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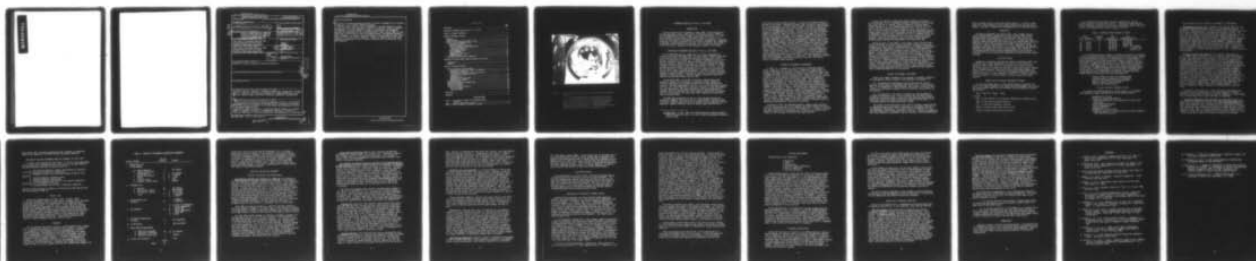
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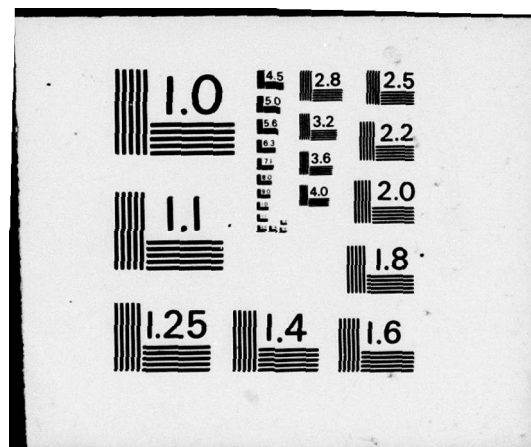
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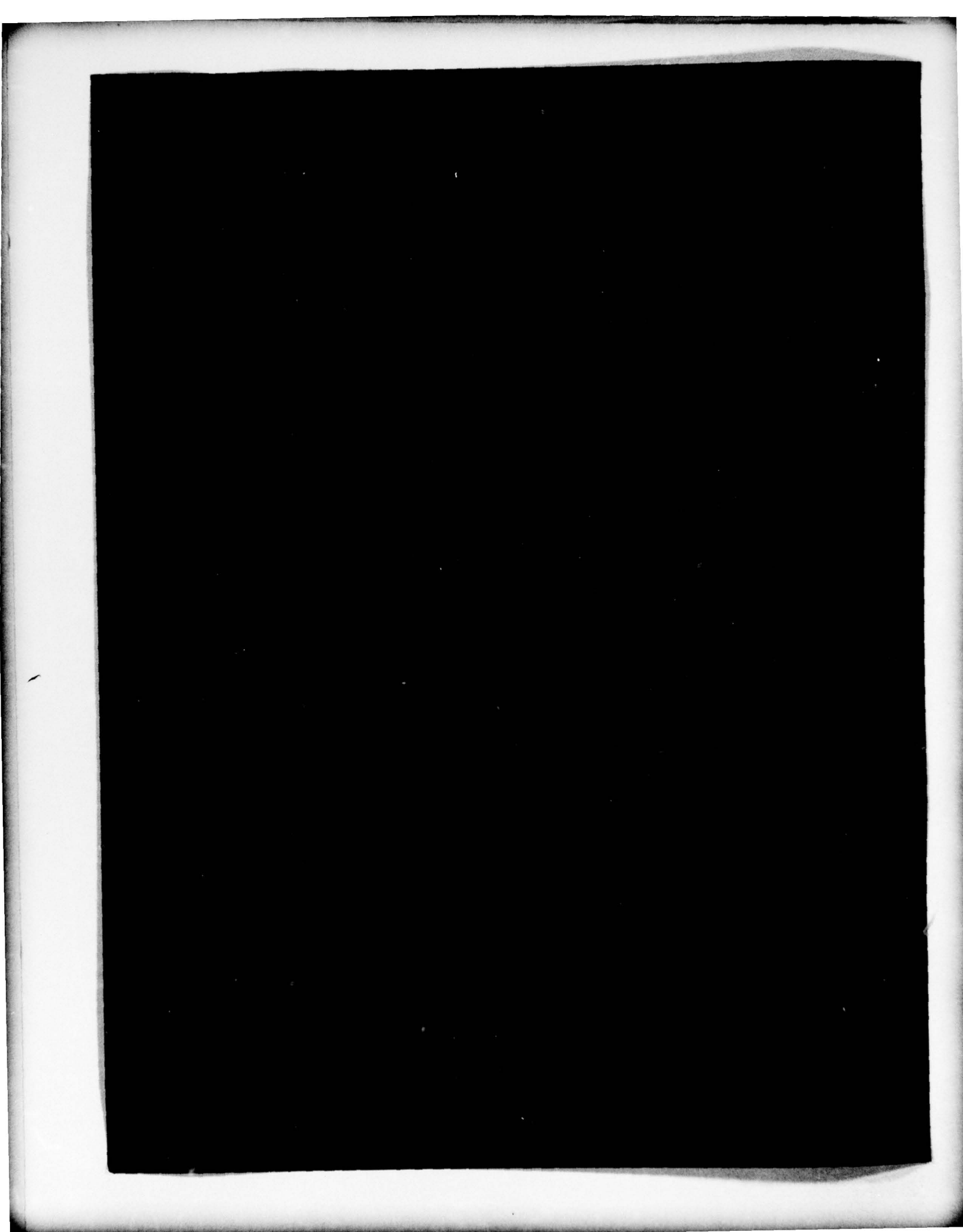


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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The history and evolution of hyperbaric medicine in the U.S. Air Force are reviewed, as well as the effects of elevated partial pressures of respirable gases, with particular reference to the physiologic and pharmacologic effects of increased oxygen tensions. Hyperbaric oxygen is defined as a drug with specific effects in a limited number of diseases, including: 1) decompression sickness; 2) arterial or venous gas embolism; 3) clostridial myonecrosis (gas gangrene) and clostridial		

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cellulitis; 4) carbon monoxide poisoning; 5) chronic osteomyelitis; 6) osteonecrosis; and 7) hypoxic nonhealing wounds.

