

Mechanical Ventilation in Hypobaric Atmosphere – Aeromedical Transport of Critically Ill Patients

Major Dr. Hernández Abadía de Barbará A.

Sector Literatos 42 4º C. Tres Cantos
28760 Madrid
SPAIN

ahabadia@inicia.es

LtCol. Dr. Gil Heras A.

Hospital Central de la Defensa. Servicio de Medicina Intensiva
Glorieta del Ejército s/n.
28047 Madrid
SPAIN

Major Dr. López López JA.

Aviation and Space Medicine Specialist
Centro de Instrucción de Medicina Aeroespacial (CIMA)
Arturo Soria 82
28027 Madrid
SPAIN

LtCol. Dr. Ríos Tejada F.

Aviation and Space Medicine Specialist
Centro de Instrucción de Medicina Aeroespacial (CIMA)
Arturo Soria 82
28027 Madrid
SPAIN

INTRODUCTION

Mechanical ventilation is used in the most of the aeroevacuations of critically ill patients. Patients and mechanical ventilators suffer from variations in the environmental Pressure, Partial Pressure of Oxygen, Humidity, Luminosity, Accelerations and Vibrations. We must describe briefly the history of Mechanical Ventilation and aeromedical transport:

Vesalius was the first author on describe one method of ventilation with positive pressure; 400 years later was applied for first time to a patient. Robert Hook in 1667 applied continuous flow ventilation to a dog. Woillez in 1876 made the first mechanical ventilator with negative pressure over the thorax, but the first “iron lung” was built in 1928 by Drinker and Shaw and after modified by Kroghs and Emerson. In 1955 the poliomyelitis epidemic was the main factor for the great success of the mechanical ventilation, with the device of the “Emerson Company” (Boston, Massachusetts) applying Mechanical Ventilation with positive pressure for the respiratory treatment of the patients affected by poliomyelitis. It could be the beginning of Mechanical Ventilation and possibly the Critical Care also.

The first aeromedical evacuation described was done in Paris in 1870 with aerostats, but the source never has been trusted. During the First World War the French Army carried out some aeroevacuations and also the US Army Air Service during the twenties. The first Military Flight Ambulance Unit was organized by Major Epanlard in the French campaign of the Riff. The German Army was pioneering on long distance aeroevacuations in the Spanish civil war, using JU-52 aircrafts rising altitudes of 18000 feet. During the

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Second World War some aeromedical units were very famous like the 38th Medical Air Squadron from the US Army. Korea and Vietnam were the big success for the Rotatory Wing Aeroevacuations.

The Doctrine show us that the Rotatory Wing must be used for aeroevacuations shorter than 300 kilometres, and the Fixed Wing aircrafts for the bigger ones. One critical difference is that the planes usually can pressurize their cabins and the helicopters not. The planes can rise higher altitudes, for this reason the inner pressure has to be under control and also the temperature.

The factors that can damage the patients and also the devices in aeromedical transport are:

- Pressure.
- Temperature.
- Accelerations.
- Vibrations.
- Humidity.
- Luminosity.

Our study was focused on the effects of the changes on the **environmental pressure** over the system: **Oxygen Tank + Mechanical Ventilator + Patient**.

The **Advanced Life Support** (Cardiac or Trauma) have been improved for the use of aircrafts (fixed or rotatory), the response-time has been decreased and the success of the EMT systems is bigger also. But the Technology has its own price, and new devices inside different scenarios implies new factors to control. In the aeromedical transport the pressure changes in the environment has to be one variable to study, specially when the mechanical ventilation is applied. Primary or secondary aeroevacuations can need mechanical ventilation on flight. Secondary aeroevacuations of patients with Adult Distress Respiratory Syndrome are happening every day with one bigger frequency. The decrease that the Partial Pressure of oxygen suffers with the decrease of the pressure in one environment, is another factor to study about the mechanical ventilation applied to aeromedical evacuation.

In **1969 Robert Kirby** et al, from the USAF studied the use of the Mechanical Ventilator Bird Mark VIII on altitude from 8000 to 34.000 feet. This mechanical ventilator cycled under airway pressure. Nowadays the Mechanical Ventilators cycle by the Tidal Volume or specifically by flow and time.

The **Boyle-Mariotte law** show us that the volume of one gas with constant temperature, is inversely proportional to the pressure that this gas receive. The decrease of pressure inside the cabin of the aircrafts, involves the increase in the volume of the gases inside. The effects of this phenomenon over the medical gases on mechanical ventilation produces changes in the mechanical devices and also can produce physiopathological consequences to the patients that suffer aeromedical evacuations with mechanical ventilation.

