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Ambient Pressure		Alveolar PO_2
Atm abs	mm Hg	mm Hg
1	760	673
2	1520	1433
3	2280	2193
4	3040	2953
5	3800	3713
6	4560	4473

Fig. 1. Alveolar oxygen pressures obtainable with oxygen administration at various ambient pressures.

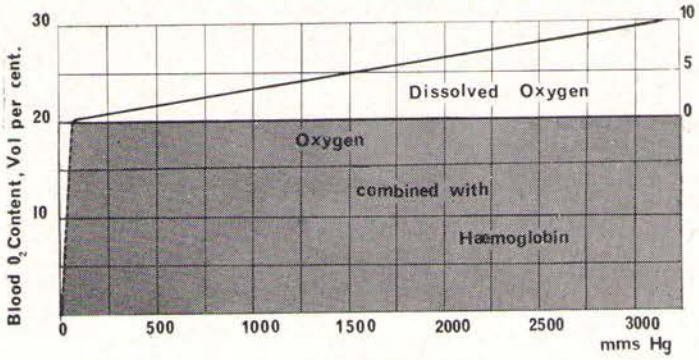

Fig. 2. Blood oxygen content at various blood oxygen pressures.

Hyperbaric Oxygenation

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THE FIRST RECORDED attempt to use a hyperbaric chamber in medicine was made by the British physician Henshaw in 1662. His chamber or 'domicilium' was fitted with a large pair of organ bellows, valved so that the air could be either compressed or rarified. The rationale was to use elevated pressures for acute, and low pressure for chronic disease. Simpson[1] commented at this time:

> *"In time of good health this domicilium is proposed as a good expedient to help digestion, to promote respiration, to facilitate breathing and expectoration, and consequently of excellent use for the prevention of most affections of the lungs".*

In the 1830's new interest arose in France, and the largest chamber of the decade was built by Pravaz[2] in Lyons. He felt that the compressed air baths would dilate the bronchi, which was considered beneficial in cases of pulmonary tuberculosis, capillary haemorrhage, deafness, cholera, chest deformities, rickets, bronchiectasis and pertussis. At this time the hyperbaric pressure chamber became another variant of the mineral water spa and the claimed cures were similar. The 1850's saw a spread of chambers across Europe and the dominant figure of the period was Paul Bert[3] whose work in the basic physiology of hyperbaric oxygenation entitles him to be called the 'Father of pressure physiology'. He studied the effects of varying pressures on plant growth and fermentation and was one of the early workers to recognize the problems of oxygen toxicity.

In 1927, Orval J. Cunningham[4] constructed a chamber in Kansas City, Mo. Therapy was directed toward the treatment of hypertension, diabetes mellitus and cancer. Treatment was based on the assumption that anaerobic infection played a major part in all these diseases. Claims were quickly attacked by the Bureau of Investigation of the American Medical Association[5] and 'tank treatment' fell into disrepute.

Modern scientific investigation of the therapeutic use of high partial pressures of oxygen only commenced in the mid-nineteen-fifties, with the simultaneous pioneer work of Professor Boerema in Amsterdam[6], Professor Illingworth in Glasgow[7], and Dr. Ian Churchill-Davidson in London[8].

Terminology

Before discussing physiological aspects of hyperbaric oxygenation the pressure terminology requires clarification.

At sea level the atmosphere exerts a pressure of 14·7 lb/sq. in or 760 mm mercury. This pressure is referred to as one atmosphere absolute. Pressure gauges are normally set to read zero at normal atmospheric pressure, i.e. 1 atmosphere absolute, so if a hyperbaric chamber is pressurised to a gauge pressure of 14·7 p.s.i., the chamber will be said to be operating at 2 atmospheres absolute.

Further confusion can occur if linear terms are used to express pressure measurements. This terminology relates the water pressure acting on a submerged body to its depth in feet. Thus, with a sea level pressure gauge setting of zero, a hyperbaric chamber pressurised to 14·7 p.s.i.g. pressure can be said to be at a depth of 33 feet, which is equivalent to one atmosphere above atmospheric pressure (i.e. two atmospheres absolute).

Physiology

Recent interest in high pressure therapy mainly concerns elevation of inspiratory oxygen partial pressure as a means of overcoming or preventing various types of hypoxia. Although the gas laws of Dalton and Henry provide the physical basis for this application, by themselves they do not provide a physiological basis.

Elevation of the alveolar oxygen pressure by a certain factor will not necessarily raise the oxygen pressure throughout the body by the same value.

The picture is complicated by the properties of haemoglobin, by rates of oxygen uptake and blood flow and by uncertainties concerning the diffusion of oxygen from capillaries into tissues[9].

