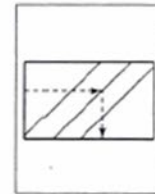
C-17 CABIN PRESSURE ALTITUDE CHART

NOTE

1. MAX DIFFERENTIAL PRESSURE 7.8 ΔP
2. RELIEF VALVE OPENS AT 8.2 ΔP

LEGEND

— CLIMB, CRUISE AND DESCENT

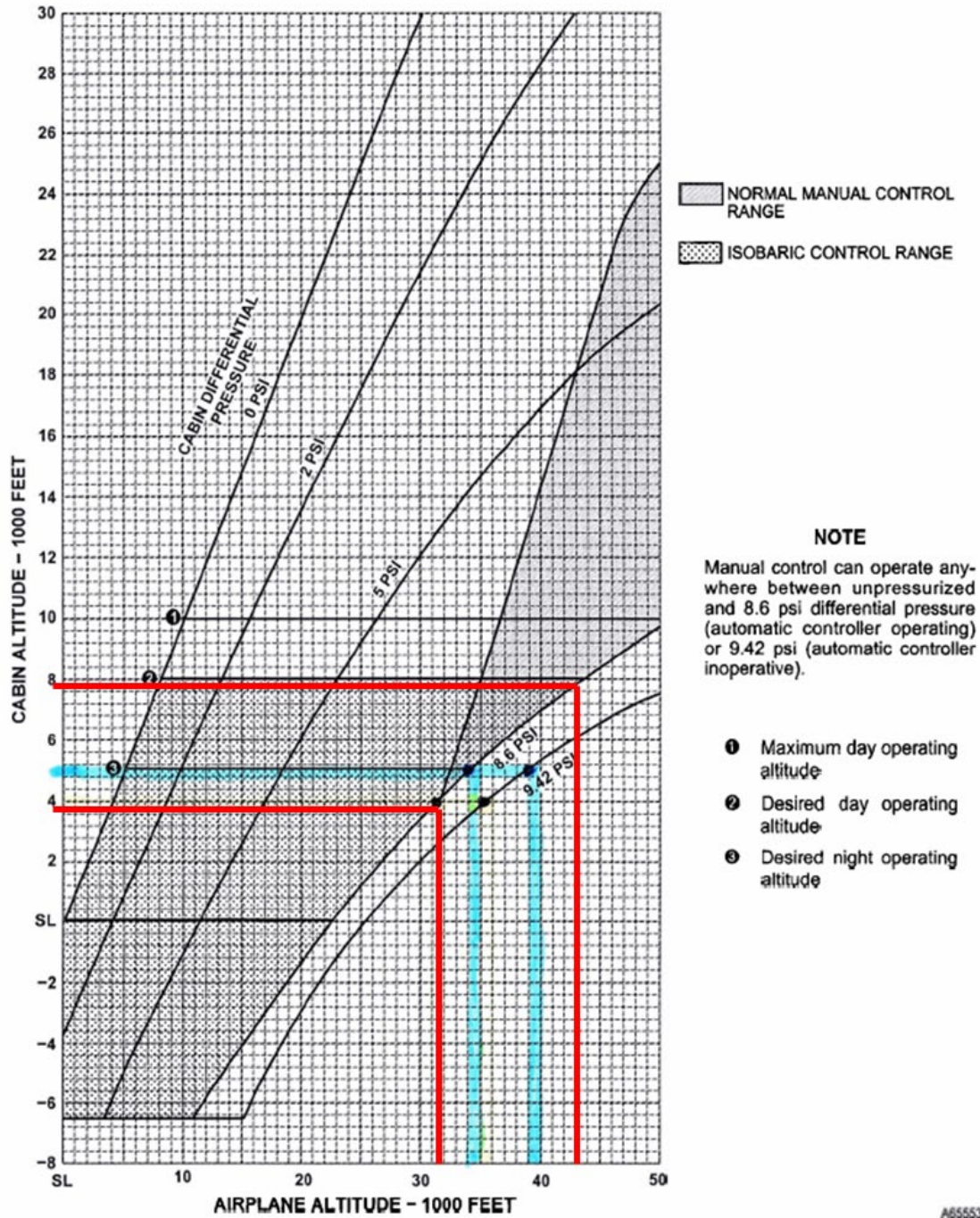


Note: Red lines depict cabin altitudes of 8,000 feet and 4,000 feet with their relative cruising altitudes of 35,000 feet and 25,000 feet, respectively. Taken from Technical Order T.O. 1C-17A-1. US government publication not subject to copyright.

KC-135 Cruising-CAR Relationship

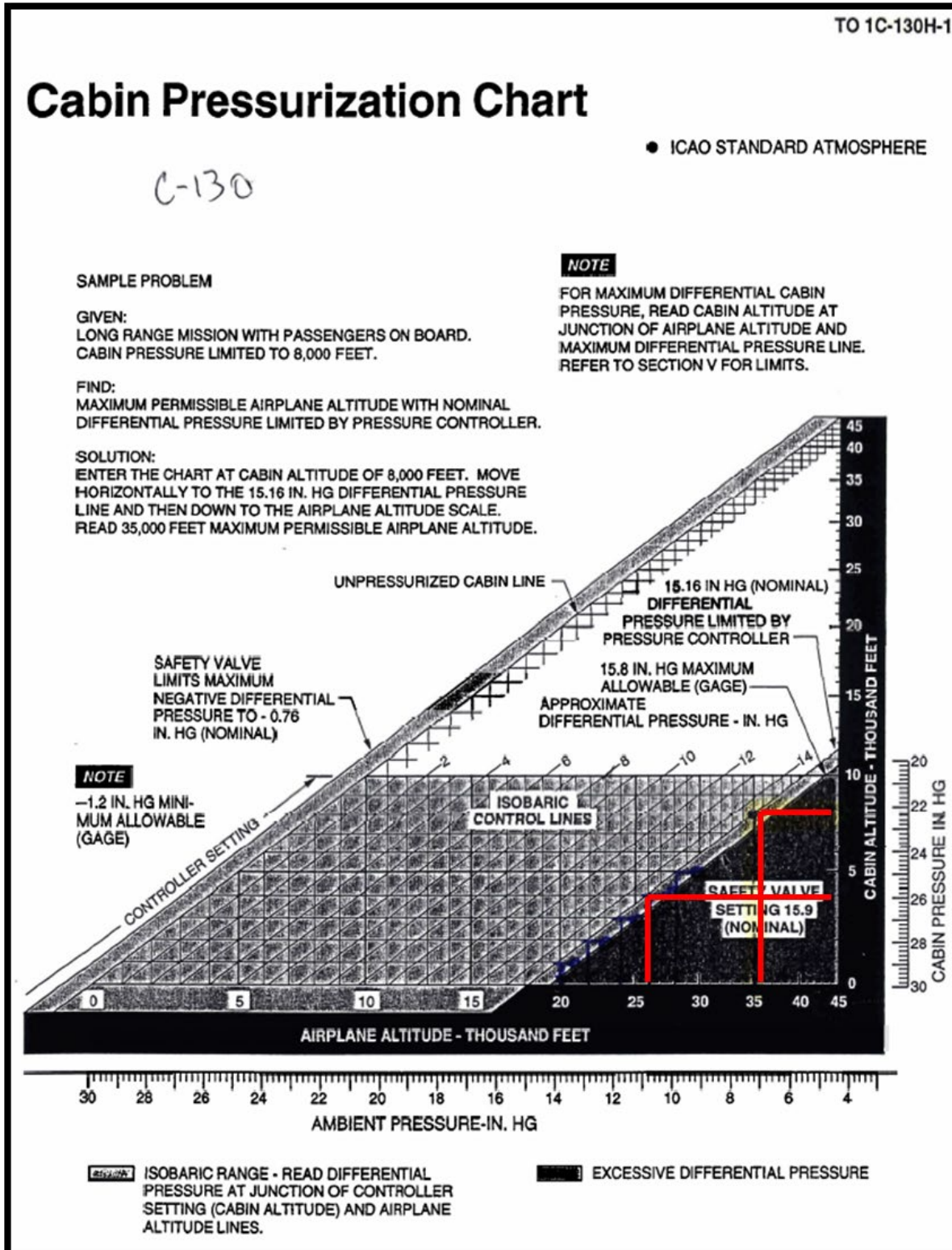
T.O. 1C-135(K)R(I)-1

Cabin Altitude Schedule



Note: Red lines depict cabin altitudes of 8,000 feet and 4,000 feet with their relative cruising altitudes of 43,000 feet and 32,000 feet, respectively. Taken from Technical Order T.O. 1C-135(K)R(I)-1. US government publication not subject to copyright.

C-130 Cruising-CAR Relationship



Note: Red lines depict cabin altitudes of 8,000 feet and 4,000 feet with their relative cruising altitudes of 36,000 feet and 26,000 feet, respectively. Taken from Technical Order T.O. 1C-130H-1. US government publication not subject to copyright.

Brief Overview of Wound VAC in AE

Since 1997, vacuum-assisted closure (VAC) has been used to encourage healing in difficult wounds. (**Morykwas, 1997**) Essentially, this is a device that uses a soft foam sponge directly applied to the wound with continuous negative pressure suction (125 mmHg). A number of explanations have been postulated to include a hydrostatic pressure gradient favoring blood flow into the area, reduction of tissue edema by removing osmotically active molecules, removal of inhibiting inflammatory cytokines, and mechanical stress stimulation of angiogenesis and cell division. (**Sjogren, 2006**) Although the exact mechanism is unclear, a number of actions have been identified. In a swine model, blood flow rose four-fold, granulation tissue formed faster, random-pattern flap survival was better, and tissue bacterial counts dropped in the VAC-applied animals. (**Morykwas, 1997**) Independent of mechanism, the wound VAC has successfully treated burns, complex wounds, and war injuries. (**Molnar, 2005; Wada, 2006; Leninger, 2006**)

The negative pressure creates a flux favoring fluid flow into the tissues perhaps equivalent to an altitude of around 5000 feet. The big difference is in the open foam sponge being suctioned. Since injured tissue is leaky, plasma normally oozes into the wound space producing a new fluid flux equilibrium that favors increased tissue edema. When the wound plasma is suctioned, a fluid flux that does not equilibrate ensues. Edema fluid is not allowed to accumulate, diffusion distance is not allowed to lengthen, and tissue hypoxia is not allowed to worsen. (**Rippe, 1994; McDonald, 1999**) As a result, less tissue dies and compartment syndrome may be less likely. Since the wound VAC is employed extensively, its use may well affect the TVFS' cabin altitude restriction decision in the "maybe" setting. Of note, at 5000 feet the wound VAC, run at its normal negative pressure, will create local tissue pressures equivalent to about 10,000 feet.

1. Leininger BE, Rasmussen TE, Smith DL, Jenkins DH, Coppola C. Experience with wound VAC and delayed primary closure of contaminated soft tissue injuries in Iraq. *J Trauma*. 2006; 61:1207-1211.
2. McDonald DM, Thurston G, Baluk P. Endothelial gaps as sites for plasma leakage in inflammation. *Microcirculation*. 1999; 6:7-22.
3. Molnar JA, Simpson JL, Voignier DM, Morykwas MJ, Argenta LC. Management of an acute thermal injury with subatmospheric pressure. *Journal of Burns and Wounds*. 2005;4:83-92.
4. Morykwas MJ, Argenta LC, Shelton-Brown EI, McGuirt W. Vacuum-assisted closure: a new method for wound control and treatment: animal studies and basic foundation. *Ann Plast Surg*. 1997; 38(6):553-562.
5. Rippe B and Haraldsson B. Transport of macromolecules across micro vascular walls: the two-pore theory. *Physiol Rev*. 1994; 74(1):163-219.
6. Sjogren J, Malmsjo M, Gustafsson R, Ingemansson R. Poststernotomy mediastinitis: a review of conventional surgical treatments, vacuum-assisted closure therapy and presentation of the Lund University Hospital mediastinitis algorithm. *European Journal of Cardio-thoracic Surgery*. 2006; 30:898-905.
7. Wada A, Ferreira MC, Junior PT, Arrunategui G. Experience with local negative pressure (vacuum method) in the treatment of complex wounds. *Sao Paulo Med J*. 2006; 124(3):150-153.

APPENDIX B --- TVFS PROGRAMMED LEARNING: CASE STUDIES

TABLE OF CONTENTS

Introduction.....	178
Case 1. The Routine Patient.....	185
Case 2. The Urgent Patient	188
Case 3. The Psychiatric Patient.....	191
Case 4. The Patient with Acute Cholecystitis.....	194
Case 5. The Patient with a Kidney Stone.....	197
Case 6. The Immediately Postoperative Patient	200
Case 7. The Patient with a Femoral Hernia	203
Case 8. The Patient with Trapped Air.....	206
Case 9. Another Psychiatric Patient.....	209
Case 10. The Cardiac Patient.....	212
Case 11. The Pregnant Patient	215
Case 12. The Patient with a Very Low Hemoglobin	218
Case 13. The Patient with a Splenectomy.....	221
Case 14. The Patient with Presumptive Eosinophilic Pneumonitis	224
Case 15. The Patient with a Long Flight to Bethesda.....	227
Case 16. The Patient with an Injured Spinal Cord.....	231
Case 17. The Patient Dies	234
Case 18. The Patient is <i>not</i> "Fit to Fly"	237
Case 19. Getting the Patient Ready	241
Case 20. The Mass Casualty Event.....	245
Conclusion	255

Introduction

A base of knowledge along with a practical set of tools rooted on that knowledge prepares the Flight Surgeon for an assignment as a Theater Validating Flight Surgeon (TVFS) and patient validation. However, application of the knowledge and tools requires patients. Short of real-time simulations, a set of case studies affords the novice an opportunity to test him or herself with real-life scenarios prior to real-time, real-life patients.

In this series, each case was selected for its nuances, complexities, and its clinical content. Each case is real with a real evacuation outcome. Each case is well over a decade old, with no accompanying identifying information, making patient recognition virtually impossible. As the flight surgeon moves through these cases, a natural progression from the relatively simple to increasingly intense is presented, culminating in a mass casualty event. A wide variety of diagnoses are employed in these exercises to emphasize the fact that patient movement is not specialty specific.

Every case is offered much as the original Patient Movement Request (PMR) appeared. The PMR template, **AF IMT 3899 Form**, is provided to better aid in the assessment of the PMR Information; a sample of the form's TRAC²ES output for a simulated patient is also included. Review of the data is performed in a formulaic fashion to encourage development of a routine system of evaluation. Additional information is provided as needed and, in some of the cases, not provided since it was never available. Each inflight prescription is accompanied by an explanation and, if applicable, the tool used to support that prescription. The various tools come from either the text or Appendix A. A specific listing of prescriptions can be found in **Table 1** or **Appendix A, Part 1 and Part 2, Prescribing Considerations for the TVFS**.

By advancing through these cases, the Flight Surgeon should gradually develop an internal checklist or algorithm for patient validation. One such algorithm is presented in the text and in **Figure 2** or **Appendix A, The TVFS's Clinical Validation Algorithm**. As this internal template is formed, the clinical scenarios become much more challenging --- the clear intent being to stretch the flight surgeon's new skill set. The end result should be, it is hoped, a flight surgeon confident in the physiologic and clinical bases for flying patients and a flight surgeon that can use the tools at his or her disposal in a systematic iterative fashion. In short, the goal is a Flight Surgeon who can prescribe the safest possible flight for a patient --- a Flight Surgeon who can become a Theater Validating Flight Surgeon.

To facilitate study, **Part 1 and Part 2, Prescribing Considerations for the TVFS** and **The TVFS's Clinical Validation Algorithm** are inserted following this introduction.

AF IMT 3899 Form --- PMR Data Submission Template

PATIENT MOVEMENT RECORD DATA PROTECTED BY PRIVACY ACT OF 1974 PERMANENT MEDICAL RECORD (S) - Information needed to submit patient movement record																													
SECTION I PATIENT IDENTIFICATION																													
(s) NAME (Last, First, Middle Initial)										(s) SSN					DATE OF BIRTH														
(s) AGE		(s) SEX		(s) STATUS		(s) SERVICE		(s) GRADE		(s) UNIT OF RECORD AND PHONE NUMBER					CITE NUMBER														
		M F																											
SECTION II VALIDATION INFORMATION																													
(s) Medical Treatment Facility Origination and Phone Number										(s) Ready Date (Julian Date)					APPOINTMENT DATE					NUMBER OF ATTENDANTS									
																				(s) MEDICAL (s) NON-MED									
(s) Medical Treatment Facility Destination and Phone Number										(s) CLASSIFICATION 1A-5F																			
															AMBULATORY					LITTER					(s) PRECEDENCE				
(s) Reason Regulated		Max # Stops		Max # RONS		Altitude Restriction		(s) CCATT Required		Name, sex, weight, rank of attendants:										U		P		R					
								yes no																					
SECTION III OTHER INFORMATION																													
(s) Attending Physician name, Phone Number and e-mail										(s) Accepting Physician name, Phone Number and e-mail																			
(s) Origination Transportation 24 Hour Phone Number										(s) Destination Transportation 24 Hour Phone Number																			
(s) Insurance Company		Address					Phone #			Policy #			Relationship to policy holder																
(s) Waivers (med equip, etc)																													
SECTION IV CLINICAL INFORMATION																													
(s) Diagnosis					(s) Allergies					LABS (Date and time drawn in Zulu)																			
										WBC					HGB					HCT					Other Labs				
(s) WEIGHT:		(S) Blood type:			Vital Signs (Date and time taken in Zulu)																								
battle casualty		disease			Date		Time (Zulu)		B/P		Pulse		Resp		Pain Level: /10		Last Pain Med:		O2/LPM:		Route:								
non-battle injury																													
CLINICAL ISSUES					Baseline 02 Sat If Applicable Temp																								
Infection Control Precautions:					LMP:					SPECIAL EQUIPMENT (Check all that apply)																			
										Suction					Traction					Orthopedic devices					OTHER:				
Date of last bowel movement:										NG Tube					Monitor					Restraints									
High Risk for Skin Breakdown					yes no					Foley					Trach					Chest Tubes									
Initial appropriate boxes:					Incubator IV Pumps IV Location:																								
Yes		No		Yes		No		Cast Location: Bivalved: yes no																					
		Hearing Impaired				Hypertension		Ventilator Ventilator Settings:																					
		Communication Barriers				Dizziness		DIET INFORMATION (Check all that apply)																					
		Vision Impaired				Voiding difficulty		NPO Soft Full Lig Cl Liq Reg																					
		Cardiac Hx				*Takes long-term meds		Renal Gm Protein Gm Na Meq K Mag Sulfate																					
		Diabetes				*Will self-medicate		Tube Feeding Type cc/hr Discontinue for Flight																					
		Motion Sickness				Has adequate supply of meds		Cardiac Diabetic cal Infant formula: Pediatric Age:																					
		Ears/Sinus Problems				Knows how to take meds (verbalized understanding)		TPN:																					
		Respiratory difficulty						Other(specify):																					
						*Medication listed on physician's orders																							
SECTION V PERTINENT CLINICAL HISTORY (Transfer Summary)																													
Physician's Signature										Date/Time																			
Signature of Clearing Flight Surgeon										Date/Time																			
AF IMT 3899, 20060819, V1																													