Results, during the first year of operation of the USAF Hyperbaric Center (Brooks AFB, Tex.), were favorable in 93% of 127 patients treated. Meanwhile the design of clinical hyperbaric chambers was optimized, and the Center assumed the responsibility for consultation with flight surgeons and with other physicians in the field on cases which might benefit from hyperbaric oxygenation. Moreover, on request, such consultation is now provided to other Federal agencies and to the civilian community. Results of these efforts have shown hyperbaric oxygenation to be a clinically effective and cost-effective treatment modality.

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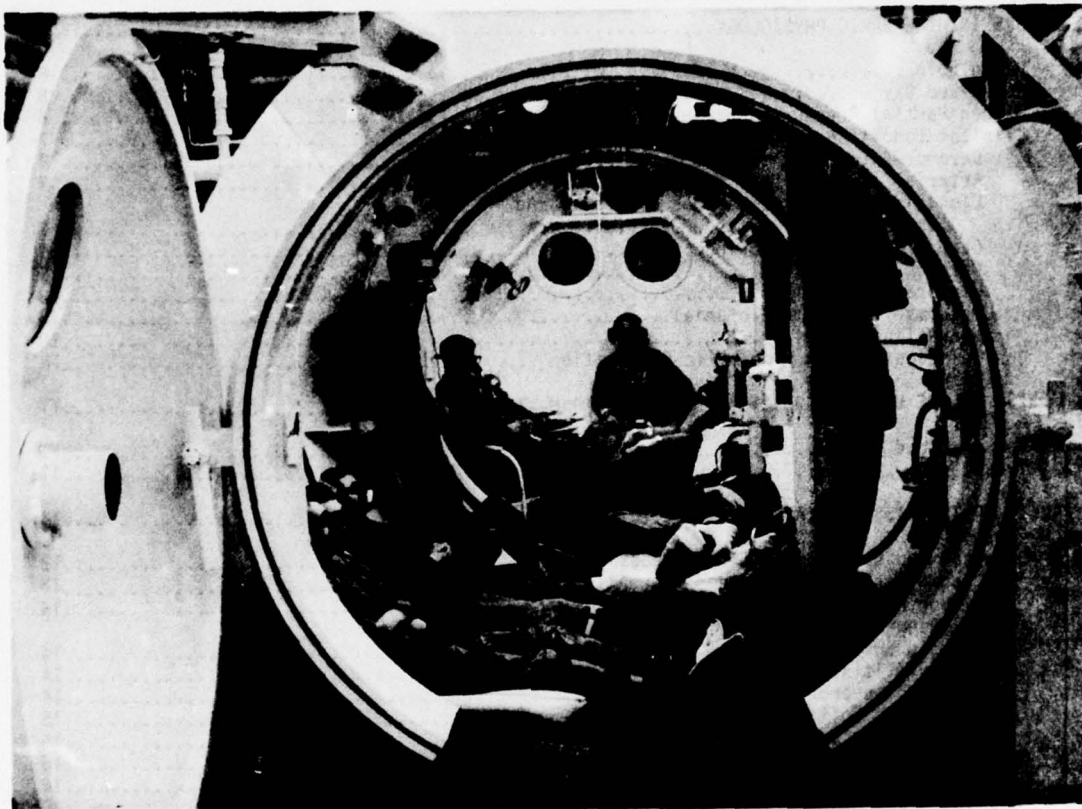


Figure 1. Main hyperbaric chamber of the USAFSAM Hyperbaric Center.

Two medical attendants accompany the patients. The entire chamber is pressurized with compressed air, and patients receive 95% - 100% oxygen by aviator's mask. Clothing is fire-retardant polybenzimidazole (PBI). Lighting is in explosion-proof housing, sealed away from the chamber environment.

HYPERBARIC MEDICINE IN THE U.S. AIR FORCE

INTRODUCTION

Clinical application of hyperbaric oxygen (HBO) is now available at the USAF Hyperbaric Center, USAF School of Aerospace Medicine (SAM), of the Aerospace Medical Division (AMD), Brooks AFB, Texas (Fig. 1). This Review presents the evolution of hyperbaric medicine in the U.S. Air Force and the historical development of hyperbaric oxygenation. Hyperbaric physiology is briefly discussed, and the clinical disorders now recognized as amenable to HBO therapy are presented. Also included are the results of the first year's operation of the Hyperbaric Center of the School.

EVOLUTION OF HYPERBARIC MEDICINE IN THE U.S. AIR FORCE

In the 1940-1959 period, 17,000 cases of altitude decompression sickness occurred in the USAF-USAF. Of these cases, 743 were classified as serious (or Type 2) altitude decompression sickness; and, in this group, 18 deaths were recorded (3). No specific treatment of such cases was then available; and, while debate continued over the etiology and specific treatment, Behnke and Saltzman (4) proposed compression chamber treatment like that used to treat the same disorder in divers. In 1959, through the work of Donnell and Norton (9) the life of an Air Force man who had been dying of altitude decompression sickness was successfully saved in a U.S. Navy recompression chamber. With this impetus, the USAF decided to explore formally, and then to institute, the use of hyperbaric chambers to treat aviators. The USAF hyperbaric medicine program was therefore established between 1959 and 1963.

In the early 1960's, the School installed a sophisticated hypo-hyperbaric chamber for the purpose of conducting animal studies to ascertain mechanisms and treatment methods for altitude decompression sickness. The past experience of the U.S. Navy in this field was utilized fully in this initial SAM effort. Monumental studies in this SAM chamber not only demonstrated the bubble etiology of altitude decompression sickness, but also confirmed the effectiveness of compression to greater than sea-level pressure for those cases where symptoms persisted after return to ground level.

The USAF then purchased 8 of the U.S. Navy standard double-lock compression chambers (6 of which are still operational), installed them at various locations about the world to augment existing Navy and civilian hyperbaric chamber locations, and thus insured ready availability of

EDITOR'S NOTE: In Nov. 1976, the USAFSAM Hyperbaric Medicine Branch (EDH)--of which the Center is a part--became the Hyperbaric Medicine Division (HM).

facilities to treat military aviators. As part of the formal education mission of the School, Compression Chamber Team Training is now conducted on a recurring basis. All USAF flight surgeons are heavily indoctrinated, during the Aerospace Medicine Primary Course, in the early recognition of altitude decompression sickness. They are also given the telephone contact of the AMD Operations Center to enable them to reach the USAFSAM hyperbaric medicine physician on-call on a 7-day-a-week, 24-hr-a-day basis. Over the past 10 years, this telephone consultation service has provided invaluable assistance to the flight surgeons in the field in treating suspected or real cases of decompression sickness among aviators (2). More than 100 cases of altitude decompression sickness, persisting at ground level, have been treated; and 80 of these were treated in USAF hyperbaric chambers. More than 20,000 man-exposures in these AF/99S-2 USAF hyperbaric chambers have been conducted safely over the past 10 years. During this period, no fatalities due to altitude decompression sickness have occurred; and, with the exception of one small permanent visual scotoma, all patients have recovered fully. Early treatment of patients with simple pain-only bends (Type 1) averted progress to neurologic manifestations in a number of these cases. Such neurologic sequelae, even if not permanent, would have resulted in the loss from flying status of valuable rated personnel.