Fresh air contains 20·94% oxygen, the remainder being mainly nitrogen. At sea level with a barometric pressure of 760 mm Hg the oxygen partial pressure of inspired air is thus 158 mm Hg. When air is inspired, however, it rapidly becomes saturated with water vapour at body temperature, which accounts for 47 mm Hg of the total alveolar gas pressure and leaves only 713 mm for the combined pressures of oxygen and other gases. Alveolar capillary blood absorbs oxygen and gives up carbon dioxide. With normal ventilation the alveolar air contains 14·0% oxygen, providing an alveolar PO_2 a few mm above 100 mm Hg. The alveolar PCO_2 is approximately 40 mm Hg ; nitrogen, water vapour and small amounts of other inert gases make up the remaining alveolar gas pressure. Ventilation of the lungs with 'pure' oxygen rapidly replaces alveolar nitrogen with oxygen, leaving only water vapour, oxygen and carbon dioxide present in the alveoli ; the alveolar PO_2 then equals the total alveolar pressure minus the saturated water vapour pressure plus the alveolar PCO_2.

Fig. 1 shows the alveolar oxygen pressures obtainable when breathing oxygen at various ambient pressures.

ARTERIAL OXYGEN PRESSURE

Alveolar PO_2 is the principal determinant of arterial PO_2 and the values are normally closely related. Sometimes however, several factors can prevent perfect agreement and can cause the arterial value to fall below the mean alveolar level—the factor accounting for such differences as venous admixture.

ARTERIAL OXYGEN CONTENT

Oxygen is carried by blood in two ways. Firstly, it is carried in physical solution in the plasma as dissolved oxygen, and secondly in chemical combination with Hb as oxyHb. Chemically, one gram of haemoglobin combines with 1·34 ml of oxygen. Assuming the haemoglobin concentration is 14·6 G. per 100 ml of blood, the amount of oxygen carried in chemical combination with haemoglobin will be 19·56 ml per 100 ml of blood. When breathing air at atmospheric pressure, haemoglobin is only 97% saturated with oxygen so only 19 ml of oxygen are carried per 100 ml of blood. When 100% oxygen is breathed in the normal subject at atmospheric pressure the Hb becomes fully saturated with oxygen.

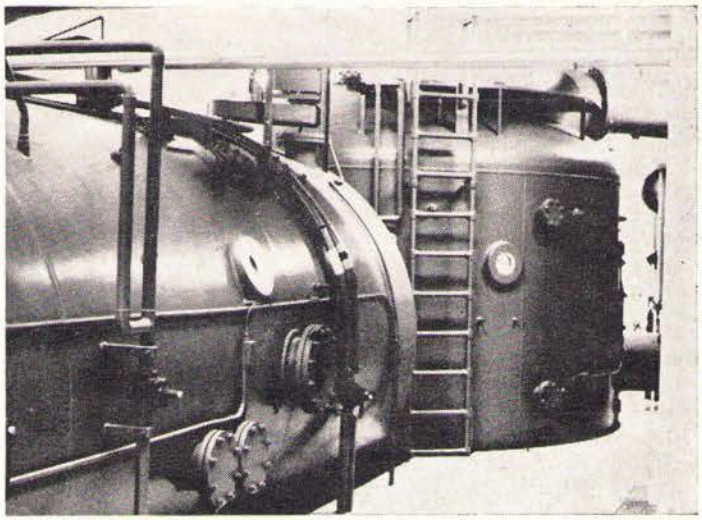

Fig. 3. Compressed air chamber, Children's Hospital Medical Centre, Boston

Further increases in inspired PO_2 (i.e. by raising the ambient pressure at which 100 per cent oxygen is breathed) can result only in an increase in the amount of oxygen in physical solution in the plasma. Therefore when breathing oxygen under hyperbaric conditions the extra oxygen made available to the tissues is derived almost entirely from the increased amount dissolved in the plasma.

Fig. 2 shows the blood oxygen content with inhalation of oxygen at various pressures. The abscissa shows the blood PO_2 level in mm Hg and the ordinate the blood oxygen content in volumes per cent or ml per 100 ml of blood. The left-hand portion of the graph illustrates the oxyhaemoglobin dissociation curve showing the dissociation of oxygen from haemoglobin over the PO_2 range 0-100 mm Hg. At an arterial PO_2 of 1800 mm Hg (i.e. breathing pure oxygen at approximately 2·5 atmospheres absolute, the pressure normally used for therapy at Whipps Cross Hospital) approximately 6 ml of oxygen is dissolved in the plasma per 100 ml of blood. It will be seen from the graph that the quantity of oxygen dissolved in the plasma is very much less than that combined with haemoglobin and that only a minor decrease in physically dissolved oxygen will reduce the arterial PO_2 much more than a similar decrease in oxyhaemoglobin.