AF IMT 3899, TRAC²ES Output --- Simulated Patient (page 1)

PATIENT MOVEMENT REQUEST DATA PROTECTED BY PRIVACY OF 1974 Julian Date 348 0200Z

PATIENT DEMOGRAPHICS

Patient Name: Waldo, Wear S.	Status: F11	Cite #:	Precedence: Urgent
ID: SSN	Grade: O4	Gender: Male	Classification: 2B
Nationality: UNITED STATES	Age: 38 Year	Special Team: CCATT	Special: Y
Date of Birth:			

UNIT INFORMATION Cite

Unit Name: 52 LOGISTICS READINES SQ	Duty Station:	Com Fax:
City: APO	Com Phone:	DSN Fax:
State/Province:	DSN Phone:	
Country: US	PCS Code:	

POR INFORMATION

Address: PSC 909 BOX 5168,	City: APO	State:
Country: UNITED STATES	Postal Code:	Phone:

MOVEMENT INFORMATION

Injury Type: Disease	Exception To Policy:	Comm Transport?: N
Space Type: LITTER	Will Return: N	
Transport ID:	Transport Origin:	Transport Destination:
Transport Other Comments:		
Movement Remarks: TPMRC-E JD018 0239z: PMR reviewed by TVFS Maj Bronson; pt validated URGENT 2B Kandahar to Bagram. Stops-none; RON-None; CAR-None. PMCC/JDC		

ADMINISTRATIVE DATA

Originating MTF: NSA Bahrain	Ready Date: 348 2015 0200	Reason
Destination MTF: Landstuhl Regional Med Ctr GE		Source System: T-WEB
Regulated: CC Appt:	Casualty Event: OFS-Disease/Non-BI	
Originating MTF:	DSN Phone:	Com Phone:
Destination MTF:	DSN Phone:	Com Phone:
Attending Physician: CDR Matthews	DSN Phone: 318-439-6033	Com Phone:
Ward Name:	DSN Phone:	Com Phone:
Last PMR State Changed By: E_KAMARAA2	DSN Phone: 3144808040	Com Phone:
Accepting Physician: Major R. Shih	DSN Phone: 318-431-4633	Com Phone:
Max Stops: No Stops	Max RONS: No RONS	Altitude Restriction: None
Last Validated: 348 2014 0200		Cl'd for Comm Trav: N

CLINICAL DATA

Primary Med Spec: Internal Medicine	Primary Diagnosis: Pericardial Effusion
Secondary Med Spec: Infectious Disease	Secondary Diagnosis: Pulmonary Embolus
Other Med Spec: Pulmonary	Other Diagnosis: MRSA

Patient History:

48 year old male, with no significant prior medical history or risk factors, deployed to Bahrain Oct 2015. On 10 Nov15 he developed malaise, fevers, cough, vomiting, diarrhea and shortness of breath. He went to Bahrain Specialist Hospital (BSH) and noted to have cellulitis and abscess over the right elbow. IND performed and placed on Augmentin. Pt returned two days later with rash progressing and pruritus. Augmentin was stopped due to concern of allergy and he was started on Linezolid. He came back the next day with worsening pruritus and antibiotics were stopped. He returned to the ER at BSH on 28Nov15 with c/o progressing SOB, chest pain and fever. CXR showed pericardial effusion and an echocardiogram confirmed a large pericardial effusion with cardiac tamponade and evidence of CHF with LV EF at 25%. Pt was transferred to Bahrain Defense Force Hospital (BDF) where he underwent a scheduled pericardiocentesis with 750mL of hemorrhagic fluid aspirated and sent to lab. Waldo was still spiking fevers and was empirically started on IV Vancomycin and Gentamycin per ID consult on 3Dec15. His fever resolved and he was transported back to the ICU at BSH. On 5Dec15 he became slightly tachycardic and tachypneic, requiring 2 L of oxygen to keep sats 94-97%. A chest CT angiogram revealed evidence suggestive of a PE in the Main PA. There was also a filling defect in the left upper, medial and lower lung segments. Peripheral venous Doppler showed evidence of a DVT in bilateral popliteal veins. Lab/Culture results return from elbow and heart growing MRSA susceptible to Vanc/Gent. MRI right elbow on 4Dec15 showed no evidence of osteomyelitis. Initial WBC on 17Nov15 was 16K and peaked on 3Dec15 at 18.6K and was 11.1K on 8Dec15. His repeat echo on 9Dec15 showed continued large pericardial effusion but no sign of tamponade. Repeat blood cultures were negative. Cardiologists recommends transfer to US medical facility for further care. PMH; HTN. No PSH. Patient received clearance from command to leave AOR fro movement back to CONUS. Patient unable to egress on and off plane and states he can equalize while flying. 0/10pain. Allergies: NKDA

Note: Simulated aeromedical evacuation patient; there is no relationship of this simulated patient to any real patient whatsoever. Simulation employed during the Advanced Clinical concepts in Aeromedical Evacuation Course held at USAF School of Aerospace Medicine 14-18 September 2020. Permission to use the simulation granted by Lieutenant Colonel Christopher Cieurzo, Chief, Patient Movement Operations Division, TRANSCOM. US government publication not subject to copyright.

AF IMT 3899, TRAC²ES Output --- Simulated Patient (page 2)

MEDICATIONS				IVs (1 rows)			
Medication Name	Dose	Frequency	Route	IV Location	IV Type	Solution	Rate cc/hr
Gentamycin	80 mg	Daily	IV	Right Arm	Saline Lock NS	NS	125
Vancomycin	1gm	Daily	IV				
Heparin	10000 units/hr		IV				
Lisinopril	5mg	1 Tab daily	PO				

Allergies: - Augmentin

VITAL SIGNS, LABS AND ARTERIAL BLOOD GASES					
T: 98 F	P: 103	R: 25	BP: 117/83	Wt: 150 lbs	Oxygen Rate: 2 Liters
HGB: 12	HCT: 36	WBC: 7800	Date Taken: 348 2015 0200		Oxygen Mode: NC
SPO ₂ Rate: 94	SPO ₂ Comments:				
Ventilator Mode:	FIO ₂ :	TV:	Ventilator Rate:	PEEP:	PS:
pH:	PO ₂ :	PCO ₂ :	HCO ₃ :	BE:	

DRAINAGE (0 rows)				Orthopedic (0 rows)	
Drainage Location:	Foley to Gravity	Type	Suction Type	Suction Amount	Type Location

PMI DATA					
Cardiac Monitor: Y	Suction: N	Pulse Ox: Y	Incubator: N	Wound Vac: N	
Ventilator: Y	Pump: Y	Stryker: N	Traction: N	Backrest: Y	
Other Equipment:					

DIET INFORMATION			
Feeding Tube Type:	Tube Type Other:	Formula:	Formula Other:
Pump Y/N: N	Infusion Rate:	Amount:	
Special Diet: NPO-Nothing By Mouth	Special Diet Other Description: Carduac		

ATTENDANTS (0 rows)										
Attendant Name	Status	Grade	Age	Date of Birth	Weight	Gender	Type	Team Type	Commercial Ticket Cost	Commercial Ticket Number
Mims, Williams	Army	O-3	49 Year		180lbs	Male				

Number of Attendants From Group PMR:
Attendant Names From Group PMR:

RONS (0 rows)		
RON Location	RON Period	RON Comments

Note: Simulated aeromedical evacuation patient; there is no relationship of this simulated patient to any real patient whatsoever. Simulation employed during the Advanced Clinical concepts in Aeromedical Evacuation Course held at USAF School of Aerospace Medicine 14-18 September 2020. Permission to use the simulation granted by Lieutenant Colonel Christopher Cieurzo, Chief, Patient Movement Operations Division, TRANSCOM. US government publication not subject to copyright.

Part 1. Prescribing Considerations for the TVFS

Prescribing Considerations for the TVFS in Aeromedical Evacuation --- Part 1			
Inflight Stressors	Physiological Effects	Clinical Effects	Countermeasures
Gravity	acceleration-deceleration	hemodynamic flow	head-first load, feet-first load, head of bed elevation, prohibit traction weights, consider Stryker™ or vacuum spine board, long steady take-off, gentle climb out, long slow landing
Humidity	reduced humidity	dehydration	rehydration (oral, intravenous), humidified breathing gases
Temperature	thermal instability	hypothermia, hyperthermia	<u>Hypo</u> : upped aircraft heat, blankets (reflective, heated), warmed IV fluids, warmed ventilator air; <u>Hyper</u> : upped aircraft cooling, upped airflow, cool misting (ground)
Noise	temporary threshold shift	temporary hearing loss	earplugs, earmuffs
Vibration	vibration	increased pain intensified pressure points upped metabolic activity tissue edema	damping with cushions (preferably air bladder or jelly/gel)*, seat/litter isolation (hammock-like), centered fuselage loading away from engines, aircraft routing
Barometric Pressure	pressure-volume-diameter changes -- <i>pneumocephalus</i>	trapped gas expansion -- headache, confusion, nausea (tension pneumocephalus)	supplemental O ₂ , head-first load, HOB elevation, avoid Valsalva, long slow take-off & landing, CAR
	-- <i>pneumothorax</i>	-- chest pain, dyspnea (tension pneumothorax)	needle/chest tube, Heimlich valve/suction water seal, lung protective ventilation, supplemental O ₂ , CAR
	-- <i>pneumomediastinum</i>	-- chest pain, dyspnea, neck pain (subq air) ("malignant" pneumomediastinum)	bedrest, avoid Valsalva, supplemental O ₂ , lung protective ventilation, CAR
	-- <i>pneumopericardium</i>	-- chest pain, shifting tympany, muffled heart (pericardial tamponade)	bedrest, avoid Valsalva, supplemental O ₂ , lung protective ventilation, needle/tube drain suction water seal, CAR
	-- <i>pneumoperitoneum</i>	-- distention, tympany, oliguria (abdominal compartment syndrome)	NGT, supine, bedrest, supplemental O ₂ , CAR
	-- <i>pneumatoxis oculi</i>	-- peri-orbital/orbital emphysema -- damaged/disrupted globe (impaired vision, expelled globe content) -- retinal reattachment bubble (pathologic IOP, impaired retinal perfusion)	avoid Valsalva/lifting, supplemental O ₂ , humidity, CAR recline w/ HOB elevated, patch & shield, contralateral pinhole patch, supplemental O ₂ , slow take-off/landing, CAR < 20% bubble, recline w/ HOB elevated, CAR (> 10%), slow take-off/landing, 2,000 ⁺ foot descent w/ sxms; supplemental O ₂ as needed for retina (of questionable resorption benefit) baseline IOP + {(cabin altitude/1,000) x 4-6 mmHg} should be < 50 mmHg
	-- <i>miscellaneous (equipment)</i>	ET (or tracheostomy) cuffs: <i>tracheal pressure necrosis</i> bladder catheter balloon: <i>balloon rupture</i> closed system drains: <i>air and/or drain fluids into wound</i> ostomies: <i>ostomy dislodgement</i> air splints: <i>tourniquet-like effect</i> epidural catheter: <i>back pain</i>	air exchange with ascent/descent; air replacement w/ saline air replacement w/ saline venting drain on ascent/descent "burping" or "pinholing" appliance air exchange with ascent/descent; substitute plaster splint analgesics via AE nursing staff
	venous gas emboli effect altered tissue dynamics	evolved, infused (tissue edema effect)	CAR
	-- <i>inflammatory upregulation</i> -- <i>Starling dysequilibrium</i>	leaky vessels, tissue edema leaky vessels, tissue edema	CAR CAR
	drop in DO₂	ischemia	CAR, transfusion, supplemental O ₂
Oxygen	hypoxia	ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>injured bone & soft tissue</i>	tissue ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>on supplemental oxygen</i>	hypoxia & ischemia	supplemental O ₂ (at least ground level equivalent)
	-- <i>immediate postop extubation</i> drop in DO₂	transient pulmonary shunt & hypoxia ischemia	postpone validation at least 4-6 hours CAR, transfusion, supplemental O ₂

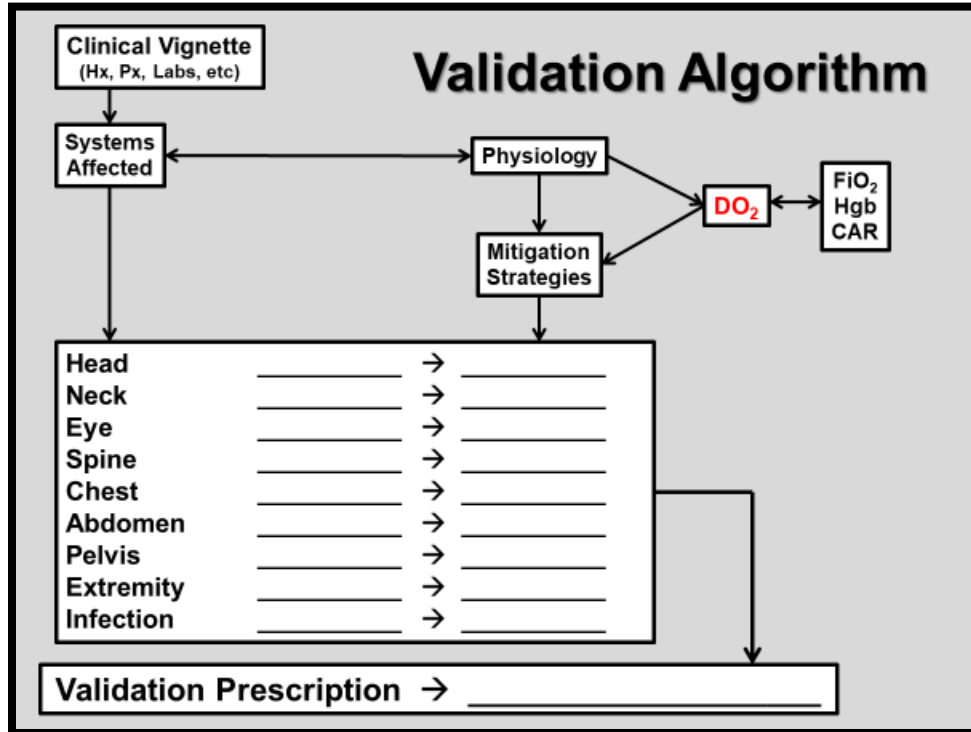
Note: * Denotes the concern for Boyle's Law effects with air bladder cushions (altitude-induced expansion with asymmetry). Hypo (hypothermia), IV (intravenous), Hyper (hyperthermia), O₂ (oxygen), w/ (with), HOB (head of bed), CAR (cabin altitude restriction), NGT (nasogastric tube), IOP (intraocular pressure), mmHg (millimeters of mercury pressure), ET (endotracheal tube), AE (aeromedical evacuation), DO₂ (tissue oxygen delivery), postop (postoperative), CCATT (Critical Care Air Transport Team), GI (gastrointestinal), ENT (Ear, Nose, & Throat = Otolaryngologic), OSL™ (oversize litter), lb (pound), DCS (decompression sickness), RON (remain overnight).

Part 2. Prescribing Considerations for the TVFS

Prescribing Considerations for the TVFS in Aeromedical Evacuation --- Part 2		
Prescriptive Category	Prescription	Clinical Setting
Medical Adjuncts	cardiac monitor; suction; pulse oximeter medical attendant (tech, nurse, doctor) CCATT	Cardiac, Pulmonary, Critical Care Cardiac, Psychiatric Critical Care, Cardiac, Pulmonary
Medical Interventions	protect airway (nasotracheal/orotracheal intubation) nasogastric tube supplemental O ₂ ; positive end-expiratory pressure sedation/physical restraints in flight deep vein thrombosis prophylaxis blood components (transfusion) medications extended ground stabilizing (fluids, vasopressors, blood, tertiary survey)	Critical Care, Immediately Post-Operation Critical Care, Abdominal Surgery (GI, splenectomy) Critical Care, Pulmonary, Trauma, Burns Psychiatric All Settings Trauma, Anemia All Settings Trauma, Critical Care
Middle Ear Adjuncts	equalization maneuvers (Valsalva, Toynbee, Frenzel, etc) Afrin TM and neosynephrine myringotomy	All Settings All Settings All Settings
Patient Paraphernalia	endotracheal (or tracheostomy) tube cuffs - cuff inflation w/ water chest tube - suction or Heimlich valve (no clamping of tubing) Jackson-Pratt TM drain - open on ascent and descent Hemovac TM drain - open on ascent and descent colostomy bag - decompress on ascent ("pinhole", "burp") bladder catheter - balloon inflation w/ water bivalve casts; control air splints cushions (litter, head, heel) blankets	Trauma, Pulmonary Trauma, Pulmonary Orthopedic, ENT, Thoracic, Abdominal Surgery Orthopedic, ENT, Thoracic, Abdominal Surgery Abdominal Surgery All Settings Orthopedic Neurologic, Orthopedic, Critical Care All Settings
Positioning Interventions	head first loading litter at aircraft airflow outlet valves head of bed elevation headrest to elevate and protect head seizure precautions spine precautions cervical spine collar OSL TM litter (regular litter = 250 lb; oversize litter = 400 lb) Stryker TM frame; vacuum spine board	Neurologic, Ophthalmologic Infectious Neurologic, Ophthalmologic, ENT, Pulmonary, Cardiac Neurologic, Ophthalmologic, ENT Neurologic Neurologic Neurologic (cervical spine injury) Orthopedic (pelvic injury), Neurologic (spine injury) Neurologic (spine injury)
Aircraft Manipulations	cabin altitude restriction full use of runway length modify rate of climb and descent (long, slow landings; long steady climbs) cabin airflow patterns aerial refueling no RONs (remain overnight); no stops	Trapped Gas, DO ₂ optimizing, Pulmonary, DCS Neurologic, Pulmonary, Cardiac Neurologic, Pulmonary, Cardiac Infectious Cabin Altitude Restriction, Extended AE Flight Critical Care, Cardiac, Pulmonary

Note: * Denotes the concern for Boyle's Law effects with air bladder cushions (altitude-induced expansion with asymmetry). Hypo (hypothermia), IV (intravenous), Hyper (hyperthermia), O₂ (oxygen), w/ (with), HOB (head of bed), CAR (cabin altitude restriction), NGT (nasogastric tube), IOP (intraocular pressure), mmHg (millimeters of mercury pressure), ET (endotracheal tube), AE (aeromedical evacuation), DO₂ (tissue oxygen delivery), postop (postoperative), CCATT (Critical Care Air Transport Team), GI (gastrointestinal), ENT (Ear, Nose, & Throat = Otolaryngologic), OSLTM (oversize litter), lb (pound), DCS (decompression sickness), RON (remain overnight).

The TVFS's Clinical Validation Algorithm



Note: Hx (history), Px (physical), DO₂ (tissue oxygen delivery), FiO₂ (oxygen fraction of inspired air), Hgb (hemoglobin level [g/dl]), CAR (cabin altitude restriction).

The Best Approach to Each Case is Stepwise.