HISTORY OF HYPERBARIC OXYGENATION

In 1955, Dr. I. Boerema, at the University of Amsterdam Medical School, began the clinical application of hyperbaric oxygen (HBO) in anerobic infections and open heart surgery (5). At about the same time, Ledingham and others in Scotland and England began the use of HBO in the treatment of carbon monoxide poisoning (10). Their results were reported at the First and the Second International Conferences on Hyperbaric Medicine in Amsterdam (1963) and Glasgow (1964). Good results were shown in the treatment of clostridial myonecrosis (gas gangrene) and carbon monoxide poisoning. These investigators also introduced the concept of open heart surgery in large (operating-room size) hyperbaric chambers; and several of these large centers were subsequently installed in U.S. civilian medical centers. Since results in the use of these chambers for vascular surgery were generally disappointing, this concept is seldom employed today and many of the large expensive chambers are no longer in use. Cheaper, monoplace chambers were introduced in the 1960's to allow radiation therapy of cancer in hyperbaric oxygen. By the late 1960's, views regarding HBO were divergent--some investigators saying it was entirely useless, and others claiming miraculous cures for everything from myocardial infarction to senility.

Beginning in 1965, the USAFSAM hyperbaric chamber began accepting life- or limb-saving cases of gas gangrene and carbon monoxide poisoning from both the military and the civilian communities. To date, 87 patients have been treated for gas gangrene; and, in those cases referred early enough in their disease, the results have been excellent.

By 1972, the results of laboratory animal studies by Niinikoski, Hunt, and others (14, 15) indicated increased fibroblastic activity when the oxygen tension of ischemic, hypoxic wounds was elevated toward normal. Ketchum et al. (11) demonstrated extensive capillary proliferation by day 18 in experimental burn wounds of rats. Perrins et al. (16), at the University of London, showed the epithelialization of experimental wounds in pigs to be accelerated--by 30% by intermittent HBO at 2 atmospheres absolute (ATA), equivalent to 33 ft of seawater (FSW); and by 4%-8% at 1.5 ATA, equivalent to 16.5 FSW--thus indicating the dose response. Many similar studies at various centers around the world pointed toward wound-healing enhancement with intermittent HBO.

During the mid- to late 1960's, from centers around the world came reports of success in clinical series using HBO in chronic refractory osteomyelitis, maxillofacial osteoradionecrosis, osteogenesis enhancement in bone grafts, preservation of failing skin grafts, and promotion of granulation and epithelial coverage of chronic nonhealing soft tissue wounds. These reports--coupled with soundly based studies on the use of HBO in burn therapy, capillary proliferation, and peripheral vascular disease--led the School to propose the use of existing USAFSAM hyperbaric facilities and expertise for an independent evaluation of this clinical modality (6). Treatment protocols have been developed in close coordination with the various departments of the Wilford Hall USAF Medical Center. HBO (which never replaces any other form of therapy for a given disorder) is used only as an adjunctive drug in those disorders where sound physiologic considerations and clinical experience have indicated that it should be beneficial to the patients.

FACTORS IN HYPERBARIC PHYSIOLOGY

Compression chamber treatment of any disorder or disease is based on only two physical factors related to the hyperbaric environment (1):

(a) The mechanical compression of gas-filled entities (such as bubbles), which respond in accordance with Boyle's Law. The Law states that, if the temperature is kept constant, the volume of a gas will vary inversely as the absolute pressure, while the density varies directly as the pressure.

(b) The elevation of the partial pressures of inspired gases in accordance with Dalton's Law. This Law states that the total pressure exerted by a mixture of gases is the sum of the pressures that would be exerted by each of the gases (the partial pressures of each gas), if it alone were present and occupied the total volume.

The effects of elevated partial pressures of nitrogen, carbon dioxide, or contaminant gases are primarily considered as detrimental effects of the hyperbaric environment. Even oxygen, which is essential for life, has detrimental effects under hyperbaric pressures. Hyperbaric oxygenation does have therapeutic advantages, however, provided it can be administered

within suitable limits to avoid the harmful effects. In order to understand fully these benefits of HBO, oxygen transport must be understood. Oxygen is carried in combination with hemoglobin and in physical solution.

Hemoglobin

One gram of hemoglobin can combine with 1.34 ml oxygen, and the normal concentration of hemoglobin is about 15 gm per 100 ml blood. Therefore, when the hemoglobin is 100% saturated, 100 ml blood can transport 20 ml oxygen (expressed as 20 vol %). At normal sea-level pressure, where the alveolar and arterial P_{O_2} are approximately 100 mm Hg, hemoglobin is about 97% saturated with oxygen and yields an oxygen content for blood of approximately 19.4 vol %. Hemoglobin will be 100% saturated with oxygen at an arterial P_{O_2} between 100 mm Hg and 200 mm Hg. Therefore, increasing the alveolar P_{O_2} much above 100 - 200 mm Hg (by increasing the inspired oxygen concentration or total pressure of inspired air) will not increase the hemoglobin-transported oxygen content of blood.

Dissolved Oxygen

Oxygen is a relatively insoluble gas having a solubility coefficient in whole blood, at body temperature, of 0.0031 vol % per mm Hg P_{O_2} . Therefore, under normal sea-level conditions with an arterial P_{O_2} of 100 mm Hg, only 0.3 ml oxygen is dissolved in each 100 ml blood. However, under increased pressure, significant levels of dissolved oxygen are present; e.g., 6.0 vol % at 3 ATA in the treatment protocol for carbon monoxide poisoning. Unlike hemoglobin, which has an S-shaped saturation curve, the amount of dissolved oxygen is linearly related to oxygen pressure.