CAPILLARY AND VENOUS BLOOD OXYGEN VALUES

On entering a tissue capillary, arterial blood immediately begins to lose oxygen to the surrounding tissues. The quantity lost depends upon the relationship between capillary blood flow and tissue oxygen uptake. When oxygen is being released from haemoglobin, the fall in arterial PO_2 reflects the oxyhaemoglobin dissociation curve and is relatively small, whereas release of oxygen from physical solution reduces the arterial PO_2 radically. This being so, under hyperbaric conditions relatively small changes in the rate of oxygen uptake or blood flow as reflected in the A-V oxygen difference can make a very great difference to the PO_2 at various points in the capillary network.

TISSUE OXYGEN TENSIONS

Capillary oxygen tensions are interesting because they can often be computed and thus provide an index of tissue oxygen tensions. It is questionable whether direct measurement of tissue oxygen tensions is at present reliable[9].

Oxygen molecules reach and enter all body cells and fluids by diffusion from the capillary blood. Administration of oxygen under pressure raises the capillary PO_2 and increases the ability of oxygen to diffuse from the capillaries to distant cells. Oxygen under pressure, therefore, may enable tissues to remain viable for longer periods during temporary reduction of the blood supply. There has been considerable experimental investigation of the oxygen consumption of brain tissue and its period of viability after circulatory arrest. Lanphier and Brown (1966)[9] have estimated that prolongation of cerebral function and survival after circulatory arrest cannot be greater than two minutes even when previously breathing oxygen at 4 atm absolute. This is considerably smaller extension of survival time than can be obtained with moderate hypothermia at normal pressure. Using hypothermia plus OHP (Oxygen at High Pressure), the resulting decrease in rate of cerebral oxygen uptake extends the extra survival period provided by any given quantity of extra dissolved oxygen, decreases the cerebral arterio-venous difference and thus

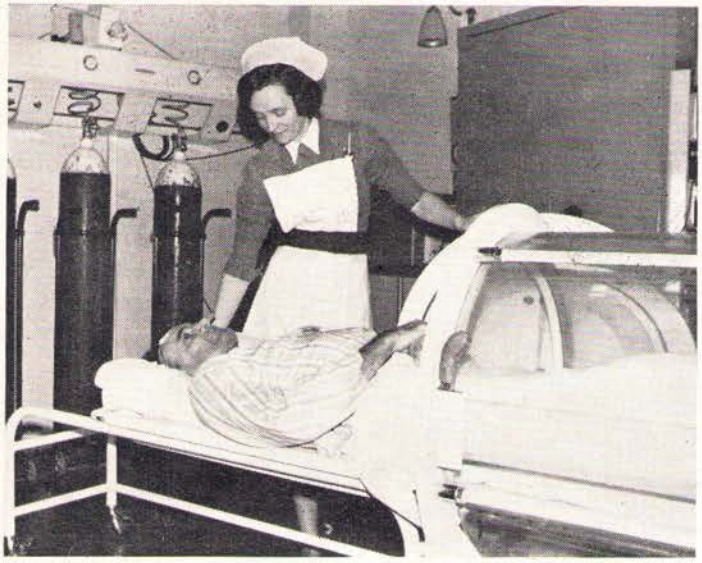

Fig. 4. Hyperbaric oxygen single patient transparent chamber or Clinical Chamber. The bed slides out onto a trolley. The rack of four 240 cu. ft. cylinders supplying oxygen to the chamber is seen behind.

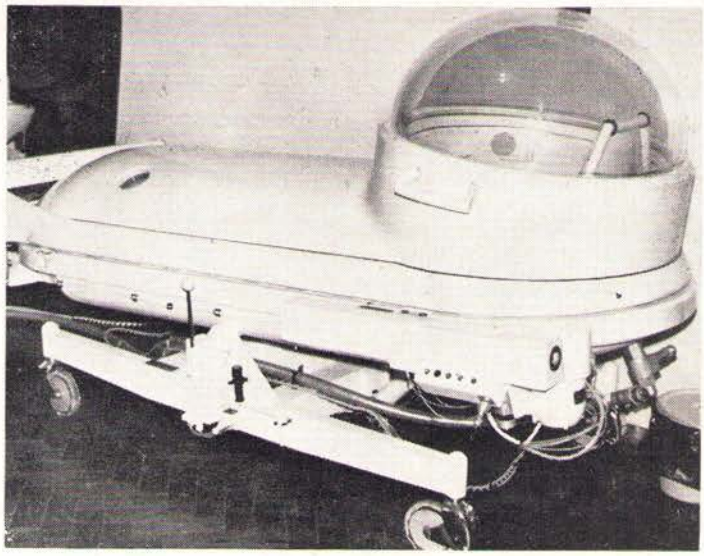

Fig. 5. The Lotus bed.

increases the capillary PO_2[9]. In addition the lower temperature increases the solubility of oxygen.