1. Study the *PMR (Patient Movement Request) Information*.
2. Evaluate that information.
 - a. Extract the pertinent validation facts from each information category.
 - b. Decide if there is enough information to validate the patient for evacuation.
 - c. Decide if more information is needed.
 - d. If added information is needed, was it provided? Was it helpful?
3. Compare your evaluation of the information to the *PMR Information Evaluation*.
4. Make a validation prescription based on your evaluation of the *PMR Information*.
 - a. Decide on *Precedence* and *Classification*.
 - b. Determine patient needs in each category found in *Part 2, Prescribing Considerations for the TVFS*.
5. Compare your prescription with the *Prescription*.
6. Compare your logic with that in the *Reasoning*.
7. Study the evacuation *Outcome*.

Case 1. The Routine Patient

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 20
	Gender	----
Patient Setting:	Precedence	Urgent
	Classification	5A (outpatient ambulatory)
	CCATT	no
	Injury Type	DNBI (disease non-battle injury)
	Space Type	ambulatory
Administrative Data:	Originating MTF	Bagram
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	Gynecology
	Primary Diagnosis	Pelvic Inflammatory Disease
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“Patient processed for urgent transport out of Bagram due to available resources exhausted in finding definitive source for pain. Ultrasound studies of pelvis and abdomen pending. Repeat KUB pending...Here for f/u for PID and swollen lymph node in groin. CBC and ESR have been stable without elevated WBCs or other evidence of infection. Patient had pelvic CT a 1 week ago and was negative for pelvic abscess. Patient continues on oral clindamycin...Urine pregnancy test negative...Pain is worse with pain today 6/10; patient has not gotten adequate rest for past 2 nights. Patient reports mild chills and body aches. Patient reports urinary urgency and frequency. Patient denies diarrhea or nausea. Patient has pain to light palpation in all quadrants of the abdomen. Positive tenderness in RLQ. Negative CVA tenderness. No pain on hip shake. No pain on leg lift or extension against resistance...KUB does show significant amounts of stool...reveal no free air. Retained fecal material is present in the ascending, descending and rectosigmoid colon, suggesting constipation. Patient has respiratory difficulty. Manages with albuterol, last ED visit was (1 year ago). Patient needs oxygen per nasal cannula up to 5 liters to keep oxygen saturation above 95%.”

Medications:	motrin doxycycline phenegan albuterol inhaler	clindamycin colace tylenol with codeine
Medical Data:	VS CBC Oxygen Delivery Vent Settings ABG Drainage PMI Data (equipment)	98.3 F 99 16 146/86 42/14 --- 7,000 5L nasal cannula NA NA NA none

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The PMR declares the patient as Urgent, yet she is classified 5A (outpatient ambulatory) and her Space Type is ambulatory. This is a clear disconnect that must be reconciled with either the Patient History and/or the attending physician.

Administrative Data/Clinical Data Evaluation

Pelvic inflammatory disease is the primary diagnosis. Listing unrestricted stops and unrestricted “remain overnights” (RONs) suggests that it is uncomplicated.

Short & Sweet Patient History/Medications

The clinical presentation is suggestive for mild pelvic inflammatory disease, a urinary tract infection, or excessive retained stool. There is no indication from the narrative that the patient is in extremis; there is no clinical justification for declaring the patient Urgent. The singular concern for the flight surgeon is the patient’s “respiratory difficulty.” Despite the patient having had no ED visits for a year, 5L nasal cannula oxygen was felt necessary for flight.

Medical Data Evaluation

There is no fever, tachycardia, tachypnea, or elevated white blood cell count. These data imply no respiratory or abdominal urgency.

Information Beyond the PMR

In discussions with the attending physician the patient was an outpatient and not on supplemental oxygen. In addition, the ultrasound of her abdomen and pelvis did not reveal abnormality.

Prescription:

Precedence	Routine
Classification	5A (outpatient ambulatory)
Medical Adjuncts	none
Medical Interventions	none
Middle Ear Interventions	none
Patient Paraphernalia	none
Positioning Interventions	none
Aircraft Manipulations	none

Reasoning

The clinical presentation and the clinical data suggest several potential diagnoses, none of which have demonstrative life, limb or eyesight threat. Although the patient has discomfort and requires a definitive diagnosis, it is clear that this is a non-urgent, non-priority evacuation. As a result, she was transported as a Routine patient without additional prescription.

Outcome

Air evacuation was successful without incident.

Case 2. The Urgent Patient

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 40
	Gender	----
Patient Setting:	Precedence	Urgent
	Classification	2A (inpatient litter)
	CCATT	no
	Injury Type	unlisted
	Space Type	litter
Administrative Data:	Originating MTF	Balad
	Destination MTF	Walter Reed
Clinical Data:	Primary Specialty	General Surgery
	Primary Diagnosis	Gunshot Wound
	Max Stops	1
	Max RONS	none
	Altitude Restriction	4,000

Patient History:

“Patient suffered a penetrating R temporal GSW sustained while walking in PT gear to her living quarters. Stable in transport from Baghdad. No LOC. Vision intact. R temporal laceration and significant proptosis. EOM somewhat limited (disconjugate gaze noted). No other injuries. CXR normal. Head CT shows retro-bulbar bullet with orbital wall fracture. Impression: large retro-bulbar bullet with proptosis and peri-orbital gas. Vision intact. Plan: Ophthalmology consult---lateral canthotomy performed in ED. Urgent air evacuation for orbital foreign body extraction by orbital specialist...Globe is intact; no air in globe. Bullet is completely intact and still within orbit; no fragments. Air seen on CT around the eye socket near bullet. CT negative for any brain injury...concerned with altitude increasing swelling due to peri-orbital air or tissue swelling. Will need altitude restriction 4,000...HOB will be raised during flight. Enplane head first keeping head up at all times.”

Medications:	cephalothin	levofloxacin
	solumedrol	morphine
	phenergan	

Medical Data:	VS	98.8 F	81	16	118/60
	CBC	37/12 ---	5,000		
	Oxygen Delivery	4L nasal cannula			
	Vent Settings	NA			
	ABG	pH = 7.36	pO ₂ = 52	pCO ₂ = 39	
	Drainage	NA			
	PMI Data (equipment)	none			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient is an inpatient on a litter that requires Urgent transport. It is unclear whether her problem is a battle injury (BI) or DNBI. A CCATT team is not requested.

Administrative Data/Clinical Data Evaluation

She is slotted for transport from Balad to Walter Reed permitting only one stop and no RONS (remain overnight). This information immediately tells the flight surgeon that there is either an eye or a neurological issue. This is because Landstuhl is limited in the breadth of ophthalmologic and neurosurgical interventions. In addition, a 4,000-foot cabin altitude restriction (CAR) is requested. The flight surgeon should now be looking for trapped air, or difficulties in oxygenation or seriously significant tissue injury.

Short & Sweet Patient History/Medications

The patient has suffered a GSW making this a battle injury. Fortunately, her injuries were isolated to the right orbit area. The bullet did not fragment and remains in place producing a marked proptosis of the eyeball. The globe itself is intact and uncompromised; however, there is significant peri-orbital air and tissue damage.

Medical Data Evaluation

The only concern here is the pO₂ = 52 on 4L nasal cannula. The patient is relatively young with an adequate hemoglobin level. This bears discussion with the attending physician.

Information Beyond the PMR

The attending physician was contacted who felt the ABG (arterial blood gas) was venous. He further related that her oxygen saturation was 98%. He felt that the patient's eyesight was in significant jeopardy. The Theater Validating Flight Surgeon-Europe (TVFS-E) was then contacted who confirmed that there was not an ophtho-orbital-plastics specialist at Landstuhl. The TVFS-E then made arrangements for the patient to transfer upon arrival at Landstuhl to an aircraft ready to fly to Walter Reed where the requisite specialist was already waiting.

Prescription:

Precedence	Urgent
Classification	2A (inpatient litter)
Medical Adjuncts	none
Medical Interventions	4L nasal cannula
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	none
Positioning Interventions	head first loading HOB elevation to 30 degrees
Aircraft Manipulations	CAR 4,000 feet air refueling, if needed no RONS, 1 stop

Reasoning

Eyesight is threatened making the patient an Urgent move. The patient should be on a litter loaded head first with the HOB elevated; this will abrogate much of the gravity effects of acceleration and deceleration. Furthermore, the HOB elevation will facilitate middle ear and sinus equalization (as does a CAR). The patient was placed on 4L nasal cannula delivering ostensibly a FiO_2 of ~30%. This ~30% equates to 21% at a cabin altitude of 8,000 feet (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency**). A CAR of 4,000 feet was imposed. As a result, the patient was no longer on a sea level equivalent oxygen dose, but on a 25% dose. Considering the patient's hemoglobin level, this should be plenty of oxygen to maintain adequate tissue oxygen delivery, or DO_2 (**Appendix A: Tables for Calculating DO_2**). The CAR will also minimize the volume expansion of the peri-orbital air. Instead of a 35% volume expansion, there should only be 16%; instead of a 10% diameter expansion, there should only be 5% (**Table 7 or Appendix A: Trapped Air Pressure-Volume-Diameter Relationships**). In the same vein, the CAR reduces the tendency toward tissue edema seen at altitude. Thus, the potential for added injury is mitigated. With a 4,000-foot CAR, the optimal cruising altitude for a C-17 is 26,000 feet as opposed to the usual 35,000 feet (**Appendix A: C-17 Cruising-CAR Relationship**). The added friction at the lower altitude could well demand air refueling; the flight surgeon must be aware and permit it. Lastly, only one stop was permitted which was used to transfer the patient to another aircraft at Landstuhl and RONS were not permitted to ensure the speediest possible transit to Walter Reed. *Although not prescribed, an argument for using a pulse oximeter, a no Valsalva order, and a long slow landings could be made.*

Outcome

Air evacuation was successful without incident.

Case 3. The Psychiatric Patient

PMR Information:

Demographics:	Status	Marine
	Grade	enlisted
	Age	< 30
	Gender	----
Patient Setting:	Precedence	Routine
	Classification	1B (psych litter --- medication & optional restraints)
	CCATT	no
	Injury Type	DNBI
	Space Type	litter
Administrative Data:	Originating MTF	Balad
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	Psychiatry
	Primary Diagnosis	Adjustment Disorder with Anxiety
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“Patient complained of suicidal ideation and depressed mood due to marital discord. Patient contracts for safety. No hallucinations...History of post-traumatic stress disorder/obsessive-compulsive disorder/anxiety/depression. No history of hospitalization. Cooperative/easily directed...Has attendant for flight. Patient will be in pajamas or PT gear and will have sedation and restraints available for flight. Attendant is familiar with keys and opening restraints in case of emergency.”

Medications:	prozac	seroquel			
	ativan prn	haldol prn			
	benadryl prn				
Medical Data:	VS	98.7 F	102	16	104/68
	CBC	unlisted			
	Oxygen Delivery	Room Air --- 99% saturation			
	Vent Settings	NA			
	ABG	NA			
	Drainage	NA			
	PMI Data (equipment)	none			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient is classified 1B, a psychiatric designator denoting a patient who requires restraining medications and “as needed” physical restraints.

Administrative Data/Clinical Data Evaluation

There is nothing significant for the flight surgeon.

Short & Sweet Patient History/Medications

The patient has been depressed from marital discord and complained of suicidal ideation. He has “contracted for safety” and is “easily directed.” In a combat zone, he readily has the tools to complete a suicide. Although he contracts for safety, he needs psychiatric care that cannot be obtained in the combat environment. And, despite his life being notionally at risk, he is, in fact, without external threat to life, limb, or eyesight. Consequently, he is moved as a Routine patient. His attending physician has prescribed restraining medications as well as “as needed” physical restraints. Furthermore, his physician has attached a psychiatric attendant and three non-medical attendants for his flight.

Medical Data Evaluation

There is nothing untoward for the flight surgeon to consider.

Information Beyond the PMR

None is needed.

Prescription:

Precedence	Routine
Classification	1B (psych litter --- medication & optional restraints)
Medical Adjuncts	1 psych technician & 3 non-medical friends
Medical Interventions	sedation/restraints in flight
Middle Ear Interventions	none
Patient Paraphernalia	none
Positioning Interventions	none
Aircraft Manipulations	none

Reasoning

The patient has had suicidal ideation and requires care in a non-combat psychiatric environment. Based on the clinical picture presented, the patient could potentially be classified 1C (psych ambulatory --- unrestrained, no attendant) (**Appendix A: Approach to Psychiatric Patients**). Most likely, there is more to the story than is being described in the PMR; in the psychiatric arena, such is not uncommon. The flight surgeon can make that assumption and go with the attending physician's recommendations. Even if the medicinal and physical restraints along with the multiple attendants are excessive, the flight surgeon can feel that safety of flight and a safely flown patient are almost certain.

Outcome

Air evacuation was successful without incident.

Case 4. The Patient with Acute Cholecystitis

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 40
	Gender	----
Patient Setting:	Precedence	Urgent
	Classification	2A (inpatient litter)
	CCATT	no
	Injury Type	unlisted
	Space Type	litter
Administrative Data:	Originating MTF	Tikrit
	Destination MTF	Kuwait
Clinical Data:	Primary Specialty	Colon & Rectal Surgery
	Primary Diagnosis	Gallstone Ileus
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“...Patient who is diabetic “controlled on diet” with current blood sugar 156, weighs 350 pounds, tender in the RUQ, has elevated WBC (and) LFTs and probable gallstone in the gallbladder on ‘Sono Site’ ultrasound exam. Presents with 6 hours of abdominal pain. He remains tender still, 6 hours after the attack and with IV antibiotics and Demerol....Discussed with the patient and we have no laparoscope for cholecystectomy thought we could do open surgery if life threatening. Would like to transfer asap as he is tender still and elevated WBC and diabetic.”

Medications:	unasyn	demerol
Medical Data:	VS	98.5 F 69 20 141/83
	CBC	44/15 --- 12,400
	Oxygen Delivery	2L nasal cannula
	Vent Settings	NA
	ABG	NA
	Drainage	NA
	PMI Data (equipment)	none

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient is relatively young and requires an Urgent inpatient move without a CCATT.

Administrative Data/Clinical Data Evaluation

This is an intra-theater transport for definitive surgical care of gallstone ileus.

Short & Sweet Patient History/Medications

Clearly, the clinical picture is not that of gallstone ileus, but that of acute cholecystitis. The patient has suffered unremitting RUQ pain despite antibiotics. A field ultrasound suggests cholelithiasis. The elevated WBC suggests ongoing infection. The elevated LFTs suggest possible common bile duct obstruction. And, the patient being a diabetic suggests a high risk for gallbladder gangrene exists. The patient is obese with a weight of 350 pounds.

Medical Data Evaluation

Nothing further is added.

Information Beyond the PMR

More information would definitely aid the flight surgeon. In CENTCOM, there was a web-based electronic medical record called the Joint Patient Tracking Application (JPTA) which could be tapped. Here, it was learned that the patient was G6PD deficient, a Type II diabetic, and borderline hypertensive. His EKG demonstrated a possible old septal infarct and his abdominal x-rays demonstrated no free air or obstruction. And, his physical exam revealed a positive Murphy's sign. Speaking with his attending surgeon was also revealing. The patient was described as "3+" sick and "would already be in the OR if I had the right tools." His biggest concerns were the unremitting pain, the diabetes, and the potential for common duct stones. Basically, he wanted this patient operated on and had a surgeon waiting in Kuwait.

Prescription:

Precedence	Urgent
Classification	2A (inpatient litter)
Medical Adjuncts	none
Medical Interventions	6L mask
Middle Ear Interventions	none
Patient Paraphernalia	none
Positioning Interventions	OWL™ litter
Aircraft Manipulations	none

Reasoning

A diabetic with acute cholecystitis usually scares general surgeons because early gallbladder gangrene is not uncommon. This patient's unremitting pain, elevated WBC, elevated LFTs, and physical exam recommend early, rather than delayed surgery. The hint of an old, silent myocardial infarct further complicates the situation. The lack of antibiotic response suggests that this illness could well be life-threatening without timely surgery. This, despite the Patient History phrase "...we could do open surgery if life threatening." Thus, this patient should be an Urgent move. The patient also should be on supplemental oxygen. The gallbladder when acutely inflamed and infected is severely compromised. At 8,000 feet cabin altitude, the FiO_2 would be ~16%; compromised tissue could easily become ischemic and even necrose. Supplemental oxygen by mask at 6L would provide ~45% oxygen; at 8,000 feet, that translates to almost 35% (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). Lastly, the patient requires an OWL™ litter since he is too heavy for a regular litter (**Appendix A: Litter Comparison**). *Although not prescribed, an argument for using a pulse oximeter could be made.*

Outcome

Air evacuation was successful without incident. However, upon arrival at Kuwait it was discovered that the operating room table could not support the patient's bulk. Meanwhile, the patient finally began to respond to the antibiotics and his pain began to abate. In fact, the patient walked from the aircraft to the waiting helicopter. Needless to say, this generated a fair degree of consternation. *Lessons beyond the validation process to be learned here include 1) when moving patients early in the course of an illness, the clinical condition can rapidly change for the worse or for the better and 2) very heavy patients require special reinforced beds and tables, always check that they are available.* Hindsight, while useful, should always be used with caution. The decision to move the patient Urgent precedence was correct based on the circumstances. Erring towards patient safety and patient well-being is always the better course of action. That is, unless other factors are present such as operational flight safety and/or crew resource conservation.

Case 5. The Patient with a Kidney Stone

PMR Information:

Demographics:	Status	Army
	Grade	officer
	Age	< 30
	Gender	----
Patient Setting:	Precedence	Routine
	Classification	2A (inpatient litter)
	CCATT	no
	Injury Type	DNBI
	Space Type	litter
Administrative Data:	Originating MTF	Tallil
	Destination MTF	Balad
Clinical Data:	Primary Specialty	Nephrology
	Primary Diagnosis	Calculus of the Ureter
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“Patient presents to clinic with 10th episode of RLQ [right lower quadrant] and R flank pain (in recent months). Associated with vomiting and gross hematuria. Diagnosis of other episodes is nephrolithiasis. Patient states two stones have been recovered. Patient denies previous episode of urinary calculi...Physical findings: Tenderness to percussion over R CVA. Moderate voluntary guarding to palpation over entire abdomen. Mild tenderness to palpation over RLQ. Pain 8/10 without meds, 3/10 with meds...Dr. ----- cannot determine if patient has hydronephrosis or hydroureter. He very much suspects ureteral obstruction...lab could not perform a WBC/CBC count. The machine is down...Urinalysis TNTC blood...BUN = 8, Creat = 1.1...”

Medications:	toradol	phenergan			
	demerol				
Medical l Data:	VS	97.6 F	82	18	142/95
	CBC	not obtainable			
	Oxygen Delivery	NA			
	Vent Settings	NA			
	ABG	NA			
	Drainage	NA			
	PMI Data (equipment)	none			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

This is a Routine move for a patient with a kidney stone.

Administrative Data/Clinical Data Evaluation

This is an intra-theater move. Nothing else of import for the flight surgeon.

Short & Sweet Patient History/Medications

Patient presents with the latest in a string of kidney stones. Clinically, it appears that there is a moving right-sided ureteral stone that has the potential to lodge at the ureteral-vesical junction. Physical exam and urinalysis support that notion. The pain is unrelenting.

Medical Data Evaluation

There is no fever or tachycardia to suggest infection and the CBC could not be obtained. There is, however, significant hematuria.