The basic **parameters of mechanical ventilation** are: Respiratory frequency (FR), Tidal volume (Vt), Minute Volume (Vm), Inspiration Fraction of Oxygen (FiO₂), Positive Expiratory End Pressure (PEEP) and all of them changes if the environmental pressure does.

Resistance of the Airway and the difference **Compliances** (Dynamic, Static and Specific) play a main role in the control of the mechanical ventilation during aeromedical transport.

The increase of the alveolar pressure can produce lung injuries. The **Ventilation Induced Lung Injury (VILI)** is a great risk on mechanical ventilation applied during Aeromedical Evacuations. The Barotrauma, the Volutrauma and their consequence the Biotrauma, can be produced for the effects of the

changes of the pressure in the environment during aeromedical evacuations of patients receiving mechanical ventilation.

ALTITUD meters	ALTITUD feet	PRESSURE mm Hg	PRESSURE pounds per square inc	TEMPERATURE Celsius degrees	TEMPERATURE Fahrenheit degress
0	0	760	14.7	15	59
400	1.312	725	14	12.4	54.4
600	1.968	707	13.7	11.1	52
800	2.625	691	13.4	9.8	49.6
1.000	3.281	674	13	8.5	47.3
1.500	4.921	634	12.3	5.3	41.5
2.000	6.562	596	11.5	2	35.5
2.500	8.202	560	10.8	-1.2	29.7
3.000	9.842	526	10.2	-4.5	23.9
3.500	11.483	493	9.5	-7.7	18.1
4.000	14.764	462	8.9	-11	12.2
4.500	16.404	433	8.4	-14.2	6.4
5.000	18.044	405	7.8	-17.5	0.5
5.500	19.865	379	7.3	-20.7	-5.3
6.000	21.325	354	6.8	-24	-11.2
6.500	22.966	331	6.4	-27.2	-16.9
7.000	24.606	308	6	-30.5	-22.9
7.500	26.246	287	5.6	-33.7	-28.6
8.000	32.808	267	5.2	-36.9	-34.5
10.000	39.370	199	3.8	-49.9	-57.8
12.000	45.931	146	2.8	-56.5	-69.7
14.000	52.493	106	2	-56.5	-69.7
16.000	59.054	78	1.5	-56.5	-69.7
18.000	65.616	57	1.1	-56.5	-69.7
20.000	82.020	41	0.8	-56.5	-69.7
25.000	98.424	19	0.37	-51.6	-60.9
30.000		9	0.17	-46.6	-51.9

* **Table 1:** Relationship among environmental pressure, temperature and altitude.

Altitud (feet)	Plane	Altitud (feet)	Cabin	Differential Pressure (PSI)*	Altitud (feet)	Plane	Altitud (feet)	Cabin	Pressure Different. (PSI)*
S.L. **		-250		0.13	16.000		6.400		3.64
1.000		70		0.48	17.000		7.150		3.64
2.000		390		0.82	18.000		7.850		3.64
3.000		710		1.15	19.000		8.550		3.64
4.000		1.030		1.46	20.000		9.300		3.64
5.000		1 350		1.75	21.000		10.000		3.64
6.000		1 670		2.05	22.000		10.650		3.64
7.000		1 990		2.33	23.000		11.350		3.64
8.000		2 300		2.6	24.000		12.000		3.64
9.000		2 620		3.09	25.000		12.700		3.64
10.000		2 940		3.3	26.000		13.350		3.64
11.000		3 280		3.5	27.000		14.000		3.64
12.000		3 670		3.64	28.000		14.650		3.64
13.000		4 300		3.64	29.000		15.250		3.64
14.000		4 900		3.64	30.000		15.900		3.64
15.000		5 650		3.64					

* **Table 2:** Relationship between the outer altitude of the aircraft with the inner altitude (equivalent pressure), and the differential pressure between them on flight.

Study objective:

We tested the changes that decreased environmental pressure produced in a mechanical ventilator and also in the individuals that were connected to this device receiving mechanical ventilation, with the main task being to evaluate the changes in Tidal Volume. Our Hypothesis was that one system with oxygen tank + mechanical ventilator (flow time cycled in Assisted/Controlled modality) + patient, can be seriously damage for the increase in the gases volumes (specially the Tidal Volume), due to the decrease in the pressure of the environment, and this phenomenon happens inside the cabin of the aircrafts during the aeromedical transport of critically ill patients with mechanical ventilation.