Estimation of the distance of effective oxygen diffusion from a functioning capillary into a totally ischaemic region has also been estimated by Lanphier and Brown (1966)[9]. It is estimated that the PO_2 would drop to zero in less than 1 mm of distance into ischaemic tissue from the arterial end of a functioning capillary at 3 atm OHP. The effective diffusion distance from the venous end of the capillary appears only slightly greater than under normal conditions. Only by marked reduction of the rate of oxygen uptake by cells along the diffusion path, as occurs in hypothermia, could the order of magnitude be increased.

CONCLUSION, PHYSIOLOGY

Knowledge of the physiological effects of administration of oxygen at increased ambient pressure enables the following conclusions to be made about its possible therapeutic value. These conclusions have been excellently summarized by Lanphier and Brown (1966)[9].

1. OHP can elevate the arterial PO_2 in conditions where pulmonary hypoxia is secondary to continued blood flow through underventilated alveoli.
2. OHP is known to increase the oxygen carrying power of the plasma and this may be valuable where haemoglobin is lost, as in haemorrhage, or inactivated, as in carbon monoxide poisoning.
3. Venous admixture may produce a serious fall in arterial PO_2. This situation may arise in congenital heart disease and if the shunt is small the arterial PO_2 can be corrected by OHP therapy.
4. OHP in conjunction with hypothermia may extend the duration of tissue survival in conditions of temporary cessation or diminution of blood flow.
5. Small increases in the diffusion pathway of oxygen, as in tissue oedema, may be counteracted by OHP. This may occur in the brain following carbon monoxide poisoning or a cerebrovascular accident.
6. OHP is known to inhibit certain anaerobic and aerobic organisms on agar plate cultures[10]. The susceptibility of neoplastic cells to irradiation is known to be increased by raising their cellular PO_2[11]. The ability of OHP to raise arterial PO_2 may therefore be valuable in the treatment of certain infections and treatment of neoplastic conditions in conjunction with irradiation.

Methods of Administration of Oxygen Under Pressure

There are two types of pressure chamber in use for hyperbaric oxygen administration. One is a large operating room pressure chamber enclosing both patient and medical attendants, while the other is a single-person chamber in which only the patient is pressurized while the staff remains outside.

THE LARGE PRESSURE CHAMBER (Fig. 3)

The large type of pressure chamber can be used for surgery. This type of chamber is compressed with air, the medical attendants thus breathing compressed air, while the patient breathes 100 per cent oxygen at the same partial pressure, from a mask or cuffed endotracheal tube according to the state of consciousness. These chambers are expensive to install, operate and maintain.

It should also be noted that when breathing oxygen from a mask, the arterial PO_2 level varies between 63 and 88 per cent of the theoretical maximum, depending upon mask efficiency[12].

THE SINGLE-PATIENT TRANSPARENT CHAMBER

The other type of chamber used for high pressure oxygen therapy is a single-patient chamber—in which the patient alone is exposed to an environment of pure oxygen. The chamber used at Whipps Cross Hospital since January 1964 is shown in Fig. 4. It consists of two concentrically mounted and pressure-tested transparent perspex cylinders with metal end caps, one of which is hinged as a door. The patient is placed on a special stretcher which slides into the tank. Two-way communication is provided. This chamber is easy to run and easy to install. More recently the Vickers hyperbaric bed has been used in addition (see Fig. 5). This chamber is hinged at the foot and opens over its whole length for access. The chamber can be tilted in either direction and the patient treated sitting or lying. This chamber can be pressurized only to 15 p.s.i.g. as opposed to a maximum of 30 p.s.i.g. in the case of the single-patient, transparent chamber.

Both chambers are operated on a closed circuit system, so that oxygen which has been used is recirculated after extraction of odours, impurities and carbon dioxide. The temperature and

humidity of the gas entering the chamber is regulated. Oxygen is supplied from a rack of four 240 cubic feet cylinders. At Whipps Cross the chambers are installed in the same room, the control consoles standing side by side between the two chambers (Fig. 6).

Therapeutic Value of Hyperbaric Oxygen

The physiological basis for high pressure oxygen therapy has been discussed earlier in this paper.

The clinical indications for hyperbaric oxygen are shown in Fig. 7 and some are discussed below.