Information Beyond the PMR

More information is required. JPTA was not helpful. The attending physician noted that this was the fourth episode in the last month. Furthermore, he described frank hematuria in the face of a KUB demonstrating a probable stone on the right side at the L2-ureteral-vesical junction. He strongly suspected early ureteral obstruction, but could not determine the presence of hydroureter or hydronephrosis. The consulting urologist vigorously urged expeditious transport.

Prescription:

Precedence	Priority
Classification	2A (inpatient litter)
Medical Adjuncts	none
Medical Interventions	none
Middle Ear Interventions	none
Patient Paraphernalia	none
Positioning Interventions	none
Aircraft Manipulations	none

Reasoning

This patient though initially submitted as a Routine transport should have been listed Priority. Although he does not have documented hydroureter or hydronephrosis, it is strongly suspected. There is continuing pain and frank hematuria with a demonstrated stone at the ureteral-vesical junction. No CBC is available and no further diagnostic/therapeutic tools are on hand. And, he is experiencing accelerating kidney stone episodes. These facts argue a Priority move (**Appendix A: Approach to Patients with Hernias or Kidney Stones**). With the degree of hematuria, consideration for supplemental oxygen is reasonable and some would prescribe it.

Outcome

Air evacuation was successful without incident.

Case 6. The Immediately Postoperative Patient

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 40
	Gender	----
Patient Setting:	Precedence	Routine
	Classification	2A (inpatient litter)
	CCATT	no
	Injury Type	BI
	Space Type	litter
Administrative Data:	Originating MTF	Balad
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	General Surgery
	Primary Diagnosis	Injuries, War Operations
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“Patient was riding in a Humvee that struck an IED...Single fragment wound to the left buttock, inferior margin of the buttock cheek. CT of abdomen/pelvis/thigh with contrast: fragment sitting at L sacroiliac junction, external to the pelvis with swelling of muscle. Diagnosis: fragment wound to L buttock, L sciatic nerve injury, tourniquet induced vasospasm-resolved...to OR for washout buttock wound. I & D of L buttock wound, fragment not removed. Betadine packing. CXR-negative. CT abdomen/pelvis fragment behind L sacroiliac joint, pelvis muscle hematoma...92% on room air. Placed on 2-4 liters O₂ in flight.”

Medications:	lovenox	colace			
	morphine pump	cephalothin			
	tylenol	percocet			
Medical Data:	VS	98.1 F	70	14	113/68
	CBC	37/13 ---	11,000		
	Oxygen Delivery	4-6L nasal cannula			
	Vent Settings	NA			
	ABG	pH = 7.33	pO ₂ = 68	pCO ₂ = 42	
	Drainage	NA			
	PMI Data (equipment)	pump for morphine			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The PMR requests Routine precedence for a non-CCATT, battle injured litter patient.

Administrative Data/Clinical Data Evaluation

There is nothing significant for the flight surgeon.

Short & Sweet Patient History/Medications

The patient has an IED fragment lodged in the left buttock with soft tissue and sciatic nerve injury. He was taken to the operating room where a washout with irrigation and devitalized tissue debridement was accomplished. The fragment was not removed. The sciatic nerve injury may well progress without expeditious removal of the fragment. There is an unknown degree of limb risk making this move, at the very least, a Priority precedence.

Medical Data Evaluation

Vital signs and hemoglobin level suggest that the patient is relatively stable; however, the respiratory situation is not so stable. He was extubated and planned for rapid evacuation on 4-6L nasal cannula. The pO_2/FiO_2 (aka PaO_2/FiO_2) ratio (68/.35) is 194 defining a moderate respiratory shunt (**Figure 28 or Appendix A: Pulmonary Shunt Ratio-Percent-Severity Depiction**). That coupled with an oxygen saturation on room air of 92% suggests the patient is still under the effects of anesthesia. The patient should not fly for the next 4-6 hours or until the temporary post-anesthetic shunt resolves.

Information Beyond the PMR

Flying the patient was delayed for several hours. Repeat studies revealed $pO_2 = 122$, $FiO_2 = 25\%$, and an oxygen saturation = 99%. The PaO_2/FiO_2 ratio rose to 488; no longer was there a respiratory shunt (**Figure 28 or Appendix A: Pulmonary Shunt Ratio-Percent-Severity Depiction**).

Prescription:

Precedence	Priority
Classification	2A (inpatient litter)
Medical Adjuncts	none
Medical Interventions	4-6L nasal cannula
Middle Ear Interventions	none
Patient Paraphernalia	none
Positioning Interventions	HOB elevation at 30 degrees
Aircraft Manipulations	none

Reasoning

The patient has an injured sciatic nerve with a retained IED fragment that potentially is putting pressure on the nerve. Long term limb function may be at stake making this, at the very least, a Priority move. However, the patient should not be moved until the temporary post-anesthetic respiratory shunt is resolved. This usually takes 4-6 hours, but can be significantly sooner; monitoring is key. The oxygen saturation moving from 92% on room air to 99% on 2L nasal cannula along with the $\text{PaO}_2/\text{FiO}_2$ ratio improvement signals shunt resolution (**Figure 28 or Appendix A: Pulmonary Shunt Ratio-Percent-Severity Depiction**). Because the patient is still early post-anesthesia, has significant tissue injury, and has a compromised major nerve, supplemental oxygen is indicated. Oxygen at 6L nasal cannula will deliver about 35% oxygen at 8,000-foot cabin altitude which should ensure good tissue oxygen delivery (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). Prescribing the HOB elevation should posturally enhance respiratory function.

Outcome

Air evacuation was successful without incident.

Case 7. The Patient with a Femoral Hernia

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 30
	Gender	----
Patient Setting:	Precedence	Priority
	Classification	2B (inpatient litter for comfort)
	CCATT	no
	Injury Type	DNBI
	Space Type	litter
Administrative Data:	Originating MTF	Salerno
	Destination MTF	Bagram
Clinical Data:	Primary Specialty	General Surgery
	Primary Diagnosis	Unilateral Inguinal Hernia
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“Patient with incarcerated femoral hernia on the right side. Patient is at risk of infection and strangulation. Patient has had previous surgical history for inguinal repair...He has been having intermittent pain and swelling in R groin for the past couple of months which had largely gone away, but about one week ago he noticed a large tender bulge developing at the middle portion of his upper thigh. He denies fever, chills, nausea, vomiting, diarrhea. In fact, he has had some constipation relieved with colace and he is passing gas normally. He denies any urinary complaints. No systemic symptoms.”

Medications: colace percocet

Medical Data:	VS	98.5 F	77	12	137/69
	CBC	not performed			
	Oxygen Delivery	Room Air --- 95% saturation			
	Vent Settings	NA			
	ABG	NA			
	Drainage	NA			
	PMI Data (equipment)	none			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient requires a Priority move for a non-battle problem.

Administrative Data/Clinical Data Evaluation

The problem appears to be a hernia.

Short & Sweet Patient History/Medications

The patient has an incarcerated femoral hernia that is associated with discomfort requiring percocet for pain control. This setting confirms the Priority precedence of the patient (**Appendix A: Approach to Patients with Hernias or Kidney Stones**).

Medical Data Evaluation

Only significant item is the room air saturation of 95%.

Information Beyond the PMR

The patient's surgeon felt it imperative to transport him for definitive non-emergent surgery. Although there was some tenderness, he felt it better to perform the surgery in a cleaner environment.

Prescription:

Precedence	Priority
Classification	2B (inpatient litter for comfort)
Medical Adjuncts	none
Medical Interventions	2L nasal cannula
Middle Ear Interventions	none
Patient Paraphernalia	none
Positioning Interventions	none
Aircraft Manipulations	none

Reasoning

An incarcerated femoral hernia puts the patient at significant risk, particularly if bowel is involved. This drives the Priority precedence. Although the room air saturation is 95%, it should not be too concerning. After all, Salerno is over 3,000 feet in elevation producing a room air FiO_2 of 18% which, assuming a normal hemoglobin level of 15 g/dl, would produce an oxygen saturation of about 95% (**Appendix A: Tables for Calculating DO_2**). By providing supplemental oxygen at 2L nasal cannula, the patient was given the sea level equivalent of room air at Bagram (elevation ~5,000 feet) (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**).

Outcome

Air evacuation was successful without incident. Interestingly, however, upon arrival the patient was found not to have a femoral hernia. He was diagnosed with a proximal, medial thigh abscess. CT scan revealed no hernia, but did show an abscess. He was then placed on IV antibiotics and transported to Landstuhl for definitive surgery. Reportedly, his inguinal hernia was repaired without incident. *Lessons beyond the validation process to be learned here include* 1) *there are different levels of experience and expertise that the flight surgeon will encounter and* 2) *always err on the patient's side. In other words, interpret the data yourself coming to your own diagnostic and therapeutic conclusions and package the patient for flight accordingly.*

Case 8. The Patient with Trapped Air

PMR Information:

Demographics: Status Army
 Grade enlisted
 Age < 40
 Gender ----

Patient Setting: Precedence Priority
 Classification 2A (inpatient litter)
 CCATT no
 Injury Type unlisted
 Space Type litter

Administrative Data: Originating MTF Balad
 Destination MTF Landstuhl

Clinical Data: Primary Specialty General Surgery
 Primary Diagnosis Injuries, War Operations
 Max Stops unrestricted
 Max RONS unrestricted
 Altitude Restriction none

Patient History:

“Patient struck with an IED blast with open RLE [right lower extremity] fractures---open tibia-fibula and malleolar fractures---in external fixators and splints; left maxillary sinus wall fracture, left scapula and underlying rib fractures with small pneumothorax. Pleural tube in place. Cervical spine negative; CT head negative; CXR left pneumothorax. Glasgow Coma Scale 15.”

Medications: morphine phenergan
 bacitracin morphine pump
 cephalothin levofloxacin

Medical Data: VS 99.2 F 121 12 117/75
 CBC 28.3/9.7 --- 10,500
 Oxygen Delivery 4L nasal cannula --- 98% saturation
 Vent Settings NA
 ABG NA
 Drainage Pleur-evacTM and foley catheter
 PMI Data (equipment) suction

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

Inpatient Priority move of a non-CCATT patient.

Administrative Data/Clinical Data Evaluation

The patient was battle-injured.

Short & Sweet Patient History/Medications

The patient was struck by an IED blast suffering RLE open fractures that were operatively stabilized. He also suffered a fractured left scapula with underlying rib fractures; this injury is of great concern since it requires high energy delivery. A pneumothorax was sought and found; a chest tube was placed and put to continuous water-seal suction. In addition, his left maxillary sinus was fractured.

Medical Data Evaluation

There is nothing significant for the flight surgeon.

Information Beyond the PMR

The only additional information that is needed concerns the left maxillary sinus. Is it fluid-filled? The answer, found in JPTA, was affirmative.

Prescription:

Precedence	Priority
Classification	2A
Medical Adjuncts	none
Medical Interventions	4L nasal cannula
Middle Ear Interventions	none
Patient Paraphernalia	chest tube to suction
Positioning Interventions	none
Aircraft Manipulations	none

Reasoning

With such significant orthopedic damage, not to mention the facial and thorax injuries, supplemental oxygen to prevent hypoxia and minimize at-altitude tissue ischemia is mandatory. The oxygen prescription is equivalent to sea level room air at maximum cabin altitude (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). Attention must also be given to the pneumothorax and fractured sinus. Both potentially involve trapped air. With a cabin altitude of 8,000 feet, the volume and diameter of air in a closed space will expand 35% and 10%, respectively (**Table 7 or Appendix A: Trapped Air Pressure-Volume-Diameter Relationships**). The expanding pleural air could produce a tension pneumothorax. So, it is important that the chest tube be placed to water seal/Heimlich valve if the lung has re-expanded and there is no air leak, but if there is an air leak, suction is especially important to employ. Here, suction was employed. Along the same lines, the expanding sinus air could cause excessive pain or track intracranially. If, however, as in this case, the sinus is filled with blood there would be no air to expand. In any event, it is important to know whether an injured sinus has trapped air or not; an air-fluid level seen on sinus x-rays answers the question easily. *Although not prescribed, an argument could be made for prescribing 7-8L mask, HOB elevation to 30 degrees, a CAR, a no Valsalva order, and a medical attendant.*

Outcome

Air evacuation was successful without incident.

Case 9. Another Psychiatric Patient

PMR Information:

Demographics:	Status	Navy
	Grade	enlisted
	Age	< 20
	Gender	----
Patient Setting:	Precedence	Routine
	Classification	1B (psych litter --- medication & optional restraints)
	CCATT	no
	Injury Type	DNBI
	Space Type	litter
Administrative Data:	Originating MTF	Bucca
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	Psychiatry
	Primary Diagnosis	Non-Psychotic Disorder
	Max Stops	unrestricted
	Max RONs	unrestricted
	Altitude Restriction	none

Patient History:

“Patient has been unable to fully perform his duty as a result of impulsive behavior. He came to theater directly from confinement as a result of assaulting an E7...he had an argument with his supervisor and refused to pull guard duty. He went to pack his things to leave. At this time he was removed for his regular duty assignment and his ammunition was taken away. He was enrolled in weekly anger management therapy. He again became angry with co-workers and went to his room to find ammunition since his weapon had not been confiscated at the time. Since he could not find ammo, he allegedly took nine Nyquil tablets in an attempt to kill himself. He was enrolled in biweekly therapy sessions at the time...a fellow sailor committed suicide, patient told previous therapist that he wondered why he had not successfully completed suicide as his friend. He stated that he thought it best to kill himself now since everyone was already grieving. This would be ‘taking care of two birds with one stone.’ At this point, his weapon was taken away. Since in theater, he has had approximately 3 angry outbursts with intent to ‘fight’ others. The latest incident...an E5 questioned him in a manner in which he did not like. He became angry and though he did not act on it, he voiced feelings of wanting to find the higher ranking sailor to ‘paralyze’ him. As a result of patient’s impulsive (behavior) and his inability to carry a weapon...he is a risk to self and others if he remains in theater...He is inappropriate to remain in theater. He will be accompanied by a unit escort. He contracts for safety at this time. Ativan prn will be available. No previous psych history. Patient presents possible suicidal and homicidal ideations.”

Medications:	valium	ativan			
Medical Data:	VS	98 F	74	16	120/70
	CBC	unlisted			
	Oxygen Delivery	NA			
	Vent Settings	NA			
	ABG	NA			
	Drainage	NA			
	PMI Data (equipment)	NA			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient requires medicinal and/or physical restraints for a Routine psychiatric move.

Administrative Data/Clinical Data Evaluation

There is nothing significant for the flight surgeon.

Short & Sweet Patient History/Medications

The patient has demonstrated repetitive, aggressive, impulsive behavior to the point of threatening self and others. Both his ammunition and weapon have been confiscated. He has not responded to therapy. He requires evacuation to definitive psychiatric care.

Medical Data Evaluation

There is nothing significant for the flight surgeon.

Information Beyond the PMR

Nothing further is necessary.

Prescription:

Precedence	Routine
Classification	1B (psych litter--- medication & optional restraints)
Medical Adjuncts	medical attendant
Medical Interventions	sedation/restraints in flight
Middle Ear Interventions	none
Patient Paraphernalia	none
Positioning Interventions	none
Aircraft Manipulations	none

Reasoning

This patient is clearly different from the previous psychiatric case. Despite the declaration that “he contracts for safety at this time,” there is no sense of confidence in the narrative. Without a doubt, this patient is a safety of flight risk as well as a risk for inflight suicide and/or homicide should, for whatever reason, he become enraged. Inflight sedation is vital. In fact, a case could be made for a 1A (psych litter --- medicinal & physical restraints) classification (**Appendix A: Approach to Psychiatric Patients**). No matter how classed, he requires a medical attendant that can intervene rapidly and attend the physical restraints. *Although not prescribed, an argument for patient positioning away from exits could be made. Not infrequently, however, the AE air crew simply effects that positioning as part of their protocols.*

Outcome

Air evacuation was successful without incident.

Case 10. The Cardiac Patient

PMR Information:

Demographics:	Status	contractor
	Grade	NA
	Age	< 50
	Gender	----
Patient Setting:	Precedence	Urgent
	Classification	2A (inpatient litter)
	CCATT	yes
	Injury Type	DNBI
	Space Type	litter
Administrative Data:	Originating MTF	Balad
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	Cardiology
	Primary Diagnosis	Myocardial Infarction
	Max Stops	none
	Max RONS	none
	Altitude Restriction	none

Patient History:

“Patient presents with an acute ST segment elevation myocardial infarction (STEMI). History: episode of pain 2 days prior, lasting 40 minutes, resolved spontaneously...Episode of 3/10 chest pressure for 1 hour then second episode radiated down both arms, no diaphoresis, no shortness of breath. CXR negative...Troponin I positive...negative CK at 2 hours post start of pain...Pain resolved with nitroglycerin, aspirin, morphine, and oxygen...patient now having more pain, now on nitroglycerin drip and pain is not going away...sats 95% on 4L nasal cannula; patient has been given IV lopressor...and heart rate is down along with blood pressure; nitroglycerin drip...patient states pain is ‘an ache’ and rates it a 4/10...ST segment persists at 1 mm elevation with new Q-waves, cardiologists on phone with fax of EKG states that MI is continuing to evolve. No resolutions of ST elevation since pain restarted...pO₂ = 80 on FiO₂ of 45% face mask...No arrhythmias.”

Medications:	nitroglycerin drip	nitroglycerin paste
	baby aspirin	morphine
	integilin	lopressor

Medical Data:	VS	97.6	114	20	151/94
	CBC	47/16 ---	8,000		
	Oxygen Delivery	45%	face mask		
	Vent Settings	NA			
	ABG	pH = 7.41	pO ₂ = 80	pCO ₂ = 33	
	Drainage	NA			
	PMI Data (equipment)	cardiac monitor			
		pulse oximeter			
		pump for nitroglycerin			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient requires an Urgent move with a CCATT team.

Administrative Data/Clinical Data Evaluation

The patient requires a direct flight, no stops and no RONS, from Balad to Landstuhl for a myocardial infarction.

Short & Sweet Patient History/Medications

Over two days, the patient has developed an unrelenting chest pain myocardial infarction with persistent ST elevation and positive Troponin I. He has experienced no arrhythmias. His medications have begun to slow the heart rate and his blood pressure has begun to fall; however, the pain and ST elevation has not subsided. Clearly, this is an evolving MI that requires emergent catheterization.

Medical Data Evaluation

The pO₂/FiO₂ (aka PaO₂/FiO₂) ratio is 177 defining a moderate-severe shunt (**Figure 28 or Appendix A: Pulmonary Shunt Ratio-Percent-Severity Depiction**). It is unlikely this will resolve while the MI is evolving.

Information Beyond the PMR

Discussions with the attending physician reveal the patient to be a smoker and obese (240+ pounds). The appearance of Q waves portends badly. The patient needs to move immediately. JPTA did not add any further information.