Oxygen Partial Pressures Obtainable At Depth

Provided the oxygen supply is pure (99.5% oxygen, or greater) and there is no inboard leakage in the oxygen-delivery equipment, the alveolar P_{O_2} at any chamber depth can be calculated from the simplified alveolar-gas equation:

$$PA_{O_2} = FI_{O_2} (PB - PA_{H_2O}) - PA_{CO_2}$$

in which

FI_{O_2} is the fraction of O_2 inspired, expressed as a decimal value;

PA_{O_2} is the alveolar-oxygen pressure;

PB is the total barometric pressure;

PA_{H_2O} is alveolar water-vapor pressure; and

PA_{CO_2} is alveolar carbon dioxide pressure.

The calculated alveolar-oxygen pressures obtainable at various ambient pressures are presented in Table 1. These values were obtained from the equation, assuming a constant body temperature, normal respiratory control, and metabolism maintaining a PA_{CO_2} of 40 mm Hg.

TABLE 1. ALVEOLAR OXYGEN PRESSURE AT DEPTH

Depth (ft)	Depth (meters)	Pressure (ATA)	PA_{O_2}	PA_{O_2}
			Breathing air	Breathing 100% O_2
0		1	100 mm Hg	673 mm Hg
33	10.06	2	260 mm Hg	1433 mm Hg
66	20.12	3	420 mm Hg	2193 mm Hg
99	30.18	4	580 mm Hg	(Note: 100% oxygen is never used below 66 ft)
132	40.23	5	740 mm Hg	
165	50.29	6	900 mm Hg	

In the USAFSAM hyperbaric chambers, hyperbaric oxygenation is achieved by having the patient breathe 100% oxygen by aviator's mask while exposed to elevated barometric pressure in a compressed air diving chamber. In those conditions in which open granulation tissue is exposed, topical application of 100% oxygen may be utilized. Oxygen content at any point in tissue is dependent on the distance of the tissue from functioning capillaries, the oxygen demand of the tissue, and the oxygen tension in the capillary. Hyperbaric oxygen works by elevating the oxygen tension in the capillary. As stated before, the use of HBO is restricted to physiologically based indications, and hyperbaric oxygen should be viewed simply as a drug with the following properties:

- Specific effects on cells and microorganisms
- A defined range of therapeutic effectiveness
- Specific dose ranges for various disorders
- Specific routes of administration
- Toxicity and overdose effects

Clinical Conditions Amenable to HBO

At present, the USAFSAM Hyperbaric Center accepts, for treatment with hyperbaric oxygen, patients with the following disorders:

- Decompression sickness
- Arterial or venous gas embolism
- Clostridial myonecrosis (gas gangrene) and clostridial cellulitis
- Carbon monoxide poisoning
- Chronic osteomyelitis
- Osteoradionecrosis
- Osteomyelitis, maxillofacial
- Nonhealing wounds (to promote granulation tissue formation and reepithelialization).

The following clinical disorders are amenable to HBO therapy:

Decompression Sickness--This disorder is the primary reason for the existence of hyperbaric chambers, which have provided the required treatment of diving casualties for over 70 years and of altitude casualties for 15 years. Manifestations of decompression sickness include: the joint pains of bends; the discrete and often confusing neurologic "stroke like" pictures; severe, life-threatening gas pulmonary embolism, or "chokes"; and vasomotor collapse with shock. Treatment requires emergency recompression and oxygen breathing in the hyperbaric chamber to reduce intravascular bubble size and to eliminate bubbles. Hyperbaric oxygen establishes a steep inert gas gradient across the bubble-tissue fluid interface at depth, thus aiding the elimination of inert gas and preventing re-formation of bubbles upon ascent to ground level. Treatment is based on standard U.S. Navy treatment tables (17), and is highly successful if used early.

Arterial or Venous Gas Embolism--If a source of compressed gas (e.g., SCUBA, hose, diving suit) is used in diving, then breath-holding or local air trapping on ascent from as little as 5-10 ft (1.52-3.05 m) of water depth can result in lung rupture. The result ranges from a pneumothorax (managed by standard surgical care) to pneumomediastinum, with substernal pain and subcutaneous crepitus (treated by bed rest and repeated neurologic examinations), and to cerebral arterial air embolism, which can occur alone or associated with any of the other disorders. Cerebral air embolism requires treatment in the hyperbaric chamber as rapidly as possible. This disorder is a minute-to-minute emergency; and, generally, the outcome depends on the time required to reach the chamber. Initial treatment is at 165 FSW (6 ATA) while breathing air. This depth, selected to obtain maximum reduction of arterial bubble size in order to restore circulation, is followed by hyperbaric oxygen at 2.8 ATA and 2.0 ATA to oxygenate embarrassed tissue. Results are excellent if treatment is begun early. Several cases have recovered full function even after several hours' delay before treatment. Thus, a trial of hyperbaric chamber treatment is indicated even in the late case.

Accidentally introduced air in the intravascular compartment from any source is also an indication for the same treatment. Although effective results depend on time from onset to compression in the chamber, even the late cases often respond favorably to treatment.

Clostridial Myonecrosis (Gas Gangrene) and Clostridial Cellulitis--Upon exposure to about 250 mm Hg P_{O_2} , the Clostridium perfringens ceases alpha toxin production and, at 1400 mm Hg, it is irreversibly damaged. HBO at 3 ATA (66 FSW) gives a measured arterial oxygen tension of greater than 1900 mm Hg with a gradient of tensions in tissues near the functioning capillaries. HBO is an established adjunct in the treatment of gas gangrene. Aside from the favorable effect on mortality rate, significant tissue saving results when the following principles are followed:

- a. Early diagnosis, based on wound appearance, overall clinical observations, plus finding of the organisms on gram stain of muscle or necrotic tissue
- b. Fasciotomy and debridement of only obviously necrotic tissue
- c. Massive intravenous antibiotic coverage
- d. Tetanus prophylaxis
- e. High index of suspicion of associated diseases with appropriate management (especially diabetes mellitus)
- f. Blood component replacement, and maintenance of intravascular fluid volume
- g. Initiation of HBO as soon as possible. [Treatment is at 66 FSW (3 ATA), while breathing 100% O₂ by mask for 90 min. Three treatments are given within the first 24 hr, followed by treatments every 12 hr until clinical evidence of the disease is no longer present.]
- h. Definitive debridement between HBO treatments as demarcation occurs.

Use of the large compressed air chamber for the critical patient allows a surgeon or anesthesiologist to continue comprehensive management in the chamber during HBO treatment.