Carbon Monoxide Poisoning

In carbon monoxide poisoning the rate of dissociation of carbon monoxide from haemoglobin is accelerated by oxygen at increased ambient pressure[13]. Consciousness usually returns within 90 minutes of OHP therapy at 22 p.s.i.g. [14, 15]. Delayed recovery indicates severe neurological damage, poisoning by an additional agent, or both[14]. Such cases may benefit from a combination of

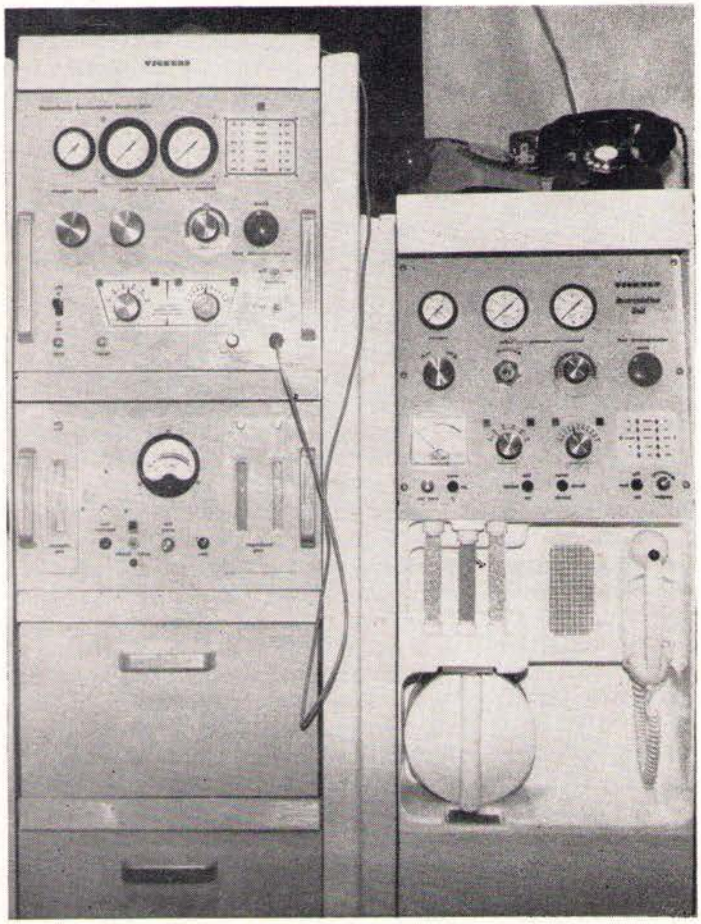

Fig. 6. (above). Control consoles of the clinical chamber (on the left) and the Lotus bed (on the right).

INDICATIONS FOR OHP THERAPY

Definite Indications:

Carbon monoxide poisoning
Cyanide poisoning
Clostridial infection

Of value in:

INFECTIONS
- Surface infections: Burns; Traumatic injuries; Ulcers; Wounds
- Deep infections: Chronic osteomyelitis; Fistulae

SURGERY: Plastic—before and after surgery; Cardiovascular

ISCHAEMIA: Acute traumatic; Embolism or thrombosis before and after surgery; Frostbite

PROPHYLAXIS against gas gangrene infection: Severe traumatic injuries; Septic abortion

MALIGNANCY: in conjunction with radiotherapy

NEONATAL: Respiratory distress syndrome

May Prove to be of Value in:

ACUTE MYOCARDIAL INFARCTION

PULMONARY EMBOLISM

CHRONIC RESPIRATORY DISEASE

SHOCK
CARDIAC ARREST
In patients who fail to regain consciousness

CARBON MONOXIDE POISONING
In patients who fail to regain consciousness after 90 minutes HBO therapy at 22 p.s.i.g.

→ In conjunction with hypothermia

INFECTIONS
In patients who have failed to respond to routine therapy

- *Fungal* in particular: Candida species; Aspergillus fumigatus
- *Leprosy*
- *Tuberculosis*
- *Bacterial*: Pseudomonas; Staphylococcus aureus; Escherichia coli; Proteus

MALIGNANCY
In conjunction with antimitotic drugs

ORGAN PRESERVATION

Fig. 7.

hypothermia and hyperbaric oxygen.

The clinical use of hyperbaric oxygen in the successful treatment of carbon monoxide poisoning has been demonstrated by a number of workers [13, 14, 16].