Prescription:

Precedence	Urgent
Classification	2A (inpatient litter)
Medical Adjuncts	cardiac monitor; pulse oximeter; CCATT team
Medical Interventions	15L non-rebreather oxygen (~100%)
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	none
Positioning Interventions	HOB elevation to 30 degrees
Aircraft Manipulations	CAR 4,000 feet no RONS, no stops

Reasoning

This patient is very sick. He is losing heart muscle. The muscle he has cannot tolerate any hypoxia; it is already ischemic. He has gone from 4L nasal cannula to 45% mask. For flying, he requires 100% oxygen as best as can be provided. Short of intubation and ventilation, a 15L non-rebreather delivers ~100% oxygen. At 8,000 feet cabin altitude, the sea level equivalent is only ~75%. Imposing a CAR of 4,000 feet will up that to ~85% (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). This requires a lower cruising altitude and, arguably, adds about 20-30 minutes flying time. Although debatable, the better oxygen delivery to the tissues probably offsets the potential extra time in the air (**Appendix A: Tables for Calculating DO₂**). The HOB elevation uses gravity to enhance alveolar aeration and minimize the impact of early congestive heart failure. Lastly, by insisting on no RONS and no stops, side trips for any other missions are prevented. *Although not prescribed, an argument could be made for prescribing an OWL™ litter.*

Outcome

Air evacuation was successful without incident. However, approximately an hour from landing, the AE crew learned that the Cardiac Cath Laboratory was unaware of the patient's arrival. TPMRC-Europe was notified. They quickly contacted the on-call team. When the patient arrived, the Cath Team was prepared for him. Despite the documentation that cardiologists were consulted and had recommended immediate catheterization, they were in-theater cardiologists, not those at Landstuhl. In short, the assumption that Landstuhl had been contacted was incorrect and, prior to flying the patient, Landstuhl should have been called to confirm that the Cath Team was ready for the patient. *Lessons beyond the validation process to be learned here include 1) make no assumptions and 2) trust, but verify.*

Case 11. The Pregnant Patient

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 20
	Gender	----
Patient Setting:	Precedence	Routine
	Classification	3A (outpatient ambulatory)
	CCATT	no
	Injury Type	DNBI
	Space Type	ambulatory
Administrative Data:	Originating MTF	Baghdad
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	Gynecology
	Primary Diagnosis	Ectopic Pregnancy
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“(The patient) at ~6 weeks by last menstrual period presents with abdominal pain and spotting, pregnancy test positive, ultrasound: no intrauterine pregnancy, L adnexal fullness. Counseled for and underwent exploratory laparotomy under general endotracheal anesthesia. Findings: hemoperitoneum ~300 cc, rupture L ampullary ectopic pregnancy incorporated into L ovary, dense pelvic adhesive disease. Patient underwent L salpingo-oophorectomy. R adnexa explored, with lysis of adhesions, normal R ovary. Is alert and oriented X3, current pain level is 4/10 without medications and 0/10 with medications. Patient is able to ambulate on own and is stable and awaiting AE. Patient had 300 ml blood loss 48 hours ago. She had pre-existing anemia with hemoglobin at 9. She has no dyspnea, no chest pain or weakness, dizziness or palpitations. She is completely asymptomatic at rest and with exertion. Pain nearly gone 0/10 on meds...Refuses transfusion.”

Medications:	ibuprofen	iron sulfate
	cephalothin	morphine
	colace	

Medical Data:	VS	98.7 F	83	14	113/76
	CBC	20.9/7.1			
	Oxygen Delivery	Room Air ---	99% saturation		
	Vent Settings	NA			
	ABG	not performed			
	Drainage	NA			
	PMI Data (equipment)	none			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient is an ambulatory outpatient.

Administrative Data/Clinical Data Evaluation

The patient was pregnant with an ectopic pregnancy.

Short & Sweet Patient History/Medications

The patient is an older teenager who apparently is chronically anemic with a hemoglobin around 9 g/dl. She presented about 6 weeks into her pregnancy with a ruptured, bleeding ectopic. At surgery, 300 cc of blood were found along with a ruptured ectopic within the left oviduct. She underwent a left salpingo-oophorectomy. Presently, she is asymptomatic and ambulatory and an outpatient.

Medical Data Evaluation

Her hemoglobin is now 7.1 g/dl. A blood loss of 300 cc at surgery in a patient with a chronic hemoglobin = 9 g/dl does not fully explain a present hemoglobin = 7.1 g/dl. There was either more blood lost at surgery than is reported, her chronic hemoglobin level is actually lower than reported, or she has ongoing blood loss. The prime concern here is the possible ongoing blood loss.

Information Beyond the PMR

It is important to know that the hemoglobin level is stable. In discussions with her physician, this was confirmed; for the past 12 hours, hemoglobin had ranged from 7.1 -7.2 g/dl.

Prescription:

Precedence	Routine
Classification	2B (inpatient optional litter)
Medical Adjuncts	none
Medical Interventions	10-12L non-rebeather
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	none
Positioning Interventions	none
Aircraft Manipulations	CAR 4,000 feet

Reasoning

Normally with pregnancy, the flight surgeon must be concerned for both the mother and the child. In fact, the fetus' hemoglobin has a greater affinity to oxygen than that of the mother and the fetus is much more sensitive to hypoxia than the mother. Indeed, these facts will color any prescription by the flight surgeon. However, in this case, the pregnancy was ectopic and surgically corrected. Now, the important thing is to fly the mother safely. She was apparently stable, having a chronic anemia with a hemoglobin of 9 g/dl that underlaid an acute anemia with a hemoglobin of 7.1 g/dl. There is no evidence for ongoing blood loss and the patient refuses transfusion. The only tissue injury she has is that of a controlled surgical wound where minimal tissue injury is the rule. The critical tissue oxygen delivery (DO_{2crit}) level in humans is < 7.3 ml O_2 per kg per min. At a cabin altitude of 8,000 feet, her DO_2 calculates to 5.7 ml O_2 per kg per min, well below 7.3 ml O_2 per kg per min (**Appendix A: Tables for Calculating DO_2**). This is unacceptable. However, she weighs 130 pounds (~ 60 kg) which is a good deal less than the assumed weight of 80 kg. Taking her weight into account, the resultant DO_2 would be higher, perhaps ≥ 7.3 ml O_2 per kg per min. Although better, it is not ideal. By delivering oxygen at 10-12L non-rebreather and imposing a CAR of 4,000 feet, her DO_2 is probably seriously > 8.0 ml O_2 per kg per min (**Appendix A: Tables for Calculating DO_2**). It could even be argued that a CAR was unnecessary, that the supplemental oxygen alone was adequate (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude and Appendix A: Tables for Calculating DO_2**). In either case, there is significant improvement in the DO_2 . Incidentally, after-the-fact employment of the DO_2 graphic user interface, confirmed the adequacy of DO_2 . *Although not prescribed, an argument could be made for prescribing a pulse oximeter.*

Outcome

Air evacuation was successful without incident.

Case 12. The Patient with a Very Low Hemoglobin

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 30
	Gender	----
Patient Setting:	Precedence	Urgent
	Classification	2B (inpatient optional litter)
	CCATT	no
	Injury Type	DNBI
	Space Type	litter
Administrative Data:	Originating MTF	Al Dhafra
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	Hematology
	Primary Diagnosis	Aplastic Anemia
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“Patient has been undergoing outpatient evaluation for 2 weeks for weakness, fatigue, and pallor. He reports feeling weak since early...For 2 weeks patient has experienced non-exertional left-sided chest pain and mild dyspnea on exertion. Current pain level is 0/10 at rest, 2/10 with exertion. He tolerates only moderate exertion before requiring rest. He denies evidence of bleeding such as bleeding gums, hematochezia, easy bruisability, epistaxis, hematuria, or melena. He denies fever or night sweats...he experienced a syncopal episode without loss of consciousness while waiting for dinner. Examination revealed a pale, weak-appearing male who is alert...Of note is significant pallor of all mucosal surfaces and skin. No petechiae were noted...ESR = 30...highly suspicious for one-cell line myelodysplastic suppression.”

Medications: none

Medical Data:	VS	97.6 F	88	12	136/78
	CBC	24/6.4	---	5,300	
	Oxygen Delivery	NA			
	Vent Settings	NA			
	ABG	NA			
	Drainage	NA			
	PMI Data (equipment)	none			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient needs an Urgent move, but requires an optional litter. This raises questions.

Administrative Data/Clinical Data Evaluation

The patient has a hematology problem, aplastic anemia. By definition, the hemoglobin will be reduced.

Short & Sweet Patient History/Medications

Over two weeks, the patient has been experiencing an increasing degree of weakness, fatigue, and pallor. Now, he has noted both non-exertional chest pain and dyspnea on exertion. Indeed, he has further noted a near-syncopal episode. There is no obvious bleeding source. Diagnosis is thought to be hematological.

Medical Data Evaluation

His hemoglobin is 6.4 g/dl.

Information Beyond the PMR

The physician described only rudimentary capabilities for their facility. There was no ability to evaluate ABGs. There was no capability for transfusion and there were no approved blood products. In light of the chest pains and near-syncope, his physician was very uncomfortable with this patient and felt his life was at high risk.

Prescription:

Precedence	Urgent
Classification	2A (inpatient litter)
Medical Adjuncts	CCATT team
Medical Interventions	12-15L non-rebreather Bring 4U pRBC for flight (brought by the AE flight) Give 1U pRBC prior to flight & 1U pRBC during flight
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	none
Positioning Interventions	none
Aircraft Manipulations	CAR 4,000 feet no RONS, no stops

Reasoning

The physician and facility were very uncomfortable with this patient. They were concerned that he would seriously deteriorate and they had no capability to care for him beyond bare basics. His history was strongly suggestive of acute coronary syndrome secondary to the anemia (easily supported by his $\text{DO}_2 = 6.1 \text{ ml O}_2 \text{ per kg per min}$ on sea level room air) (**Appendix A: Tables for Calculating DO_2**); however, acute cardiac damage could not be evaluated or treated. In addition, the condition causing the anemia continued unchecked and would only make the situation worse. Acceptable blood products were unavailable. For these reasons, it was felt that the patient's life was imminently threatened necessitating an Urgent evacuation. Going to altitude would serve to magnify any clinical deterioration. As a result, a CCATT team was tasked to care for the patient. A sudden cardiac event could now be treated. To avoid such an event, acceptable blood products were transported (along with the CCATT team) to the patient. One unit was prescribed prior to flight and one during flight. Transfusion could confuse later diagnostic efforts, so Landstuhl hematologists were consulted. They recommended several types of blood draw prior to transfusion to avoid any diagnostic uncertainty. To add further safety to the patient's transport, oxygen at 12-15L non-rebreather and a CAR of 4,000 feet were prescribed. Instead of a DO_2 of $\sim 5.3 \text{ ml O}_2 \text{ per kg per min}$ at altitude, his DO_2 would be, at best, borderline at $\sim 7.1 \text{ ml O}_2 \text{ per kg per min}$ (**Appendix A: Tables for Calculating DO_2**). Even so, this may well be at or below the $\text{DO}_{2\text{crit}}$. No RONS and no stops were imposed to expedite the patient's transit; cardiac concerns persisted.

Outcome

Air evacuation was successful without incident. That being said, the trip was definitely interesting from the TVFS viewpoint. The CCATT physician measured an iSTAT hemoglobin, finding it to be $\sim 7 \text{ g/dl}$ on one occasion and $\sim 8 \text{ g/dl}$ on another. He did not transfuse the patient feeling the 6.4 g/dl value to be inaccurate. Upon uneventful arrival at Landstuhl, he declared the patient Routine (Note: only the validating flight surgeon can alter the patient's precedence). Once admitted to Landstuhl repeat hemoglobin by the facility laboratory confirmed the earlier 6.4 g/dl laboratory value. In this case, by imposing a CAR and delivering almost 100% oxygen to the patient, a seriously possible clinical deterioration was averted. The fact that the anemia was to some extent chronic, the patient remained resting throughout the flight, and there was no significantly injured tissue proved fortuitous as well. In short, always err on the patient's side. Incidentally, after-the-fact employment of the DO_2 graphic user interface, confirmed the barely borderline DO_2 . *Lessons beyond the validation process to be learned here include 1) iSTAT values are not as reliable as laboratory values (iSTAT values are most helpful when used to follow trends) and 2) do not expect the medical attendant, especially if a CCATT team, to carry out your prescriptions and package the patient accordingly (remember, once the TVFS delivers the patient to the CCATT team, there is no obligation for that team to carry out the TVFS's orders).*

Case 13. The Patient with a Splenectomy

PMR Information:

Demographics: Status Army
 Grade enlisted
 Age < 40
 Gender ----

Patient Setting: Precedence Priority
 Classification 2A (inpatient litter)
 CCATT no
 Injury Type DNBI
 Space Type litter

Administrative Data: Originating MTF Baghdad
 Destination MTF Landstuhl

Clinical Data: Primary Specialty General Surgery
 Primary Diagnosis Splenomegaly
 Max Stops unrestricted
 Max RONS unrestricted
 Altitude Restriction none

Patient History:

“Patient with splenomegaly was wrestling in the barracks and noticed abdominal pain and syncope. Noted to have a hematocrit of 25...and a CT scan revealed massive hemoperitoneum. Was taken to the OR where a large capsular hematoma was noted with a hole in the spleen and more than a liter of blood in his abdomen. A splenectomy was performed...Uneventful recovery. Transfused 1U pRBC and hematocrit is now 30....current pain level is 7/10 without medications and 1/10 with medications. CXR is clear and C-spine is clear...Will observe overnight in ICU and evac out tomorrow...Hemoglobin 8.6...Transfused 2U pRBC. Hemoglobin 10.3...KUB showed excess air in stomach...NGT placed and hooked to low intermittent suction.”

Medications: morphine phenergan

Medical Data: VS 97.8 F 97 14 139/74
 CBC 31/10.3 --- 9,000
 Oxygen Delivery 4L mask
 Vent Settings NA
 ABG pH = 7.29 pO₂ = 98 pCO₂ = 51
 Drainage NGT & foley
 PMI Data (equipment) suction

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient suffered a non-battle injury.

Administrative Data/Clinical Data Evaluation

The patient had splenomegaly.

Short & Sweet Patient History/Medications

While wrestling in the barracks, the patient experienced abdominal pain and syncope. CT revealed massive hemoperitoneum and hematocrit was only 25%. In the operating room, a capsular hematoma was encountered along with a hole in the spleen. Splenectomy was performed with a 1U transfusion (hemoglobin = 10 g/dl). Overnight his hemoglobin dropped to 8.6 g/dl; he was transfused another 2U to a hemoglobin of 10.3 g/dl. KUB demonstrated excessive air in the stomach; an NGT was placed.

Medical Data Evaluation

Although the hemoglobin is now good at 10.3 g/dl, there is no guarantee that there is not going to be further bleeding or postoperative equilibration.

Information Beyond the PMR

The surgeon reported no excessive oozing or bleeding once the spleen was controlled.

Prescription:

Precedence	Priority
Classification	2A (inpatient litter)
Medical Adjuncts	CCATT
Medical Interventions	4L nasal cannula
	Bring 2U pRBC for flight
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	NGT to suction
Positioning Interventions	none
Aircraft Manipulations	CAR 5,000 feet

Reasoning

The patient is a Priority move. Although stabilized, he is not yet stable. Witness the drop in hemoglobin overnight that required further transfusion. The drop may have been the result of intravascular equilibration from the injury and surgery or it could be continued blood loss. Since the surgeon was confident there was no further active bleeding, it was probably equilibration. However, following the “err on the patient’s side” dictum, 2U pRBC were ordered for flight. In addition, having suffered serious tissue injury from the wrestling and the surgery, good tissue oxygen delivery can be assured with 4L nasal cannula oxygen (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude** and **Appendix A: Tables for Calculating DO₂**). Furthermore, this is even more assured with the CAR of 5,000 feet. But, more importantly, the CAR is to minimize stomach air expansion. The patient accumulated an excessive amount of gastric air postoperatively necessitating NGT placement. This is an important fact; it suggests some degree of gastric atony. As the stomach balloons with air, its wall is distended and the short gastric arteries are stretched. During a splenectomy, they are tied off and divided. But, an air-filled stomach can disrupt these ties releasing an arterial stream. These short gastric arteries, on the cephalad portion of the greater curvature wall, supply a small, but significant portion of the spleen’s blood. Preventing this well known complication is crucial. The CAR will reduce the volume expansion from 35% to 20% (**Table 7 or Appendix A: Trapped Air Pressure-Volume-Diameter Relationships**) and the NGT to suction will remove the air; combined, both should avert an in flight catastrophe. Because this patient has considerable risk with flight, it is reasonable to task a CCATT team to his care (**Appendix A: CCATT Decision Tree**). Another patient on the flight, requiring ventilator care, was already assigned a CCATT team. It was easy to attach that same team to this patient. In that way, resource allocation was optimized.

Outcome

Air evacuation was successful without incident. (Note: This patient will need the pneumococcal vaccine, pneumovax, once safely recuperating from surgery...usually 1-2 weeks post-surgery.)

Case 14. The Patient with Presumptive Eosinophilic Pneumonitis

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 30
	Gender	----
Patient Setting:	Precedence	Routine
	Classification	2B (inpatient optional litter)
	CCATT	no
	Injury Type	DNBI
	Space Type	litter
Administrative Data:	Originating MTF	Balad
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	Pulmonary Disease
	Primary Diagnosis	Viral Pneumonia
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“...went on a long run...then developed 3 days of fever, chills, malaise, and R chest pain. He was given oral and IV ciprofloxacin with no relief. CT chest showed patchy air space opacification and ground glass opacification which has an upper lobe predominance and a nodular appearance. Differential diagnosis includes: Loeffler’s syndrome, diffuse pneumonia, lymphangitic spread of cancer, hemorrhage such as can be seen with vasculitis or Goodpasture’s syndrome, or lung injury from caustic exposure. Patient has smoked for less than 1 week...Patient is ROC negative. No bronchoscopy done.”

Medications:	levofloxacin	percose			
	ibuprofen	proventil nebulizer			
	albuterol	tylenol			
Medical Data:	VS	98 F	91	24	108/56
	CBC	37.8/12.1 --- 8,100			
		(Segs 57, Bands 1, Lymphs 24, Eos 10, Monos 8)			
	Oxygen Delivery	4L nasal cannula --- 98% saturation			
	Vent Settings	NA			
	ABG	pH = 7.41	pO ₂ = 75	pCO ₂ = 39	
	Drainage	NA			
	PMI Data (equipment)	none			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient is a Routine transport for disease, non-battle injury.

Administrative Data/Clinical Data Evaluation

The transport reason is pulmonary. An initial thought in the CENTCOM region should be eosinophilic pneumonitis. Also, infection should be considered.

Short & Sweet Patient History/Medications

The patient presented with a three day history of fever, chills, malaise, and right-sided chest pain. Chest CT scan demonstrated bilateral patchy, ground glass opacification. The patient had just begun smoking. He was treated with ciprofloxacin without relief. This presentation is compatible with eosinophilic pneumonitis. The patient is obese at 240+ pounds.

Medical Data Evaluation

The patient has tachypnea. The WBC is not elevated; however, the differential includes significant lymphocytes and eosinophils. Viral pneumonia and eosinophilic pneumonia are strong considerations. The "ROC," or rule out communicable disease, checklist should be run.

Information Beyond the PMR

There is nothing significant for the flight surgeon.