Carbon Monoxide Poisoning--Two benefits are obtained with HBO: A physical solution of 6.0 vol % oxygen in plasma to bypass bound hemoglobin; and an increased rate of dissociation of carbon monoxide from hemoglobin (in the early case). Improvement has been found with HBO in the patient with persistent neurologic abnormalities, even after carboxyhemoglobin (COHb) has been normal for 24-48 hr. The mechanism is probably the reduction in cerebral edema found when HBO is used in combination with the edema-reducing drugs.

The half-life of COHb at sea level, breathing 100% oxygen, is 80 min. Breathing 100% O₂ at 66 FSW (3 ATA) reduces the half-life to 23 min. Treatment with HBO is at 3 ATA for two COHb half-lives (46 min), followed by ascent to 2 ATA with intermittent air-oxygen until maximum improvement is obtained (12).

Chronic Osteomyelitis--Clinical series from hyperbaric centers worldwide indicate a 60% - 90% rate of arrest of previously refractory chronic osteomyelitis (8). Treatment with HBO must be coupled with excision of existing sequestra and with appropriate antibiotic coverage. Treatment is at 45 FSW (2.4 ATA), breathing 100% oxygen for 1-1/2 hr daily, 6 days a week for approximately 30 days, or until complete healing occurs.

The mechanism of action is primarily that of stimulating osteogenesis and fibroblastic activity with increased collagen production and neovascularization to fill dead space. It appears that chronic, nonhealing wounds of bone and soft tissue are hypoxic, and that hyperbaric oxygen permits diffusion of elevated oxygen partial pressures from functioning capillaries to provide tissue tensions adequate to activate fibroblasts and osteoblasts (15).

The effect of HBO on microorganisms in chronic osteomyelitis is less clear, but may be the result of activation of phagocyte killing activity. Certainly, any anerobic organism will be suppressed.

Osteoradionecrosis--Clinical experience (13) with mandibular osteoradionecrosis leaves little question but that HBO combined with sequestrectomy is the treatment of choice. The mechanism of action is the same as that for osteomyelitis; therefore, the treatment profiles are also the same. Limited experience with soft tissue vasculitis and cellulitis shows promise, the effect probably being based on improved oxygenation of tissue, previously rendered hypoxic as a result of radiation vasculitis with ischemia.

Osteomyelitis, Maxillofacial--The treatment profile and mechanism of action for osteomyelitis of the maxillofacial region is the same as for osteomyelitis of the extremities, but the results approach 100% effectiveness. The effectiveness appears to be the result of the rich blood supply to the maxillofacial region leading to higher tissue oxygen levels.

Nonhealing Wounds--Based upon the mechanism of increased fibroblastic activity with collagen production, fibroblastic migration, and capillary budding, HBO has been used extensively to promote granulation tissue formation, neovascularization, and reepithelialization. HBO is most effective in establishing a healthy granulation base for skin grafting in stasis or decubitus ulcers and other nonhealing wounds. New granulation buds are noted in most wounds within 5-10 days of beginning HBO; and, within 30 days, the bases of most lesions are richly granulated and vascular. Failing or marginal skin-graft remnants in such wounds have been seen to flourish and spread rapidly.

The treatment includes 100% oxygen, both topically and by mask, for 1-1/2 hr daily, 6 days a week, at 2.4 ATA. Insignificant amounts of oxygen are absorbed by intact skin, but open wounds and granulation tissue absorb significant oxygen when it is applied topically at 2.4 ATA.

Contraindications to Hyperbaric Oxygenation

The four principal contraindications to treatment by hyperbaric oxygenation are:

- a. Pulmonary blebs or bullae, lung cysts or pneumothorax (absolute contraindications to HBO therapy)
- b. Acute viral systemic disease, until fully cleared
- c. History of optic neuritis
- d. Inability to clear the ears during a dive. This condition may be secondary to an acute upper respiratory infection or allergic rhinitis. In the emergency patient, this problem can be circumvented by

myringotomy; and in patients undergoing 30-day treatment, polyethylene tubes can be temporarily inserted through the tympanic membranes.

MISSION OF THE USAF HYPERBARIC MEDICINE PROGRAM--THE FIRST YEAR

On 2 April 1974, Headquarters USAF (Dept. of the Air Force, Washington, D.C.) established the Hyperbaric Medicine Program, at the USAF School of Aerospace Medicine, with the following mission--to:

- a. Use existing hyperbaric chamber installations to establish clinical indications for hyperbaric oxygenation
- b. Determine clinical and cost-effectiveness of HBO for USAF hospitals
- c. Optimize hyperbaric chamber design
- d. Determine staffing requirements
- e. Provide telephone consultation in the field of hyperbaric medicine for all USAF medical facilities
- f. Provide guidance for the USAF in hyperbaric medicine.

Results of the first year of operation include the clinical applications and effectiveness of HBO (3).

Patient Load

During the 12-month period (10 Sept. 1974 - 10 Sept. 1975), 127 patients received a total of 3,095 patient treatment dives (including 18 patients who received 227 treatment dives on an emergency basis during the period 2 Apr. - 10 Sept. 1974). Of the total 127 patients, 87 were active duty, dependent, or retired patients referred from the Wilford Hall USAF Medical Center; 3 were referred from the Brooke Army Medical Center, 9 from the Audie Murphy Veterans Administration Hospital, and 5 from the Medical and Dental School of the University of Texas at San Antonio; and 23 were space-available civilian humanitarian cases referred from San Antonio physicians. The entities treated and the results of these treatment dives are listed in Table 2.

Treatment

The 127 patients were given a total of 3,095 treatment dives, ranging from 1 treatment per patient for decompression sickness, an average of 5-7 treatments for gas gangrene and 30 for osteomyelitis, to 45 for osteoradionecrosis. Some patients received more treatments for wound-healing enhancement in osteomyelitis and soft tissue wounds, with the total determined by clinical response. Treatment schedules were the standard U.S. Navy Treatment Tables V or VI (17) for decompression sickness; 3 ATA, equivalent to 66 FSW, for gas gangrene; and 2.4 ATA (45 FSW) for the other entities. Treatment times ranged: from 90 min oxygen by mask, on a 20-min oxygen and 5-min air intermittent schedule, for