Cyanide Poisoning

Cyanide is used extensively in industry but, in spite of its extreme toxicity, it causes only about 40 deaths a year[17]. Cyanide causes chelation of certain intracellular enzymes necessary for utilisation of oxygen in the tissues. Cyanide is readily detoxicated by conversion to thiocyanate, so the usual treatment for poisoning consists of an injection of sodium thiosulphate. Additionally, intravenous sodium nitrite administration converts haemoglobin to met-haemoglobin which reacts with hydrocyanic acid and frees the respiratory enzymes. It appears, from recent experimental work, that "hyperbaric oxygen may be useful in the treatment of cyanide poisoning"[18].

Anaerobic Infections

Clostridial infections are caused by bacteria which grow anaerobically but which suffer inhibition of growth in an oxygen environment[10]. Such infections, therefore, tend to develop in deep-seated, poorly vascularised, dirty wounds, where there is dead tissue present, thus providing relatively anaerobic conditions.

Gas gangrene is a serious form of clostridial infection, generally developing in severe injuries such as gunshot wounds and industrial or road traffic accidents. Occasionally it occurs in an infected area with diminished blood supply as may occur in a patient with diabetic gangrene, or following amputation of an atherosclerotic limb. Gas gangrene presents as swelling and discolourisation of the affected part associated with gas formation in the muscles, which rapidly become gangrenous. There is severe toxaemia. Before the therapeutic value of hyperbaric oxygen was recognised, many patients died unless diagnosis was made early, followed by radical, and often mutilating, surgery.

Hyperbaric oxygen therapy is thus the treatment of choice in gas gangrene and its value is well recognised. [19, 20, 21]

Hyperbaric oxygen therapy quickly and dramatically relieves the toxaemia, thus reducing the risks of any necessary surgery for the removal of dead tissue [15, 19]. Further OHP therapy and antibiotics can then be given, thus providing a definitive treatment. It is imperative that patients with gas gangrene are treated as soon as the diagnosis is suspected, as their condition deteriorates rapidly. The typical appearance of a limb with a clostridial gas gangrene infection is shown in Fig. 8.

Fig. 8. Clostridial gas gangrene of the thigh. Appearances at operation showing the black necrotic musculature.

OHP can also be effectively used prophylactically in the treatment of patients with wounds from which clostridia have been cultured, but without any evidence of clinical gas gangrene[15].

Aerobic Infections

(a) Surface Infections

Experimentally it has been demonstrated *in vitro* that hyperbaric oxygen is bacteriostatic to a number of common aerobic pathogenic organisms in surface cultures[10]. It has also been shown experimentally *in vivo* that in infected surface wounds exposure of the wounds to oxygen at increased ambient pressure is an effective method of control of infection[22]. Pennock (1966)[23] also has demonstrated the inhibitory effect of hyperbaric oxygen on aerobic organisms on surface cultures but has shown as well that growth stimulation occurs in deeper cultures. It has been suggested from *in vitro* experimental studies that bacterial growth stimulation might occur beneath exudates overlying surface infections which are being treated with exposure to oxygen at increased pressure[24]. From clinical results it seems doubtful whether this interesting *in vitro* observation can be applied directly to the *in vivo* situation[15].

Clinically, encouraging results have been obtained in the treatment of infected burns[21, 25], infected gravitational and decubitus ulcers[26, 27, 28, 29] and in surface infections following trauma[15].

A typical example of infected burns treated with OHP is shown in Figs. 9 and 10.

Figs. 11 and 12 show varicose ulcers which had been present for 26 years and healed following a course of OHP.

(b) Deeper Infections

Hyperbaric oxygen therapy has had little use so far in the treatment of deep infections, except in clostridial septicaemia[15], although cure of systemic pyocyaneus infection has been reported[30].

In bone infection, however, oxygen therapy at increased ambient pressure appears a useful method of treatment[31, 32].

Encouraging results have been reported in the treatment of sinuses following chronic osteomyelitis[31, 32]. In some cases delineation of sequestra appears to be encouraged[15], and effective surgery can then be carried out, and followed by further hyperbaric oxygen therapy.

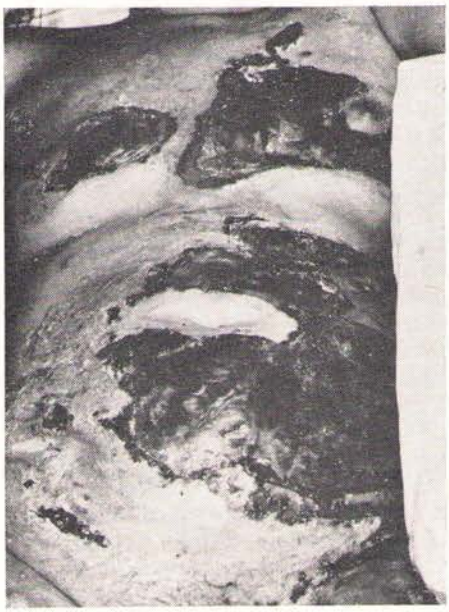

Fig. 9. Burns involving 30 per cent of the body surface area.