Prescription:

Precedence	Priority
Classification	2B (inpatient optional litter)
Medical Adjuncts	none
Medical Interventions	8L mask
Middle Ear Interventions	none
Patient Paraphernalia	none
Positioning Interventions	HOB elevation to 30 degrees
Aircraft Manipulations	none

Reasoning

The patient may well have eosinophilic pneumonitis. This is a rapidly progressive process leading to severe respiratory failure. Early in the conflict, there were a number of cases reported. Opacified lungs in a recent onset smoker with bronchoscopic eosinophils and/or peripheral eosinophilia mark these severely ill individuals. In fact, almost 10% of soldiers with eosinophilic pneumonitis have died. Since this patient possessed some of these findings, it was prudent to upgrade him to a Priority move. His $pO_2 = 75$ mmHg while breathing ~35% oxygen defined a moderate shunt ($75/0.35 = 214$) to the point of acute lung injury, maybe early acute respiratory distress syndrome (ARDS) (**Figure 28 or Appendix A: Pulmonary Shunt Ratio-Percent-Severity Depiction and Table 15 or Appendix A: PaO_2/FiO_2 versus SpO_2/FiO_2 Pulmonary Shunt Ratio Correlation**). The swift respiratory deterioration described in these patients mandated early transport for this man while relatively stable. For this, 8L mask oxygen was prescribed. This equated to ~50% oxygen or a sea level equivalent, at 8,000 feet, of ~35% oxygen (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). And, if the shunt remained stable, the pO_2 should remain stable at ~75 mmHg, securing adequate oxygenation at altitude. Transport following deterioration would become much more dangerous. Debatably, HOB elevation to 30 degrees used gravity to enhance natural pulmonary function and maximize alveolar aeration. *Although not prescribed, an argument could be made for prescribing a pulse oximeter, a CCATT team, an OWL™ litter, and a CAR. In addition, an argument could be made for prophylactic intubation and transport with a CCATT team.*

Outcome

Air evacuation was successful without incident.

Case 15. The Patient with a Long Flight to Bethesda

PMR Information:

Demographics:	Status	Marine
	Grade	enlisted
	Age	< 30
	Gender	----
Patient Setting:	Precedence	Urgent
	Classification	2A (inpatient litter)
	CCATT	yes
	Injury Type	BI
	Space Type	litter
Administrative Data:	Originating MTF	Balad
	Destination MTF	Bethesda
Clinical Data:	Primary Specialty	Neurosurgery
	Primary Diagnosis	Subdural Hemorrhage
	Max Stops	none
	Max RONS	none
	Altitude Restriction	4000

Patient History:

“...troop involved in grenade blast...Upon arrival GCS was 3T, intubated for airway protection...Right frontal scalp laceration, left ring finger open fracture, left arm and bilateral LE puncture wounds. FAST scan negative. CT scan of head revealed right frontal SDH and fragment. Pan scan otherwise negative. Neurosurgical...plan is to awaken patient from sedation and note exam. If ICP monitor is needed...it will be inserted...patient will be taken to OR tonight for soft tissue washouts...(per JPTA: left arm and bilateral lower extremity wounds irrigated and debrided, prophylactic right arm fasciotomies performed...‘CT head with right 4-5 mm subdural hematoma, penetrating head injury with embedded bone fragments to anterior right frontal lobe and a track to the anterior left frontal lobe where the fragment stopped, possible injury to the anterior sagittal sinus, open basilar cisterns. No midline shift or ventricular effacement.’)...Patient with persistently elevated ICP by monitor from 23-29. Patient with evidence of cerebral edema by CT head...Patient taken to OR for right decompressive craniectomy...right fronto-temporal-parietal craniectomy bone flap turned...Dura opened...Right hemisphere appeared swollen upon opening. Frontal lobe was debrided along fragment penetration path. Several bleeding surface and bridging veins were coagulated...SDH was irrigated and resected...Dura was loosely laid over the decompressed brain...10 Fr JP was placed in wound bed and scalp flap was re-approximated and closed in 2 layers...ICP post-op was 3.4...(per JPTA: ‘Post-op CT head obtained and demonstrated bilateral parasagittal infarcts in the posterior frontal and anterior parietal lobes. Subsequent CT arterial/venous of brain obtained and demonstrated approximately 3 cm partial sinus thrombosis.’)”

Medications:	protonix fentanyl drip rocephin levofloxacin	lacrilube propofol drip phosphenytoin lovenox
Medical Data:	VS CBC Oxygen Delivery Vent Settings ABG Drainage PMI Data (equipment)	100.8 F 114 20 109/67 28/10 ventilator --- 35% FiO ₂ TV = 550 Rate = 20 PEEP = 10 pH = 7.42 pO ₂ = 134 pCO ₂ = 35 NGT, foley, JP drain monitor ventilator suction pump pulse oximeter

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

Severe battle injured patient requiring Urgent move with CCATT team.

Administrative Data/Clinical Data Evaluation

The patient has a subdural hematoma.

Short & Sweet Patient History/Medications

The patient suffered a grenade blast. His left arm and both lower extremities bore serious soft tissue wounds requiring irrigation and debridement. Prophylactic fasciotomy of the arm was performed. He also had a penetrating brain injury from the right to left frontal lobes; there was a small non-expanding subdural hematoma. Subsequently, the patient deteriorated neurologically. ICP ranged from 23-29 and CT scan demonstrated cerebral edema complicated by a 3 cm partial sagittal sinus thrombosis. This situation prompted an emergent right-sided decompressive craniectomy lifting a right fronto-temporal-parietal bone flap.

Medical Data Evaluation

The patient's medical data suggested a stabilized patient that could emergently fly.

Information Beyond the PMR

Discussions with the neurosurgeon not only confirmed the critical nature of the patient, but also defined the patient's only hope for a functional recovery. Apparently, the sole, sufficiently aggressive, neurosurgeon interventionalist that could address the sagittal sinus thrombosis practiced at National Naval Medical Center in Bethesda, Maryland. Further discussions with the Bethesda specialist confirmed that direct travel to Bethesda was the patient's best chance. An Urgent transport from Balad to Bethesda was validated.

Prescription:

Precedence	Urgent
Classification	2A (inpatient litter)
Medical Adjuncts	CCATT team
Medical Interventions	ventilator --- 45% FiO ₂ maintain pCO ₂ at ~35 mmHg maintain pO ₂ at ~100 mmHg
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	none
Positioning Interventions	head first loading
Aircraft Manipulations	CAR 4,000 feet no RONS, no stops air re-fueling, if needed

Reasoning

Discussions with the neurosurgeon identified the pO₂ and pCO₂ transport limits. The CCATT team would use respiratory rate to manipulate the pCO₂ and use FiO₂ for the pO₂. Starting at FiO₂ of 45% ensured that the patient would initially fly at a sea level equivalent of 35% (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). The 35% was achieving the neurosurgical goals. To mitigate the effects of gravity on acceleration and deceleration, head first loading was prescribed. A CAR of 4,000 feet was imposed with air re-fueling authorized. This upped the FiO₂ to ~40% (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). In addition, the CAR would counter expansion of any air trapped beneath the dural and skin flaps. More importantly, it would reduce the net driving force of fluid from the vasculature to the tissues, moderating the tendency for edema formation in the brain. In addition, the CAR essentially upped the Lastly, no RONS and no stops guaranteed the quickest routing to Bethesda and authorizing air re-fueling ensured the quickest route was taken. *Although not prescribed, an argument could be made for prescribing HOB elevation to 30 degrees, a long slow landing, and opening the JP drain on ascent and descent.*

Outcome

Air evacuation was successful without incident. Initial PMR to arrival at Bethesda took ~18 hours; the 5,400 mile flight itself lasted 13 hours. Approximately one month later, he was transferred to a rehabilitation unit in good spirits and without glaring deficits. Of note, to dedicate this flight for the patient, a number of other patients that were traveling with him to Landstuhl were not flown. Careful evaluation of each patient by CASF staff (Contingency Aeromedical Staging Facility) and on-ground flight surgeons confirmed this action would not be to anyone's detriment. These "bumped" patients were evacuated on the next flight (within 24 hours).

Case 16. The Patient with an Injured Spinal Cord

PMR Information:

Demographics:	Status	Army
	Grade	enlisted
	Age	< 30
	Gender	----
Patient Setting:	Precedence	Urgent
	Classification	2A (inpatient litter)
	CCATT	yes
	Injury Type	BI
	Space Type	litter
Administrative Data:	Originating MTF	Balad
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	General Surgery
	Primary Diagnosis	Injuries, War Operations
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“...troop involved in an IED...On arrival, somnolent, with GCS 13 (V4, M6, E3), HR 85, BP 77/28. No external bleeding, FAST negative X2. Follows commands with both hands, but no movement below waist and decreased rectal tone on exam...Mental status declined in ED and patient intubated without difficulty. BP supported with IV fluids and intermittent small boluses of neosynephrine. CT shows normal brain, linear skull fracture from mid-upper cranium down to skull base. Fractures noted at C2, T3, and T6, with modest cord impingement at T3. Also has sterno-manubrial dislocation and small sacral fracture...Evaluated by neurosurgery – no steroids indicated, log-roll precautions, support BP with dopamine...Multiple level spinal fractures in neurogenic shock. Cardiovascularly stable on pressors.”

Medications:	propofol drip	fentanyl drip
	dopamine drip	lovenox
	protonix	

Medical Data:	VS	98.5 F	100	16	140/52
	CBC	34/12			
	Oxygen Delivery	ventilator --- 40% FiO ₂			
	Vent Settings	TV = 550	Rate = 14	PEEP = 5	
	ABG	pH = 7.35	pO ₂ = 233	pCO ₂ = 23	
	Drainage	NGT, foley			
	PMI Data (equipment)	monitor	ventilator		
		suction	pump		
		pulse oximeter			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient is battle injured and requires Urgent evacuation.

Administrative Data/Clinical Data Evaluation

There is nothing significant for the flight surgeon.

Short & Sweet Patient History/Medications

The patient was injured by an IED suffering a small sacral fracture, a sterno-manubrial dislocation, a linear skull fracture from upper cranium to skull base, and fractures of C2, T6, and T3 with T3 cord impingement. The patient deteriorated requiring intubation with ventilation. Cord impingement was complicated by spinal shock.

Medical Data Evaluation

The patient's pCO₂ = 23 mmHg suggests hyperventilation. The rest of the recorded values do not generate concern for the flight surgeon.

Information Beyond the PMR

The information in the PMR is tantalizing. Spinal shock is mentioned without any details. Examining JPTA and speaking with the intensivist remedied the situation. The sterno-manubrial dislocation was unassociated with great vessel disruption or lung injury. In addition, the skull fracture penetrated the frontal sinus; blood was in both the frontal and sphenoid sinuses (air-fluid levels were seen on x-ray). Fortunately, there was no underlying cerebral parenchyma injury. However, added to the already listed vertebral injuries were fractures of C1, C2, C7, and T4. The T4 fracture sent fragments into the spinal canal encroaching on the cord. On admission, his hemoglobin was 6 g/dl with hypotension to 50s/20s. After 4U pRBC and 2U fresh frozen plasma along with multiple pressors (dopamine, neosynephrine, and levophed), his blood pressure rose to 160s/90s. Hemoglobin stabilized at 10 g/dl and ABGs moderated to pH = 7.30,

pO₂ = 193, and pCO₂ = 39. To secure the best chance for cord recovery, surgery for fragment extraction was emergently required. Urgent transport was mandatory.

Prescription:

Precedence	Urgent
Classification	2A (inpatient litter)
Medical Adjuncts	CCATT team
Medical Interventions	ventilator --- 50% FiO ₂
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	none
Positioning Interventions	spine precautions - cervical collar head first loading OWL™ litter
Aircraft Manipulations	CAR 5,000 feet long slow landing

Reasoning

Clearly, the patient requires an Urgent move to definitive spinal surgery. Being on pressors for spinal shock and a ventilator mandates a CCATT team assignment (**Appendix A: CCATT Decision Tree**). To ensure an equivalent oxygen level at altitude, an FiO₂ of 50% is prescribed (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). This still leaves a fair amount of room for increasing the FiO₂ (**Table 13 or Appendix A: CCATT CPG – ARDSNet Lung Protective Ventilator Strategy**). This is further enhanced with a CAR of 5,000 feet; however, the CAR is primarily aimed to mitigate the effects of hypobaria on the sinuses (**Table 7 or Appendix A: Trapped Air Pressure-Volume-Diameter Relationships**). Both the frontal and sphenoid sinuses (disrupted with the linear skull fracture) demonstrate air-fluid levels on x-ray. The CAR may well prevent any intracranial infiltration of expanding sinus air. Most important is to stabilize the spinal column injuries. Using an OWL™ litter along with a cervical collar and spine precautions (eg, log rolling) should prevent further injury. In addition, head first loading and a long slow landing will counter any acceleration/deceleration effects on the injured cord; this should also minimize movement of the bone fragments. *Although not prescribed, an argument could be made for prescribing no RONS, no stops.*

Outcome

Air evacuation was successful without incident.

Case 17. The Patient Dies

PMR Information:

Demographics: Status Army
 Grade enlisted
 Age < 40
 Gender ----

Patient Setting: Precedence Urgent
 Classification 2A (inpatient litter)
 CCATT yes
 Injury Type DNBI
 Space Type litter

Administrative Data: Originating MTF Baghdad
 Destination MTF Landstuhl

Clinical Data: Primary Specialty Thoracic Surgery
 Primary Diagnosis Aortic Aneurysm
 Max Stops none
 Max RONs none
 Altitude Restriction 4,000

Patient History:

“Patient presents with acute Type I aortic dissection. Aortic valve regurgitation and cardiogenic shock. Needs urgent evac to center capable of cardiopulmonary and vascular repair...Anterior lateral infarct on EKG. CT (shows) dissecting thoracic aneurysm Type A.”

Medications: unlisted

Medical Data: VS -- F 84 18 77/31
 CBC 49.4/16.5 --- 23,600
 Oxygen Delivery ventilator --- 60% FiO₂
 Vent Settings TV = 550 Rate = 18 PEEP = 5
 ABG pH = 7.15 pO₂ = 83 pCO₂ = 21 sat = 92%
 Drainage foley
 PMI Data (equipment) unlisted

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient requires Urgent evacuation with a CCATT team.

Administrative Data/Clinical Data Evaluation

The patient requires thoracic surgery to repair an aortic aneurysm.

Short & Sweet Patient History/Medications

The patient had an acutely evolving thoracic aortic aneurysm Type A (aortic arch). Accompanying this catastrophe was acute aortic regurgitation secondary to valvular encroachment. At the same time, he was evolving an anterolateral MI (seen in ~10% of cases, due to coronary artery occlusion). Cardiogenic shock was present. Further details of his treatment were not readily available because his intensivists were actively engaged at bedside. Specific medications were not forthcoming. The patient was not going to improve without surgery. Despite incomplete clinical information, he had to fly.

Medical Data Evaluation

The patient was dying. He was ventilated with an FiO_2 of 60% generating a pO_2 of 83. The pO_2/FiO_2 (aka $\text{PaO}_2/\text{FiO}_2$) ratio demonstrated a severe shunt ($83/0.60 = 138$) probably secondary to cardiogenic shock and pump failure (**Figure 28 or Appendix A: Pulmonary Shunt Ratio-Percent-Severity Depiction**).

Information Beyond the PMR

An aircraft was located, but its primary pressurization device was inoperative. Its secondary pressurization device was operative; however, should it fail (estimated operational risk was 5%), the aircraft could lose pressurization completely. Another aircraft was not readily available; therefore, this aircraft was accepted and flown to pick up the patient. Arrangements were made to move the patient, upon landing at Landstuhl, directly to a fully equipped and staffed civilian operating room.

Prescription:

Precedence	Urgent
Classification	2A (inpatient litter)
Medical Adjuncts	CCATT team
Medical Interventions	ventilator --- 100% FiO ₂ CCATT to manipulate PEEP to enhance oxygenation intensivists to run medications
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	none
Positioning Interventions	none
Aircraft Manipulations	CAR 4,000 feet long slow landing no RONS, no stops

Reasoning

The patient was dying and had to be flown; it was the only way he might survive. Although the aircraft had a defective pressurization system, it was the only aircraft available; the TVFS had to accept the flight risk. To maximize oxygenation the TVFS had to fly the patient on 100% oxygen with a CAR of 4,000 feet. The only CCATT option to improve oxygenation, at altitude, was upping the PEEP (**Table 13 or Appendix A: CCATT CPG – ARDSNet Lung Protective Ventilatory Strategy**). Even so, oxygenation was probably ineffective, what with the malfunctioning aortic valve and evolving MI and gradually closing thoracic aorta.

Outcome

The patient was successfully loaded onto the aircraft; however, four hours into the six-hour flight, the patient died. This case demonstrates that the TVFS must occasionally fly unstable patients. Without this flight, the patient had absolutely no chance of survival. The fact that he survived as long as he did preflight and inflight was a testament not only to the intensivists' skills, but also to the proper inflight configuration of the patient.

Case 18. The Patient is *not* “Fit to Fly”

PMR Information:

Demographics:	Status	Marine
	Grade	enlisted
	Age	< 30
	Gender	----
Patient Setting:	Precedence	Urgent
	Classification	2A (inpatient litter)
	CCATT	yes
	Injury Type	BI
	Space Type	litter
Administrative Data:	Originating MTF	Balad
	Destination MTF	Landstuhl
Clinical Data:	Primary Specialty	General Surgery
	Primary Diagnosis	Injuries, War Operations
	Max Stops	unrestricted
	Max RONS	unrestricted
	Altitude Restriction	none

Patient History:

“Patient suffered IED blast. On arrival GCS 15, unstable hemodynamics, moving both upper extremities. Traumatic amputation left thigh and right calf, multiple penetrating injuries to both groins and perineum. CXR normal. Pelvic x-ray multiple foreign bodies in perineum and groin. To OR: exploratory laparotomy negative, vascular control of bilateral external iliac vessels obtained. Left hip disarticulated, right through knee amputation done, devastating scrotal and penile injuries...Resuscitation ongoing and has received thus far 30U fresh whole blood, 5U pRBC, and recombinant Factor VII. Abdomen open with vessel loops...around external iliac vessels (non-occlusive). Ophthalmology --- OS appears normal other than conjunctiva and lid peppering. OD with complex central corneal laceration with macerated wound edges, vitreous and iris out of wound. Right upper lid with marginal laceration, right brow laceration. Corneal wound closed with 10-0 nylon and dry at the end of procedure...No intraocular air noted...Will need urgent referral to Ophthalmology at Landstuhl for likely follow up surgery. Urology --- careful penile and scrotal exploration, neither testicle salvageable, glans also destroyed. Penis repaired, bilateral orchiectomies performed, suprapubic tube and foley left.”

Medications:	morphine	propofol			
	cephalothin	levofloxacin			
	protonix	pred forte			
	vigamox	fentanyl			
Medical Data:	VS	100.9 F	148	19	108/65
	CBC	32/11 ---	4,000		
	Oxygen Delivery	ventilator ---	40% FiO ₂		
	Vent Settings	TV = 550	Rate = 22	PEEP = 5	
	ABG	pH = 7.37	pO ₂ = 172	pCO ₂ = 48	
	Drainage	foley, OGT, suprapubic tube & foley			
		multiple JPs & hemovacs			
		(hip, scrotum, abdomen)			
	PMI Data (equipment)	monitor	ventilator		
		pump			

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient requires an Urgent move with CCATT team due to battle injury.