TABLE 2. RESULTS OF HYPERBARIC OXYGENATION TREATMENTS

Entity Treated	No. of Patients	Results
1. Nonhealing soft tissue wounds:		
a. Postirradiation	4	All healed
b. Venous stasis ulcer and dermatitis	4	All healed
c. Nonhealing surgical wounds	10	{ 9 healed 1 poor
d. Diabetic ulcer	1	Poor
e. Arterial insufficiency	1	Healed
2. Osteomyelitis:		
a. Mandible	15	All healed
b. Maxilla and sinuses	2	Both healed
c. Extremities, pelvis, spine	23	{ 15 arrested 5 improved 3 failed
3. Osteoradionecrosis, mandible	10	9 healed 1 improved
4. Gas gangrene	10	{ 5 cured, no amputation 1 cured, amputation before HBO 1 cured, amputation after HBO 3 died
5. Altitude decompression sickness	11	All excellent
6. CO poisoning	2	Both excellent
7. Bone healing enhancement:		
a. Maxillary osteotomy	32	{ All healed
b. Mandibular osteotomy	1	Healed
c. Mandibular bone graft	1	
8. Sick cell hematuria	1	Poor
TOTAL		127

osteomyelitis and soft tissue healing enhancement--or, on a 25-min oxygen and 5-min air schedule, for gas gangrene--to the total 285-min intermittent oxygen-air schedule, for neurologic decompression sickness. The purpose of intermittent air-oxygen during each treatment as well as separation of treatments by 2-22 hr was to prevent pulmonary oxygen toxicity. The long-term osteomyelitis and wound-healing cases were given 1 treatment per day, 6 days a week. Weekly vital capacity and forced expiratory volume, 1-sec (FEV-1) determinations on these patients have shown no significant decrements.

FACETS OF THE MISSION STATEMENT

Clinical Indications and Effectiveness

Decompression Sickness and Traumatic Air Embolism--The response of altitude decompression sickness treated early with HBO is most dramatic, with full clearing of symptoms occurring within minutes. Early hyperbaric treatment of altitude bends, persisting or recurring at ground level, not only relieves pain but prevents progression to more serious manifestations. A recent review of 130 cases of altitude decompression sickness revealed that pain-only bends was the initial presenting complaint in 17% of cases who went on to develop more serious forms of the disease (7). Additional work, using the precordial Doppler bubble detector in divers, has shown the uniform presence of central venous bubbles when bends pain exists. These findings support our current efforts to provide early compression chamber treatment of altitude-bends pain before it progresses to more serious manifestations; for these could possibly result in permanent deficits, and certainly in permanent loss of flying status.

Since 1965, 16 cases of cerebral air embolism have been treated in Air Force hyperbaric chambers. Of these cases, 3 were surgically induced; 2 were the result of ascent in hyperbaric chambers; and 11 were associated with SCUBA diving, in which 4 cases resulted from swimming ascent training.

The time from initial symptoms to hyperbaric treatment averaged 4 hr, ranging from 12 min to 11 hr. Of the 16 patients, 2 (12.5%) died; but the remaining 14 made a full functional recovery. The 2 deaths occurred in patients where the time from onset to treatment was, respectively, 11 hr, and 5 hr 15 min. In 3 of the survivors, however, the delay between onset and treatment was over 5 hr--with 3 hr 20 min being the average in the total group of survivors. Only 2 patients received treatment in less than one hour (12 min and 30 min, respectively). These data strongly support our contention that, while cerebral air embolism represents a minute-to-minute emergency where no delay in instituting hyperbaric treatment can be justified, patients may yet receive benefit from such treatment even when a significant delay has occurred.

Carbon Monoxide Poisoning--Results with 2 patients are good and match those of a larger series from Kindwall (12). Hyperbaric oxygen at the treatment depth of 3 ATA physically dissolves 6 vol % oxygen in plasma, shifts the carboxyhemoglobin dissociation curve favorably, and reduces intracranial pressure.

Gas Gangrene (Including Clostridial Cellulitis with Rapid Spread and Systemic Toxicity)--Results of HBO treatment of gas gangrene are dependent on the time from onset until hyperbaric oxygen is instituted. Management requires early recognition, institution of massive antibiotic coverage, control of associated disorders (such as diabetes), blood component replacement therapy for blood loss and hemolysis, maintenance of intravascular fluid volume, fasciotomies and necrotic tissue debridement, and rapid transfer to the nearest hyperbaric chamber. Hyperbaric oxygen stops alpha toxin production by the Clostridium perfringens wherever the organism is presented at least 250 mm Hg P_{O_2} . At 3 ATA, breathing 100% oxygen, our measurements show a minimum arterial P_{O_2} of 1900 mm Hg, diffusing high oxygen tensions into tissues which still have viable circulation.

The overall gas gangrene case fatality rate among those treated in less than 24 hr from onset is 5.1%, rising to 35% in those treated at over 24 hr. Results are worse (18% case fatality with early treatment) in abdominal wall infections--but excellent (with zero mortality) in extremity cases. Of great importance, both clinically and economically, is avoidance of amputation, thus saving functional limbs and precluding the need for rehabilitation, prostheses, and disability compensation.

Osteomyelitis--Because of the inherently good vascularity of bone about the head and neck, the best and most rapid results of hyperbaric treatment have been noted in osteomyelitis involving the facial bones. Good results are seen in osteomyelitis of the extremities, spine and pelvis, but longer periods of treatment are necessary. Results, thus far, indicate that HBO is most useful for achieving a permanent cure in chronic refractory cases if it is combined with sequestrectomy and appropriate antibiotics, the wound packed with cancellous bone and marrow after 10 - 14 HBO treatments, and HBO continued after this bone-graft procedure. In previous series, cases treated without sequestrectomy have recurred; and, while we have seen improvement in a few we treated without sequestrectomy and debridement of sinus tracts, we predict recurrence. With a 1-year followup, we have observed no recurrences in any of the osteomyelitis cases. All must be followed for at least 2 years before claims of arrest can be made.

Osteoradionecrosis--This very difficult form of osteomyelitis and osteonecrosis in previously irradiated bone represents a great challenge. The basic pathophysiology is radiation vasculitis and proliferative endarteritis with loss of blood supply and infection. The excellent results of hyperbaric oxygen treatment recently reported by the Long Beach U.S. Naval Hospital (13) have been confirmed by our own series to

date. HBO must be combined with meticulous oral surgical care, debridement, sequestrectomy, and antibiotics. Communication with the M. D. Anderson Hospital in Houston revealed failure to achieve good results in their cases, when HBO alone was used. This difference in results again emphasizes the role of HBO in such disorders as an adjunct only--to promote healthy granulation and re-vascularization of ischemic, hypoxic bone. These cases have been highly rewarding, with uniformly early relief of disabling pain and trismus; and thus far the need for mandibulectomy, a procedure which carries a 20% mortality rate, has been averted.