Material and Methods:

We applied Invasive Mechanical Ventilation (endotracheal tube) in Assisted/Controlled modality with a transport mechanical ventilator (Dräger Oxylog 2000), with a Fraction Inspiration (FiO₂) of Oxygen of 100%, Respiratory Frequency of 12-16 breaths per minute and Positive End Expiratory Pressure of 5-6 centimetres of water to 10 beagle dogs with weights from 8-17 kilograms under intravenous sedation. The animals with the mechanical ventilator and the oxygen tank were introduced into the Hypobaric Chamber for Physiological Studies of the Spanish Unit of Aviation and Space Medicine of the Air Force. The pressure conditions of a profile of High Altitude Flight (from 2000 to 35000 feet) were applied inside the chamber.

The dogs were ventilated for 45 minutes before the experimental flight and along the whole test. Parameters from the mechanical ventilator were measured and also vital signs (monitoring) from the animals. The controls of the Tidal Volume were measured at 14 altitudes in the climbing phase and 6 in the descent phase. All the measures were taken one minute after to arise the altitudes and to stabilize the pressures. The Tidal Volume was measured three times every altitude (equivalent atmospheric pressure).

Results:

The Tidal Volume was always bigger with the decrease in the environmental pressure and even in the descent phase, we found bigger Tidal Volumes than in the same altitudes in the climbing phase. The increase of the Tidal Volume with the decreasing atmospheric pressure was checked statistically with a bilateral significance of $P < 0,01$ applying one Pearson Test. But the increases on the Tidal Volumes were not as big as expected by the Boyle-Mariotte law.

DOG/DATE	Kg	FLOW	Vm	ALT.(m)	V.T1	V.T2	V.T3	V.T M. RF	CF	
1A/31298	8,5	9,4	2,6	680	270	270	270	270	27	54
2A/181298	8,5	9,5	2,6	680	150	150	150	150	35	70
3A/50199	14	9,1	2,4	680	150	150	150	150	38	90
4A/80199	10	10,6	2,6	680	180	180	180	180	28	93
5A/2802299	16	10,7	3,1	680	230	230	230	230	37	84
6A/90499	12	13,3	4,1	680	250	250	250	250	30,2	54
7A/120499	11,5	11,6	3,2	680	195	195	195	195	26	100
8A/251199	12	12,8	5,4	680	250	250	250	250	20	68
9A/201299	16	9,5	4,5	680	190	190	190	190	28	101
10A/221299	17	10,4	5,1	680	210	210	210	210	28	63

DOG/DATE	Sp O2	Paw(Peak)	PEEP	Pmed	Tinsp.	Perim.	P.Atm.	V.Theo.	Complian.	Res.
1A/31298	98	22,8	6	9,8	1,98	48,3	701	270	20,7692	0,0481
2A/181298	99	17,8	6	9,5	1,116	47,5	701	150	18,0722	0,0553
3A/50199	98	17,5	6,2	9,8	1,34	57,7	701	150	19,4805	0,0513
4A/80199	94	19	6,1	9,6	1,15	51,3	701	180	19,1489	0,0522
5A/2802299	99	20,5	6,2	9,5	1,31	60,8	701	230	20,9090	0,0478
6A/90499	98	22,3	6	10	1,01	54,5	701	250	20,3252	0,0492
7A/120499	98	19,8	6	9,6	1,01	56	701	195	19,1176	0,0523
8A/251199	96	22,7	5,1	9,6	1	53	701	250	19,0839	0,0524
9A/201299	99	19	5,1	9	1	56	701	190	19	0,0526
10A/221299	95	21,1	5	9,3	1	54,5	701	210	17,7966	0,0561

* **Table 3:** Results of the different parameters measured at the beginning of the flight (first altitude) of the 10 dogs. These data were measured in twenty different altitudes.

Conclusions:

The Tidal Volume increases or decreases with changes in the environmental pressure when the mechanical ventilation is used. This is very important in the transport of critically ill patients. These changes can produce damages to patients that are under mechanical ventilation during aeromedical evacuations.

Correction rules can be calculated for this phenomenon using the Compliance, the Saturation of Oxygen, the different Airway Pressures, the Expiratory Tension of CO₂, the continuous Monitoring of the Mechanical Ventilation applied (specially curves and loops), the Oxygen Partial Pressure and finally the continuous Blood Arterial Gas Analysis. This is a new investigation area in which the monitoring of different parameters (specially the Compliances) plays the main role to control the Mechanical Ventilation during Aeromedical Transport.

Mechanical ventilation on medical transport (and especially on aeromedical) is a different concept of mechanical ventilation than the one applied on Emergency Medicine. The devices (mechanical ventilators) have to fit to these different scenarios, or different mechanical ventilators should be used for every one.

The perfect Mechanical Ventilator should change by itself (its parameters and modality of mechanical ventilation), with the analysis of the atmospheric changes of the scenario and the repercussions to patients, for avoiding the VILI.

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