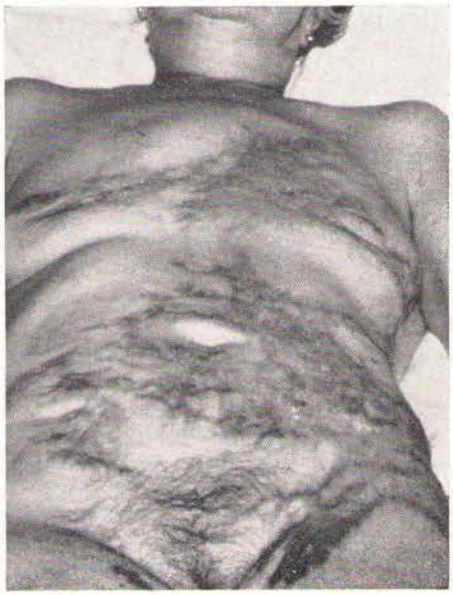

Fig. 10. Healing of burns after 25 hours' hyperbaric oxygen therapy over eight weeks.

Ischaemia

There has been little objective clinical support for the early hopes for hyperbaric oxygen therapy in the treatment of limb ischaemia due to peripheral vascular disease. In most cases only temporary improvement occurs while the patient is actually being treated, with reversion to the previous state as soon as the treatment ends[27].

Hyperbaric oxygen therapy, however, does seem to be beneficial following acute traumatic vascular injuries. Reports of its use are encouraging[26, 32] especially if treatment is started early[15] and combined with any necessary vascular surgery.

Where ischaemia is confined to surface tissues as in ischaemic or decubitus ulceration, benefit can be expected from hyperbaric oxygen therapy[15, 29]. Most of these ulcers are also infected and hyperbaric oxygen probably helps by its antibacterial action and also by promoting healing by increased oxygenation of the tissues.

Once healed, healing often can be maintained as the metabolic demands of intact skin are relatively low.

Frostbite is a special form of ischaemic lesion. The fact that mountain climbers using oxygen have a lower incidence of frostbite than those not doing so suggests that tissue hypoxia is a predisposing factor in frostbite[34]. Successful treatment of frostbite with OHP has been reported and it is suggested that patients with cold injury should be treated with OHP early to try to preserve marginally viable tissue and reduce tissue loss[35].

Surgery, Plastic

It seems that skin flaps which are questionably viable may be saved by OHP therapy[13, 35] and that breakdown of a skin graft is less likely[36].

Surgery, Cardiovascular

Cardiovascular surgery necessitates the use of a compressed air operating chamber. Experimentally, hyperbaric oxygenation, especially when combined with hypothermia, can prolong the period of safe circulatory arrest for surgery on the cardiovascular system[37].

Bernhard (1964)[38] from his extensive experience of the use of hyperbaric oxygenation during the operative correction of congenital cardiac lesions in infants concludes that the prime indication for hyperbaric oxygenation, in the surgical management of such patients, is for the performance of palliative or corrective operations during the interval of biochemical and metabolic improvement which occurs while the patient is breathing oxygen at increased ambient pressure.

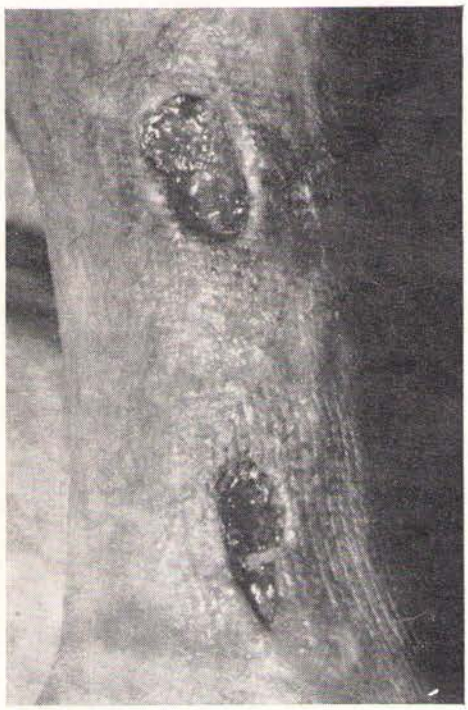

Fig. 11. Gravitational ulceration appearances prior to hyperbaric oxygen therapy.