Nonhealing Soft Tissue Wounds--It is in the category of soft tissue radiation necrosis that some of the most dramatic responses to HBO have been seen. Pharmacologically, such responses are to be expected, based on the fibroblastic activation and neovascularization promoted by HBO in hypoxic wounds already discussed. These difficult wounds, rendered ischemic and hypoxic by required radiation for malignancy, can easily become infected; and attempts at various skin-grafting techniques frequently fail. Capillary proliferation, rapid granulation, and epithelial coverage have been seen repeatedly following HBO therapy. Overall results in these patients have been frankly phenomenal. When one remembers the surgically hopeless cases of postradiation soft tissue necrosis, and then watches healthy vascular granulation, followed by epithelial growth across the wound, he is struck by the need to expand this modality in order to care for such patients.

We have treated a number of patients with venous stasis ulcers which have persisted after successful venous ligation and stripping. In all cases, the ulcerations healed with HBO therapy, either by epithelialization or the acceptance of a split thickness skin graft. Included in this series is one case where the ulcer had been present for over 40 years.

Between Sept. 1974 and Sept. 1975, a single case of a gangrenous diabetic ulcer was treated unsuccessfully. Another patient, with persisting ulcerations along the site of a surgical incision for by-pass surgery to correct arterial insufficiency, was treated and the wounds healed successfully. Since Sept. 1975, further experience with the treatment of soft tissue ulcerations secondary to diabetes or arterial atherosclerosis has led us to recognize that patients with circulation so embarrassed that impending or frank gangrene is present will not benefit from HBO. However, in patients whose circulation is adequate enough to maintain the integrity of tissue immediately surrounding the wound, HBO can be of great benefit in wound healing. These are patients whose tissue oxygen tensions are high enough to maintain normal tissue, but not high enough for adequate healing to take place in wounds induced by trauma, infection, or neurotropic changes seen in diabetes.

Bone-Healing Enhancement--Based on reports of osteogenesis enhancement by HBO in animal models and in human mandibular autografts, confirmatory animal studies are underway in the research laboratory at the Wilford

Hall USAF Medical Center (WHMC). These studies will be followed shortly by an approved control series, with and without HBO, to determine the degree of shortened healing time in routine maxillary osteotomy patients. Observations in a small pilot series indicate that healing may be shortened by as much as one-third. The potential for bone-healing enhancement with HBO, suggested by these studies, is highly important in terms of early return of the patient to duty and military effectiveness.

Cost-Effectiveness

Cost effectiveness of the first year's operation was determined by calculating the cost of operation (including fixed equipment). This cost was compared with savings--based upon estimates by the patients' physicians--of bed days and surgical procedures saved; early return to duty, and avoidance of disability payments. The ratio of savings to cost was 1.9 to 1. This ratio should increase in subsequent years as fixed equipment costs are minimized and operating cost per patient treatment decreases with increasing patient loads.

Optimization of Hyperbaric Chamber Design

Important design features for future hospital-based hyperbaric chambers have been developed at the School during daily operations with existing equipment. In general, the present concept would be for a multiplace chamber with a large, lower cost, 3 ATA man-rated chamber (instead of the current 8 ATA man-rated capability) for treatment of up to 15 elective, wound-healing enhancement patients per 2-hr dive. The large chamber should have a lockout capability, but would be cheaper because structural strength would be less. An adjacent 8 ATA man-rated chamber for emergency air-embolism treatment could be much smaller, to accommodate only one patient and two attendants. The chambers would share a single lock.

In cost trade-offs between such a large chamber complex and monoplace chamber installations, the former would receive favorable consideration. A maximum patient load of 60 elective patients per day could be treated on a schedule of 3 hr per treatment (2 hr for treatment, plus 1 hr for cleanup and turnaround) in a 12-hr workday on a crew-shift schedule. In order to treat 60 patients per 12 hr in monoplace chambers, at least 12 chambers would be required to run simultaneously--even if the turnaround time allowed for the monoplace chamber were reduced to 30 min between patients. Even if the basic unit cost of these chambers were to be held to \$32,000, the total cost of the monoplace chambers would be \$384,000. This price would, of course, rival chamber and compressor costs for the clinically preferable large chamber complex.

The large, multiplace hyperbaric chamber with oxygen supplied by well-fitted masks gives 95% - 100% oxygen delivery, as shown by our mask

oxygen measurements and arterial blood gas analyses. Topical oxygen is applied by bags, or cups, to open granulating wounds. A medical attendant is always inside the chamber, providing moment-to-moment patient care capability during treatment. Our experience has shown this care to be invaluable when, during treatment, a patient: becomes anxious; has difficulty clearing his ears during descent, and nasal spray is required; becomes ill and vomits; has discomfort, requiring pain medication; requires routine oral, IV, or IM medications; or develops any other symptoms requiring immediate medical care. At 3 ATA (required for best results in gas gangrene), the critically ill patient may require such care as insertion of an endotracheal tube, wound management to control bleeding, or dressing changes. Because of such complications, the comfort of the large chambers--plus the psychologic value to patients of a trained "inside observer" in attendance--is of great importance to patient well-being. None of this information, however, is intended to negate the role of the monoplace chamber. This type of chamber will be considered mandatory if current research (e.g., at the Long Beach Naval Hospital, Sherman Oaks Burn Center, in Los Angeles; and the Shriners Burn Institute, in Galveston) proves the value of HBO in burn therapy. The burn patient, who generally cannot wear a mask and needs topical oxygen, must be treated in the monoplace chamber on the burn ward. This requirement supports the thesis that the complete hyperbaric facility of the future must consist of a family of chambers: the multiplace, compressed air, low-pressure wound-healing chamber; the high-pressure air-embolism chamber, for one patient with two attendants; and the monoplace 100% oxygen chamber for burn victims or other patients who cannot wear masks.

The properly operated large chamber, with continuous oxygen monitoring, never exceeds 23% oxygen in the chamber environment. Fire-retardant clothing, bedding, and pillows of polybenzimidazole (PBI) Beta cloth, or Durette Gold are in use because they will not support combustion in the 23% oxygen environment. Explosion-proof, shielded light bulbs, with all ballasts and starters outside the chamber, reduce the spark source hazard. In the next generation chamber, however, fiberoptic lighting from outside the chamber, through ports, will reduce this risk to zero. Finally, the water deluge system currently in use should be installed.

A good oxygen overboard-dump system in the future clinical chambers will eliminate the minimal oxygen buildup problem, now managed by chamber oxygen monitoring and ventilations as indicated for oxygen concentrations above 23%.