Administrative Data/Clinical Data Evaluation

There is nothing significant for the flight surgeon.

Short & Sweet Patient History/Medications

The patient presented with severe injuries from an IED blast including traumatic amputations of the left thigh and right calf with serious soft tissue injuries to both groins and perineum; the right globe was lacerated with extrusion of vitreous and iris. A left hip disarticulation, right knee disarticulation, bilateral orchiectomy and penile revision followed. To stem the bleeding, an exploratory laparotomy focusing on external iliac control was performed. Intraoperative resuscitation using 30U fresh whole blood, 5U pRBCs, and multiple doses of recombinant Factor VII moderated his hemodynamic instability. Multiple drains were placed.

Medical Data Evaluation

The patient's ventilation and oxygenation appears good demonstrating no shunting. In contrast, his vital signs are not so good. The pulse is 148 with borderline blood pressure. In light of the earlier hemodynamic volatility, careful monitoring of vital signs, hemoglobin, and other parameters is indicated prior to validating for flight.

Information Beyond the PMR

Intraoperative resuscitation using 30U fresh whole blood, 5U pRBCs, and multiple doses of recombinant Factor VII moderated his hemodynamic instability. However, the instability forced early termination of operative procedures making further irrigation and debridement necessary. Vital signs and hemoglobin were closely followed.

BP	108/65	→	100/60	→	97/43	→	117/57	→	118/60	→	97/38	→	122/43	→	95/48
P	148	→	133	→	136	→	129	→	124	→	133	→	148	→	133
Hgb	10.9	→		→	10.7	→	7.7	→		→	10.9	→		→	8.2

When his hemoglobin fell to 8.2 g/dl, transfusion of 4U pRBCs, 4U fresh frozen plasma, and 6U cryoprecipitate was begun. At that point, the flight was only 1-2 hours away. Since the TVFS felt the patient unstable, he did not validate him for flight (**Table 16 or Appendix A: Classes of Hemorrhagic Shock**). Over the ensuing 6-8 hours, the patient stabilized to a BP 146/56, P 133, and Hgb 11.2 g/dl. CT scan revealed a small amount of air in the left hemipelvis and a large, deep hematoma of the left hip; this explained the patient's earlier instability. The patient was then evacuated with the following parameters.

Prescription:

Precedence	Urgent
Classification	2A (inpatient litter)
Medical Adjuncts	CCATT team
Medical Interventions	ventilator --- 50% FiO ₂
Middle Ear Interventions	none
Patient Paraphernalia	open JP & hemevac on ascent and descent
Positioning Interventions	none
Aircraft Manipulations	none

Reasoning

In today's aeromedical evacuation world, flying stable patients is no longer the norm. With the advent of CCATT teams, flying stabilized patients has become the norm. This is a major paradigm shift. Stable patients are not labile and unlikely to decompensate; unstable patients are highly labile and hovering near disaster. In contrast, stabilized patients are neither stable nor unstable; they ride that nebulous fence that is so very hard to definitively describe. This patient's blood pressure was clearly labile, at one time acceptable and at the next low. The very high pulse strongly suggested something else was happening; the dropping hemoglobin and later CT scan confirmed it to be bleeding. Flying the patient in that setting --- unstable without an etiology --- would have been unsafe. Following transfusion, the clinical picture stabilized making evacuation a much safer proposition. *Although not prescribed, an argument could be made for carrying several units of blood, a CAR, and no RONS, no stops.*

Outcome

Air evacuation was successful without incident.

Case 19. Getting the Patient Ready

PMR Information:

Demographics: Status Army
 Grade enlisted
 Age < 30
 Gender ----

Patient Setting: Precedence Priority
 Classification 2A (inpatient litter)
 CCATT yes
 Injury Type BI
 Space Type litter

Administrative Data: Originating MTF Tikrit
 Destination MTF Landstuhl

Clinical Data: Primary Specialty Orthopedic Surgery
 Primary Diagnosis Amputation Leg, Bilateral
 Max Stops unrestricted
 Max RONs unrestricted
 Altitude Restriction none

Patient History:

“Both leg injuries due to rocket-propelled grenade attack, now status post bilateral lower extremity BKA. Critically low platelet level, but pending transfusion of platelets. Need evac to Landstuhl for further care.”

Medications: cephalothin protonix

Medical Data: VS 99.7 F 120 24 113/40
 CBC unlisted
 Oxygen Delivery ventilator --- unlisted FiO₂
 Vent Settings TV = unlisted Rate = unlisted PEEP = 10
 ABG unlisted
 Drainage unlisted
 PMI Data (equipment) monitor ventilator

PMR Information Evaluation:

Patient Demographics/Setting Evaluation

The patient had a battle injury and was a Priority move requiring a CCATT team.

Administrative Data/Clinical Data Evaluation

The patient had bilateral leg amputations.

Short & Sweet Patient History/Medications

The patient suffered injuries from a rocket-propelled grenade resulting in bilateral below the knee amputations. In addition, he has some sort of critical shortage of platelets mandating transfusion. There is paltry little here to evaluate for evacuation.

Medical Data Evaluation

The patient's pulse is 120 suggesting an active, unstable situation (**Table 16 or Appendix A: Classes of Hemorrhagic Shock**) and the patient is ventilated with a PEEP of 10 cmH₂O. However, no other interpretation can be levied due to lack of information.

Information Beyond the PMR

In this case, it is imperative to go to both JPTA and the attending physician. The patient was in a Humvee that was struck by a grenade. He was evacuated via a Bradley armored personnel vehicle arriving with a GCS 15, tachycardic, class 3 hemorrhage (1500-2000 ml blood loss or 30-40% blood volume loss) (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). Chest, pelvis, and cervical spine were unmarred. "He was taken to the OR where numerous injuries were catalogued to include scrotal fragments, massive soft tissue/skin loss from the right posterior thigh and leg, right open foot fractures, left open knee, multiple fragment injuries to the upper and lower left leg, mangled left foot with near complete amputation of the leg at the level of the distal tibia." The patient underwent a series of closely spaced operations with the eventual final result being a left above the knee amputation and a right below the knee amputation. Hemorrhage was difficult to control, finally responding to right superficial femoral artery and vein suture ligation. In the meantime, the patient was transfused a total of 10U pRBCs, 1U whole blood, 4U fresh frozen plasma, and 2U cryoprecipitate. Serial medical data were as follows:

VS	99.7 F	120	24	113/40
CBC	41/14			
Oxygen Delivery	ventilator --- 60% FiO ₂			
Vent Settings	TV = 900	Rate = 18	PEEP = 5	
ABG	pH = 7.26	pO ₂ = 86	pCO ₂ = 46	sat = 100%

The patient exhibited a moderate to severe pulmonary shunt ($86/0.60 = 143$) as well as a troubling acidosis (**Figure 28 or Appendix A: Pulmonary Shunt Ratio-Percent-Severity Depiction**). Over the next several hours, he deteriorated.

VS	99.7 F	123	20	88/61
CBC	45/16			
Oxygen Delivery	ventilator ---	100% FiO ₂		
Vent Settings	TV = 900	Rate = 20	PEEP = 10	
ABG	pH = 7.20	pO ₂ = 57	pCO ₂ = 58	sat = 78%

Now, the patient can not be safely flown. He has an even more severe pulmonary shunt ($57/1.0 = 57$) despite an increased PEEP of 10 cm H₂O. Consequent to the shunt is poor hemoglobin loading (sat = 78%) and hypoxia (pO₂ = 57) resulting in tissue ischemia and acidosis (pH = 7.20). The best FiO₂ that can be achieved at 8,000 feet cabin altitude in this setting is 75%, at 5,000 feet 83%, and at 4,000 feet 86% (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). Clearly, the patient would not tolerate even a short, few hours in the air. Chest x-ray revealed ARDS (acute respiratory distress syndrome). Over the next several days, the patient improved as seen highlighted below.

H/H	38/13	32/11	26/9	26/9	28/10	31/10
Vent	APRV*	SIMV*	PCV*-assist	PCV*	PCV*	PCV*
FiO₂	100%	100%	65%	60%	60%	60%
PEEP	----	14	14	14	12	12
pH	7.26	7.45	7.49	7.46	7.44	7.45
pO₂	87	58	65	74	80	69
pCO₂	61	34	30	32	40	38
sat	93%	90%	94%	95%	95%	94%
Shunt	87	58	100	123	133	115

 *APRV = airway pressure release ventilation

*SIMV = synchronized intermittent mandatory ventilation

*PCV = pressure control ventilation

Accompanying the improved oxygenation was a gradual clearing of the chest x-ray. Although the patient was still very ill, he was “stabilized.” Unfortunately, he required PCV as opposed to the standard volume-controlled ventilation. In order to fly him, the LTV-1000 ventilator would be required. It is a portable ventilator that can deliver PCV. The TVFS, at this point, arranged a telephone meet between the CCATT intensivist and the Tikrit intensivist so that both teams would be comfortable with the move. Following that discussion, it was felt that the patient could be handled clinically in the air. It was now the flight surgeon’s job to configure the flight to safely transport the patient.

Prescription:

Precedence	Priority
Classification	2A (inpatient litter)
Medical Adjuncts	CCATT team
Medical Interventions	LTV-1000 ventilator --- 80% FiO ₂
Middle Ear Interventions	none --- CAR is useful here
Patient Paraphernalia	none
Positioning Interventions	HOB elevation to 30 degrees
Aircraft Manipulations	CAR 5,000 feet no RONS, 1 stop

Reasoning

The above narrative describes the process of taking a critically ill patient that could not safely fly and monitoring his progress to the point where evacuation could happen. He remained a Priority move because his condition did not demand movement to Landstuhl immediately. After all, he had been resting and healing over the last few days. He did require a CCATT team not only to care for him, but to also run the specialized LTV-1000 ventilator (**Appendix A: CCATT Decision Tree**). To ensure sea level equivalency, his FiO₂ was raised from 60% to 80% (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). Of course, with a CAR of 5,000 feet, sea level equivalency could be maintained with an FiO₂ of 70%. HOB elevation to 30 degrees was imposed to take advantage of gravity to improve aeration and to continue prophylactic measures for ventilator-associated pneumonia. The CAR provided more management room for the CCATT team to manipulate the FiO₂ (**Table 13 or Appendix A: CCATT CPG – ARDSNet Lung Protective Ventilator Strategy**). It also reduced the driving pressure for fluid into the injured tissues and the damaged lungs. And, lastly, the no RONS ensured rapid movement to the final destination; however, the one stop was Balad where there was an extraordinary team of intensivists. It was reasoned that any subtle clinical changes for the worse would be discovered and treated. As it turned out, this is indeed what happened.

Outcome

The patient tolerated the flight to Balad relatively well. Once there, however, he demonstrated an increased lability that prompted admission to the ICU. Over the next 36 hours, he once again stabilized. He was then loaded with the same flight parameters and flown to Landstuhl without incident.

Case 20. The Mass Casualty Event

This case will be structured different from the previous ones. A brief history of the inciting incident will be related (some specifics intentionally scrubbed). Next, will be the casualty histories as relayed to the TVFS. Notice that validation for flight and prescription for flight was performed with much less information than in earlier cases. This is the nature of a mass casualty event. It is a fluid environment that often requires thinking and decisions “outside the box.” Unusual maneuvers to bring off an outstanding response are highlighted.

History

An aircraft crashed with a number of soldiers on board. Initial reports suggested at least fifteen casualties. This was later revised to fourteen. At the same time, the TVFS wanted an estimate of criticality; nine Urgent, four Priority, and one Routine was relayed. Notably, there were no direct communications to the physicians caring for the patients. All interchange had to flow through a third party and sometimes even a fourth party.

Armed with this information, the TVFS and the Director, Joint Patient Movement Requirements Center (JPMRC), alerted the Aeromedical Evacuation Control Team (AECT --- Line of the Air Force part of the operation) to begin the search for an aircraft. Generally, this does not even begin until a clinically and administratively validated PMR is in the system. While the AECT was identifying potential aircraft, it was key for the TVFS to gather enough clinical data to validate at least one of the casualties. Without that validation, there was no mission requirement and, without that requirement, an aircraft could not be assigned the mission. The mission, aeromedical evacuation from the crash site medical facility to Landstuhl.

Casualties

What follows is the clinical report obtained third hand over a telephone charged with static. The casualty list is as it was received. As each patient vignette is read, determine whether validation can be determined with the limited information provided. Remember, no aircraft can be attached to a mission without a validated PMR.

1. Closed head injury with intraventricular bleed and subarachnoid hemorrhage. Treatment with levophed and mannitol was ongoing. The patient was on a ventilator and being hyperventilated.
2. Closed head injury on a ventilator. The patient also had an “open book” pelvic fracture. He was transfused with 2U pRBC with another 4U pRBC ready; a retroperitoneal bleed and bladder rupture were suspected.
3. Multiple extremity fractures: right humerus, ulna, tibia, fibula. Bilateral pneumothoraces were treated with bilateral chest tubes. The patient also had a ruptured spleen; he was being taken to the operating room. Not ventilated yet.
4. Vital signs stable. Emergency cricothyroidotomy unsuccessful; has left chest tube and lots of subcutaneous emphysema in the neck and upper chest. Possible abdominal bleeding, but CT scan and ultrasound negative. Had scapular fracture and burst fractures of T12 and L1.
5. Pelvic fracture with suspected bleeding (halted); CT scan showed iliac hematoma.

6. Spinal cord injury and neurogenic shock; given steroids; not on pressors, yet. L1 body fracture and L2 burst fracture; no sensation below L1 level (some return perineally). Being given 2U pRBC.
7. Multiple comminuted sacral fractures, on spine board. Also, scrotal trauma.
8. Open right and left sided mandibular fractures; right tibia and left ulna fractures; right inferior pelvis fracture. Ventilated with tracheostomy in place.
9. Right massive hemothorax with 1,500 cc drainage; autotransfused and given 10U pRBC, 9U fresh frozen plasma, 18U platelets, and recombinant Factor VII. Right femur fracture. CT abdomen negative. Multisystem failure: ARDS, ARF, rhabdomyolysis.
10. Cervical spine injury, C1 posterior ring fracture and C2 body fracture. Complex fractures of L1-L3.
11. Closed head injury. Shoulder injury...ambulatory (?). Open bilateral tibia/fibula fractures externally fixated in the OR. Pelvic fracture with bleeding. Already given 3U pRBC.
12. Right scapular fracture and two right lower extremity injuries.
13. L2-L3 burst fractures.
14. Isolated right wrist injury.

Validating Flight Surgeon Casualty Evaluation

	<u>Tentative Precedence</u>	<u>Ventilator</u>	<u>OWL™ litter</u>	<u>CAR</u>	<u>CCATT</u>	<u>Validate</u>
1.	Urgent	yes	no	maybe	yes	no
2.	Urgent	yes	yes	maybe	yes	no
3.	Urgent	maybe	no	yes	yes	no (?)
4.	Urgent	no	yes	yes	maybe	no
5.	Priority	no	yes	no	no	no
6.	Urgent	no	yes	yes	yes	no
7.	Urgent	no	yes	no	no	yes
8.	Urgent	yes	maybe	maybe	yes	no (?)
9.	Urgent	yes	no	maybe	yes	no
10.	Priority	no	yes	no	no	yes
11.	Urgent	no	yes	maybe	no	no
12.	Priority	no	no	no	no	yes
13.	Priority	no	yes	no	no	no
14.	Routine	no	no	no	no	yes

Patient #7 and Patient #10 had no history suggesting instability or need for further information to better configure for flight. Thus, Patient #7 and Patient #10 can be validated with this information and the aircraft can be tasked. With six tentative CCATT patients and possibly four or five ventilators, it was felt that two CCATT teams would be needed. Innovatively, one was tasked from the AE aircraft's site of origin and the other was flown to the patients from another location. The two teams would join when picking up the patients. Simultaneously, it was recognized that 8-9 OWL™ litters were required. The numerous very serious spine injuries and pelvic fractures mandated these litters. Unfortunately, the normal litter, during flight or vehicle transfers, can have excursions ranging from 4-6 inches; further tissue damage might occur with such excursions. In contrast, OWL™ litters are not only more rigid, but also floor-loaded

protecting spine and pelvic injuries from unwanted flexion motion (**Appendix A: Litter Comparison**). Flying this many OWL™ litters was another unique feature of this flight. While marshalling all these resources, word of shrinking blood supplies came. Weather had delayed the usual shipment. Rapid coordination with the theater blood transshipment program made a full re-supply as well as extra blood products available for the flight to Landstuhl. This intricate movement was another unique aspect of the mission. In fact, it set the stage for future blood product moves on AE flights.