These are but some of the observations of the experienced crew operating the USAFSAM complex on a daily basis. It must be noted that, as chambers proliferate, they will be operated by less experienced crews; and all systems must therefore be engineered to be fail-safe.

Staffing Requirements

The past year's staff comprised:

- 2 physicians
- 2 nurses
- 1 physiologist
- 6 altitude chamber technicians
- 2 medical technicians
- 1 civilian secretary

Careful observation has shown that this staff, all working between 50 hr and 70 hr per week, was adequate for the current 2 dives a day, 6 days-a-week, plus the requirement for a full-time emergency on-call team. Among other requirements in this new program were: facilities maintenance; medical supplies control; medical photographic repository maintenance; teaching; medical school and medical society lectures; hospital visits to evaluate prospective patients; and the extensive telephone consultation service. Without the inside observer assistance of off-duty nurses, surgeons, and anesthesiologists from WHMC, the treatment program at the School would have been curtailed. These 30 people, all graduates of the one-week "Compression Therapy Training" course, have been on orders as supplemental team members to provide life-saving care for emergency patients in the chamber. In order to maintain familiarity with chamber equipment, each supplemental team member performs 2 dives per month with elective daily patients. This number of dives is the minimum needed to insure off-duty availability for 7 gas-gangrene dives in 3 days when these cases occur on a once monthly average basis during the year.

For inside observers, the minimum safe interval between dives has been established as 72 hr. In addition, unlike the oxygen-breathing patients, the inside observer breathes chamber air during each dive; thus he is in a physiologic position comparable to that of compressed air divers, and must be protected against the risk of aseptic bone necrosis by limiting exposure frequency. When hyperbaric chambers are installed in USAF Medical Centers in the future, the necessary level of patient load in each could be handled by the full-time staff if augmented then, as now, from the clinical staff of a hospital.

Telephone Consultations

During the first year of operation, the USAFSAM Hyperbaric Medicine Branch managed 327 separate cases or operational aeromedical problems, with an average of 3-5 calls per case or problem handled. The majority of calls were from USAF flight surgeons who were caring for certain or suspected cases of altitude decompression sickness. When needed, multiple calls were made, with the assistance of the AMD Operations Center, to arrange transportation to and acceptance by the nearest hyperbaric chamber. Consultation was then provided to the receiving chamber crew during actual hyperbaric therapy.

The USAF diving mission (Para SCUBA Rescue) and others are afforded consultation on preventive medicine and decompression techniques, as well as 24-hr emergency telephone availability to assist with accidents. The same service is provided to the divers in the U.S. Army Corps of Engineers. Moreover, the Army Special Forces recently sent a flight surgeon through the 2-week Compression Chamber Team Training Course at the School.

In the category of phone calls, the next most common is from various USAF levels to request information on the risk and prevention of decompression sickness in various flight profiles, and prevention of other physiologic problems of flight. Assistance is given also in the recognition of disorders which would benefit from hyperbaric oxygen therapy, particularly gas gangrene, and in obtaining such therapy for these patients from all military services. Finally, as a further community service, this 24-hr telephone consultation is made available to the civilian community, nationwide. Physicians caring for cases of suspected gas gangrene, decompression sickness, or air embolism in civilian divers or aviators are provided advice and hyperbaric chamber locations on request.

The entire system is dependent on the extremely valuable assistance and vigilance of the AMD Operations Center to whom the U.S. military and civilian communities are becoming increasingly indebted.

Objectives in Hyperbaric Medicine

Based on the foregoing facts, recommendations concerning objectives in hyperbaric medicine fall in two categories: near-term and long-term.

Near-Term Category (The exploration of promising new clinical directions)--Recently (through the Undersea Medical Society) a 1974 textbook on Hyperbaric Oxygen, published in the Soviet Union, was received. This book reveals that the Russians show great interest and progress in the clinical applications of hyperbaric oxygen. Not only are their chamber installation philosophy, physiology, and clinical practice generally in accord with the principles outlined in our Review, but possibly promising new directions are also indicated. For example, they report good results in the use of HBO to promote microvascular proliferation and reduce pain in some 750 patients with chronic peripheral vascular disease. In the past, HBO was generally considered useless in this disorder; but recent evidence of capillary proliferation with HBO demands a new appraisal of this application. Another exciting possibility with a good physiologic basis in theory and animal studies is the shortening of healing time of fractures. This application could hold special promise in notoriously difficult and avascular fractures, such as the carpal navicular bone and fractures of the lower tibia. Again, controlled human series should be evaluated.

Long-Term Category--The long-term recommendations must be considered tentative only inasmuch as they rely on results of current patient followup, clinical studies such as those already described, developments in other parts of the nation or the world, and pertinent current events. A major long-term example was the workshop in hyperbaric medicine held at the University of California in San Francisco in Oct. 1975. This workshop not only brought together the entire scientific and medical community involved in all aspects of wound healing, including HBO enhancement, but also covered current clinical HBO efforts worldwide. One result of the HBO workshop will be the Textbook of Hyperbaric Oxygen Therapy, to be published by the Plenum Publishing Co. (N.Y., N.Y.) in 1977. The entire textbook effort is funded jointly by several agencies, including the National Heart and Lung Association, and the National Library of Medicine. The Chief of the USAFSAM Hyperbaric Medicine Division, Jefferson C. Davis, Colonel, USAF, MC, was selected--along with Dr. Thomas K. Hunt, Professor of Surgery, University of California, San Francisco--to coordinate the workshop and to be coeditor of the book. Forty-nine authors, working in the field of hyperbaric medicine, have been participating in this effort.

The findings and recommendations of this international group will delineate directions for the future of hyperbaric medicine. The following general objectives for the U.S. Air Force parallel those in the medical community at large:

- a. To plan for hospital based hyperbaric chamber installations at three large USAF Medical Centers--East Coast, Central Region, and West Coast of the United States.
- b. To continue the effort at the USAFSAM, at an increased level of: 4 dives daily; 30 patients per day, with the primary missions of clinical research with the Wilford Hall USAF Medical Center; refining treatment methods and exploration of new applications and chamber safety, as well as education of crews to man the other installations.

CONCLUSIONS

Hyperbaric oxygen is neither new nor miraculous. Its judicious use as an adjunctive drug can be of great benefit when combined with medical and surgical management of many frustrating medical problems. HBO is a safe, clinically sound, and cost-effective addition to our medical armamentarium.

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