Additional Casualty Information with Flight Surgeon's Final Prescription

1. Closed head injury with intraventricular bleed and subarachnoid hemorrhage. Treatment with levophed and mannitol was ongoing. The patient was on a ventilator and being hyperventilated. **Isolated head injury; no surgery. Hgb = 13; FiO₂ = 45%, PEEP = 5, pH = 7.19, pO₂ = 31, pCO₂ = 54 (venous ABG).**

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>CCATT team</i>
Medical Interventions	<i>ventilator --- at least 50% FiO₂</i>
Middle Ear Interventions	<i>none</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>head first loading</i> <i>HOB elevation to 30 degrees</i>
Aircraft Manipulations	<i>none</i>

***** Although not prescribed, an argument could be made for 60% FiO₂, imposing a CAR, a long slow landing, and no RONS, no stops.*

2. Closed head injury on a ventilator. The patient also had an "open book" pelvic fracture. He was transfused with 2U pRBC with another 4U pRBC ready; a retroperitoneal bleed and bladder rupture were suspected. **In shock; laparotomy revealed large retroperitoneal and pelvic hematoma; unstable pelvis externally fixated; abdomen packed open; >8U pRBC and 6U FFP. Hgb = 7.1; FiO₂ = 30%, pH = 7.17, pO₂ = 137, pCO₂ = 43.**

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>CCATT team</i>
Medical Interventions	<i>ventilator --- at least 50% FiO₂</i> <i>transfuse 1-2U pRBC</i>
Middle Ear Interventions	<i>none --- CAR is useful here</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>head first loading</i> <i>OWL™ litter</i>
Aircraft Manipulations	<i>CAR 5,000 feet</i>

***** Although not prescribed, an argument could be made for a 40% FiO₂, a long slow landing, and no RONS, no stops.*

3. Multiple extremity fractures: right humerus, ulna, tibia, fibula. Bilateral pneumothoraces were treated with bilateral chest tubes. The patient also had a ruptured spleen; he was being taken to the operating room. Not ventilated yet. **Only a left pneumothorax. Hgb = 15. Returned from the OR on a ventilator.**

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>CCATT team (postop on ventilator)</i>
Medical Interventions	<i>ventilator --- at least 50% FiO₂</i>
Middle Ear Interventions	<i>none --- CAR is useful here</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>none</i>
Aircraft Manipulations	<i>CAR 5,000 feet</i>

***** Although not prescribed, an argument could be made for Priority precedence, serial hematocrit/hemoglobin levels during flight, chest tube to suction, and no RONS, no stops.*

4. Vital signs stable. Emergency cricothyroidotomy unsuccessful; has left chest tube and lots of subcutaneous emphysema in the neck and upper chest. Possible abdominal bleeding, but CT scan and ultrasound negative. Had scapular fracture and burst fractures of T12 and L1. **Left hemo/pneumothorax; right scapular fracture. Hgb = 13; sat = 101%.**

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>none</i>
Medical Interventions	<i>6L nasal cannula</i>
Middle Ear Interventions	<i>none --- CAR is useful here</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>OWL™ litter</i>
Aircraft Manipulations	<i>CAR 5,000 feet</i>

***** Although not prescribed, an argument could be made for a CCATT team, chest tube to suction, spine precautions, head first loading, long slow landing, and no RONS, no stops.*

5. Pelvic fracture with suspected bleeding (halted); CT scan showed iliac hematoma. **Bilateral acetabular fractures, left pubic ramus fracture; pelvis stable; positive tenderness at L5 spinous process; CT scan revealed no spinal cord or abdominal injury, but did show large abdominal wall hematoma. Hgb = 10.9; pH = 7.36, sat = 100%.**

Precedence	<i>Priority</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>none</i>
Medical Interventions	<i>6L nasal cannula</i>
Middle Ear Interventions	<i>none</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>OWL™ litter</i>
Aircraft Manipulations	<i>none</i>

**** *Although not prescribed, an argument could be made for serial hematocrit/hemoglobin levels during flight, spine precautions, head first loading, long slow landing, and no RONS, no stops.*

6. Spinal cord injury and neurogenic shock; given steroids; not on pressors, yet. L1 body fracture and L2 burst fracture; no sensation below L1 level (some return perineally). Being given 2U pRBC. **C4-C5 fractures with left vertebral artery compression; possible C6-C7 fractures; T1-T3 fractures without spinal cord compression; L1 fracture; L2 fracture with spinal cord compression; bilateral small hemothoraces; patient does not have chest tubes; patient does have cervical collar. Hct = 23%. Patient placed on ventilator sometime between validation and loading onto the aircraft.**

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>CCATT team</i>
Medical Interventions	<i>8-10L non-rebreather transfuse 1-2U pRBC</i>
Middle Ear Interventions	<i>none --- CAR is useful here</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>spine precautions OWL™ litter</i>
Aircraft Manipulations	<i>none</i>

**** *Although not prescribed, an argument could be made for bilateral chest tube insertion, a CAR, head first loading, long slow landing, and no RONS, no stops.*

7. Multiple comminuted sacral fractures, on spine board. Also, scrotal trauma.
Lumbosacral ecchymosis; CT scan abdomen and pelvis showed right sacral fracture, no bladder extravasation. Hgb = 12.3; CK > 5000; K = 3.1, BUN = 6.7; sat = 100% on room air. On cardiac monitor.

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>cardiac monitor</i>
	<i>CCATT team --- for monitor watch</i>
Medical Interventions	<i>2-4L nasal cannula</i>
Middle Ear Interventions	<i>none</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>OWL™ litter</i>
Aircraft Manipulations	<i>none</i>

**** *Although not prescribed, an argument could be made for spine precautions, head first loading, long slow landing, and no RONS, no stops.*

8. Open right and left sided mandibular fractures; right tibia and left ulna fractures; right inferior pelvis fracture. Ventilated with tracheostomy in place. **Unstable mandibular fracture, operative fixation; right radius and left ulna splinted; right tibia/fibula fractures splinted; right pubic rami fractures stable; patient returned to OR for further mandibular/tracheostomy revision, jaw was not wired shut.**

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>ALRT team --- monitoring</i>
Medical Interventions	<i>7-8L tracheostomy mask</i>
Middle Ear Interventions	<i>none</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>HOB elevation to 30 degrees</i>
	<i>OWL™ litter</i>
Aircraft Manipulations	<i>no RONS, no stops</i>
	<i>air refueling as needed</i>

**** *Although not prescribed, an argument could be made for head first loading and long slow landing.*

9. Right massive hemothorax with 1,500 cc drainage; autotransfused and given 10U pRBC, 9U fresh frozen plasma, 18U platelets, and recombinant Factor VII. Right femur fracture. CT abdomen negative. Multisystem failure: ARDS, ARF, rhabdomyolysis. **Femur with external fixator; pulmonary edema. Hgb = 12; FiO₂ = 90%, PEEP = 15, pH = 7.46, pO₂ = 125, pCO₂ = 38.7, sat = 99%; BUN and Creatinine rising; CK too high to register.**

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>ALRT team</i>
Medical Interventions	<i>FiO₂ per ALRT team</i>
	<i>LTV-1000 ventilator available</i>
	<i>VDR-4 ventilator available</i>
	<i>Nova Lung waived</i>
Middle Ear Interventions	<i>none --- CAR is useful here</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>none</i>
Aircraft Manipulations	<i>CAR 5,000 feet</i>
	<i>no RONS, no stops</i>
	<i>air refueling as needed</i>

***** Although not prescribed, an argument could be made for chest tube suction, head first loading, and long slow landing.*

10. Cervical spine injury, C1 posterior ring fracture and C2 body fracture. Complex fractures of L1-L3. **CT scan shows C1-C2 fractures, C3-C4 fractures with anterior dislocation, L1-L3 compression fractures.**

Precedence	<i>Priority</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>CCATT team</i>
Medical Interventions	<i>4L nasal cannula</i>
Middle Ear Interventions	<i>none</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>spine precautions</i>
	<i>OWL™ litter</i>
Aircraft Manipulations	<i>none</i>

***** Although not prescribed, an argument could be made for head first loading, long slow landing, and no RONS, no stops.*

11. Closed head injury. Shoulder injury...ambulatory (?). Open bilateral tibia/fibula fractures externally fixated in the OR. Pelvic fracture with bleeding. Already given 3U pRBC. **Bilateral tibia/fibula fractures with external fixators; pelvic fracture with widened pubic symphysis; confusion prompted CT head that revealed small ventricles, loss of sulci; given mannitol. Hgb = 11.**

Precedence	<i>Urgent</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>none</i>
Medical Interventions	<i>4L nasal cannula --- maintain sat $\geq$ 97%</i>
Middle Ear Interventions	<i>none</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>head first loading</i> <i>HOB elevation to 30 degrees</i> <i>OWL™ litter</i>
Aircraft Manipulations	<i>none</i>

**** *Although not prescribed, an argument could be made for a CCATT team, CAR, and no RONS, no stops.*

12. Right scapular fracture and two right lower extremity injuries. **Hgb = 11; sat = 100% on 4L nasal cannula.**

Precedence	<i>Priority</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>none</i>
Medical Interventions	<i>4L nasal cannula</i>
Middle Ear Interventions	<i>none</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>none</i>
Aircraft Manipulations	<i>none</i>

**** *Although not prescribed, an argument could be made for a delayed, less emergent aeromedical evacuation.*

13. L2-L3 burst fractures. **CT scan showed L2-L3 burst fractures; neurovascularly intact. Hgb = 12.**

Precedence	<i>Priority</i>
Classification	<i>2A (inpatient litter)</i>
Medical Adjuncts	<i>none</i>
Medical Interventions	<i>4L nasal cannula</i>
Middle Ear Interventions	<i>none</i>
Patient Paraphernalia	<i>none</i>
Positioning Interventions	<i>OWL™ litter</i>
Aircraft Manipulations	<i>none</i>

**** *Although not prescribed, an argument could be made for an Urgent precedence, head first loading, long slow landing, and no RONS, no stops.*

14. Isolated right wrist injury. **Patient did not require aeromedical evacuation.**

Final Discussion

The aeromedical evacuation aircraft arrived with an augmented aircrew and a standard AE medical crew, the CCATT teams married up, and the blood was divided and distributed. After a little over three hours on the ground, seven Urgent and four Priority patients lifted off for Landstuhl. The two CCATT teams cared for six patients; four were on ventilators. Careful review of the above prescriptions (excluding Patients #8 and #9) reveal only three ventilator patients. Patient #6 was placed on a ventilator sometime from the point of validation to loading. Review of the very limited history, neurogenic shock, should have alerted the TVFS to that likelihood; he could have then strongly suggested ventilating the patient for flight. Of note, the TVFS would usually be appraised of a change in patient status; he would then re-evaluate the patient for flight. However, as often happens in such highly charged environments as a mass casualty event, there is a “fog” that occasionally obscures some details. In this instance, extra capability was brought to the scene making this oversight of little consequence. Indeed, extra capability should always be sought in settings like this, particularly when communications can be such a challenge. The following table demonstrates how the early picture can differ from the later picture.

Comparison of Tentative and Final Validation Status										
Patient	Precedence		Ventilator		OWL™ Litter		CAR		CCATT	
	Tentative	Final	Tentative	Final	Tentative	Final	Tentative	Final	Tentative	Final
1	Urgent	Urgent	yes	yes	no	no	maybe	no	yes	yes
2	Urgent	Urgent	yes	yes	yes	yes	maybe	yes	yes	yes
3	Urgent	Urgent	maybe	yes	no	no	yes	yes	yes	yes
4	Urgent	Urgent	no	no	yes	yes	yes	yes	maybe	no
5	Priority	Priority	no	no	yes	yes	no	no	no	no
6	Urgent	Urgent	no	yes	yes	yes	yes	no	yes	yes
7	Urgent	Urgent	no	no	yes	yes	no	no	no	yes
8	Urgent	Urgent	yes	yes	maybe	yes	maybe	no	yes	ALRT
9	Urgent	Urgent	yes	yes	no	no	maybe	yes	yes	ALRT
10	Priority	Priority	no	no	yes	yes	no	no	no	yes
11	Urgent	Urgent	no	no	yes	yes	maybe	no	no	no
12	Priority	Priority	no	no	no	no	no	no	no	no
13	Priority	Priority	no	no	yes	yes	no	no	no	no
14	Routine	Routine	no	no	no	no	no	no	no	no

Turning now to Patients #8 and #9. Patient #9 was in florid ARDS --- probably from a combination of his massive right-sided hemothorax and fat emboli from his femoral fracture. He was in no condition for flight with an $\text{FiO}_2 = 90\%$ and $\text{pO}_2 = 125$. Even imposing a CAR of 4,000 feet and using 100% oxygen, the FiO_2 (sea level equivalent), at best, would only be around 85% (**Table 14 or Appendix A: Table for Determining Sea Level Oxygen Equivalency at Altitude**). That coupled with the PEEP of 15 cm H_2O left no real tools to enhance oxygenation should the patient deteriorate (**Table 13 or Appendix A: CCATT CPG – ARDSNet Lung Protective Ventilator Strategy**). It was decided that the Acute Lung Rescue Team (**ALRT team**) was needed. After physicians caring for the patient had consulted with the ALRT team physicians, it was decided that the patient required specialized ventilators (e.g., LTV-1000, VDR-4) or, in the worst case scenario, a membrane oxygenator (e.g., ECMO (extracorporeal membrane oxygenation), as used by pediatric intensivists). Arrangements were made to fly the ALRT team from Landstuhl to the patient with the necessary devices. In fact, the ALRT team arrived early the next morning. After several hours of work with the various devices, the patient was stabilized for transport, was loaded on the aircraft, and successfully made the flight to Landstuhl. Patient #8 had just returned from surgical revision of his jaw injuries while the

earlier aircraft was being loaded. He was not really ready for flight. However, since the ALRT team was coming to prepare and fly with Patient #9, it was decided to attach Patient #8 to that flight. Both traveled to Landstuhl successfully. The following diagram depicts the various flights involved in this mission.



Lessons beyond the validation process to be learned here include:

- 1) expect poor communications during any mass casualty event,*
- 2) expect “fog” during any mass casualty event,*
- 3) add excess capability to counter any “fog,” and*
- 4) be flexible --- it is a fluid environment that often demands “fluid” thinking (e.g., the how of gathering together 8-9 OWL™ litters, AE as blood re-supply, marrying geographically separated CCATT teams at the patient site).*

Conclusion

Having studied the text of this monograph and carefully reviewed these selected case studies, the Flight Surgeon should now be ready to begin validating patients for aeromedical evacuation. If possible, as with any discipline in medicine, the novice should spend time with an experienced Flight Surgeon, even better a Theater Validating Flight Surgeon. In other words, he/she should spend time with a preceptor. This is familiar to all physicians; internship and residency are merely extended preceptorships. In this way, text is reinforced with simulations (case studies) and simulations are reinforced with “coached” real life. In the end, an expert Theater Validating Flight Surgeon will be created.

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

~	approximately
ABG	arterial blood gases
ACS	abdominal compartment syndrome
AE	aeromedical evacuation
AECT	Aeromedical Evacuation Control Team
AIREVAC	aeromedical evacuation (fixed wing)
ALRT	Acute Lung Rescue Team
APRV	airway pressure release ventilation
ARDS	Acute Respiratory Distress Syndrome
ARF	acute renal failure
BI	Battle Injury
BJA	below the knee amputation
BP	blood pressure
BUN	blood urea nitrogen
C	Celsius/Centigrade or cervical vertebra (depends on context)
Cath	catheterization (e.g., Cath Team)
CCAT	Critical Care Air Transport
CCATT	Critical Care Air Transport Team
CAR	cabin altitude restriction
CASEVAC	casualty evacuation (no medical assets)
CASF	Contingency Aeromedical Staging Facility
CBC	complete blood count
CENTCOM	United States Central Command
C₃F₈	perfluoropropane
CK	creatinine kinase
cm	centimeter
cmH₂O	centimeters water pressure
CO₂	carbon dioxide
CPG	Clinical Practice Guideline
Creat	creatinine
CSF	cerebral spinal fluid
CT	computed tomography

CVA	costovertebral angle
CXR	chest x-ray
dB	decibel
DCS	decompression sickness
dl	deciliter
DNBI	Disease, Non-Battle Injury
DO₂	tissue oxygen delivery
DO_{2crit}	critical DO ₂ (tissue oxygen delivery)
ECMO	extracorporeal member oxygenation
ED	Emergency Department
EKG	electrocardiogram
ENT	Ears, Nose, Throat (Otolaryngologic)
EOM	extraocular muscle (movement)
Eos	eosinophils
ESR	erythrocyte sedimentation rate
ET	endotracheal tube
F	Fahrenheit
FAST	focused assessment with sonography for trauma
FiO₂	oxygen fraction of inspired air
FL350	Flight Level 350 (aka 35,000 feet)
Fr	French (gauge measurement)
FS	flight surgeon
ft	feet
g	gram
g/dl	grams per deciliter
G_x	longitudinal axis
G_y	lateral axis
G_z	vertical axis
G	gravity (e.g., G-induced loss of consciousness)
G6PD	glucose-6-phosphate dehydrogenase
GCS	Glasgow Coma Scale
GCS-3T	Glasgow Coma Scale (patient intubated)
GCS (V,M,T)	Glasgow Coma Scale (Verbal Response, Motor Response, Eye Opening)

GI	gastrointestinal
GSW	gunshot wound
H₂O	water
hgb	hemoglobin level
HOB	head of bed
HR	heart rate
Hyper	hyperthermia
Hypo	hypothermia
Hz	cycles per second (Hertz)
I & D	incision and debridement or drainage (depends on context)
IAH	intra-abdominal hypertension
ICP	intracranial pressure
ICU	intensive care unit
IED	improvised explosive device
IOP	intraocular pressure
ISR	Institute of Surgical Research
IV	intravenous
JPMRC	Joint Patient Movement Requirements Center
JPTA	Joint Patient Tracking Application (electronic health record; no longer exists)
JPTM	Jackson-Pratt drain
J_v	driving force for fluid movement
K	potassium
K_f	capillary permeability factor
kg	kilogram
KUB	kidney, ureter, bladder flatplate x-ray
L	left or liter or lumbar vertebra (depends on context)
lb	pound
LE	lower extremity
LFT	liver function test
LOC	level or loss of consciousness (depends on context)
LTV-1000	specialized type of ventilator
Lymphs	lymphocytes
m	meter

m/sec	meters per second
max	maximum
MEDEVAC	medical evacuation (rotary wing)
MI	myocardial infarction
min	minute
ml	milliliter
ml O₂/min/kg	milliliters oxygen per minute per kilogram
mmHg	millimeter of mercury pressure
Monos	monocytes
mph	miles per hour
MTF	Medical Treatment Facility
NA	not applicable
NATO	North Atlantic Treaty Organization
NGT	nasogastric tube
O₂	oxygen
OD	right eye (Latin: <i>oculus dexter</i>)
OGT	orogastric tube
OR	Operating Room
OS	left eye (Latin: <i>oculus sinister</i>)
OSL™	Oversize Litter
OWL™	Overweight Litter
P	pulse rate
PaCO₂	arterial carbon dioxide partial pressure
PaO₂	arterial oxygen partial pressure
PaO₂/FiO₂	pulmonary shunt ratio (arterial blood gas based)
P_B	ambient barometric pressure
P_c	capillary hydrostatic pressure
pCO₂	arterial carbon dioxide partial pressure
PCT	prospective controlled trial
PCV	pressure control ventilation
PEEP	positive end-expiratory pressure
pH	potential of hydrogen (acid level in blood; normal = 7.4)
PID	pelvic inflammatory disease

PMI	patient movement items (equipment and supplies)
PMR	Patient Movement Request
pO₂	arterial oxygen partial pressure
ppH₂O	partial pressure water vapor
pRBC	packed red blood cells (component transfusion)
PRCT	prospective randomized controlled trial
psi	pounds per square inch pressure
psych	psychiatry (psychiatric)
P_T	interstitial tissue hydrostatic pressure
PT	physical training
Q	Q segment of electrocardiogram
R	right
RBC	red blood cell
RLE	right lower extremity
RLQ	right lower quadrant
ROC	rule out communicable (disease)
RON	remain overnight
RPV	remotely piloted vehicle
RR	respiratory rate
SaO₂	arterial hemoglobin oxygen saturation (%)
sat	oxygen saturation of hemoglobin
SDH	subdural hematoma
sec	second
Segs	segmented (leukocytes)
SIMV	synchronized intermittent mandatory ventilation
SpO₂	pulse oximetry measured hemoglobin oxygen saturation (%)
SpO₂/FiO₂	pulmonary shunt ratio (pulse oximetry based)
ST	ST segment of electrocardiogram
STEMI	ST segment elevation myocardial infarction
T	thoracic vertebra
TBI	traumatic brain injury
TBI_{mod-sev}	moderate-to-severe traumatic brain injury
TNTC	too numerous to count

TPMRC	Theater Patient Movement Requirements Center
TRAC²ES	TRANSCOM Regulating and Command and Control Evacuation System
TRANSCOM	Transportation Command
TV	Tidal Volume
TVFS	Theater Validating Flight Surgeon
TVFS-E	Theater Validating Flight Surgeon – Europe
U	unit (e.g., blood component)
VAP	ventilator-associated pneumonia
VDR-4	specialized type of ventilator
Vent	ventilator
VS	vital signs
w/	with
WBC	white blood cell
π	pi (numerical constant = 3.14)
π_C	capillary osmotic pressure
π_T	interstitial tissue osmotic pressure