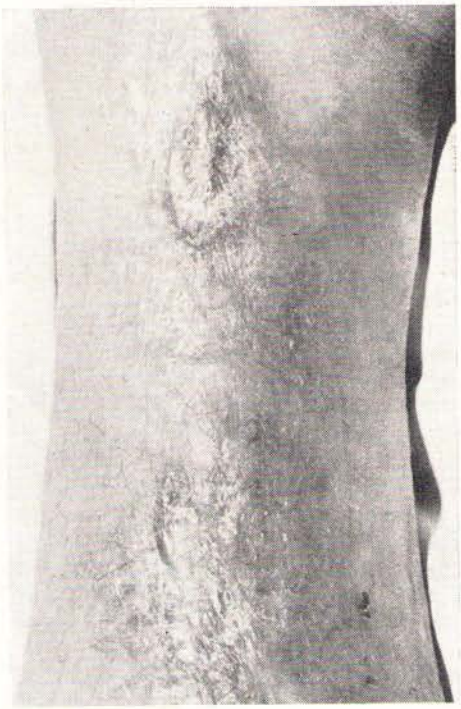

Fig. 12. Complete healing of the gravitational ulcers after 23 hours' hyperbaric oxygen therapy over 26 days.

Malignancy

The use of hyperbaric oxygen in combination with radiotherapy in the treatment of malignant disease is now well established[8, 39].

The results of this form of treatment in patients with malignant disease, so locally advanced that cure by conventional treatment was not considered possible, have recently been analysed[39]. It was concluded that OHP combined with radiotherapy leads to a maximum response in tumours already designated as radiosensitive and the greatest 'oxygen effect' was with moderate sized tumours with a reasonable blood supply which had not already caused excessive damage to surrounding normal tissue. The authors thought that the improvement in their results were partly due to the oxygen effect and partly to the method of fractionation of radiation dose.

Neonatal Resuscitation

Hutchison *et al* (1966)[40] recently conducted controlled clinical trials on the treatment of asphyxia neonatorum, comparing the use of OHP alone with tracheal intubation and IPPR. They concluded that under the every-day conditions of obstetric practice both techniques are equally effective methods of resuscitation. Tracheal intubation requires special training and skill, whereas the use of the neonatal OHP chamber can be taught to relatively inexperienced staff in a very brief period of time.

Possible Future Therapeutic Indications or Hyperbaric Oxygen

The conditions in which high pressure oxygen therapy may be valuable in the future are listed in Fig. 7. Cameron and his co-workers (1966)[41] have recently investigated the haemodynamic and metabolic effects of hyperbaric oxygen in ten patients with myocardial infarction. Hyperbaric oxygen may prove most useful in patients with severe hypoxia, hypotension and metabolic acidosis, who have failed to respond to conventional therapy.

In experimental pulmonary embolism, hyperbaric oxygen therapy increases the survival rate by relieving hypoxia, thereby improving cardiac function and resulting in displacement of the clot towards the periphery of the lung[42].

The usefulness of hyperbaric oxygen in respiratory disease is debatable. Oxygen under pressure might be useful in conditions where alveolar ventilation is deficient compared to perfusion with a resulting fall in arterial PO_2[9]. Generally the PO_2 of the underventilated alveoli can be maintained by artificial respiration with oxygen, but with closure or collapse of still perfused alveoli this may be insufficient. Such a situation may arise in severe hypoxic pneumonia and asphyxia neonatorum[9].

Douglas and Crowell (1966)[43] have recently reviewed the value of OHP in shock. They concluded that it might be useful in the treatment of haemorrhagic but not endotoxic shock.

Hypothermia in combination with hyperbaric oxygen should improve cerebral function and survival of tissue in circulatory arrest. It is also known that the solubility coefficient of oxygen increases with depression of body temperature[9]. It therefore seems rational in patients who fail to regain consciousness following cardiac arrest, in spite of return to sinus rhythm and correction of metabolic acidosis, to combine OHP therapy with hypothermia. This combination has already been mentioned in the treatment of severe carbon monoxide poisoning.

McAllister *et al* (1964) have shown that OHP has an inhibitory effect on the growth of certain organisms on agar plate culture[10]. These organisms include *Pseudomonas pyocyanea, Staphylococcus aureus, Aspergillus fumigatus, E. coli* and *Candida albicans*.

Gottlieb (1963)[44] has found that growth of the lepra bacillus and the tubercle bacillus (including the Scotochromogenic and Battey-type organisms) is inhibited by OHP. In the future OHP may prove useful in treatment of such infections. The findings of Pennock[23], which have been mentioned, concerning growth stimulation of organisms in deep culture when exposed to OHP must be remembered, however.

Experimental studies have suggested that OHP may enhance the effect of chemotherapeutic agents in cancer therapy[45] and in the future this application of OHP may prove a useful form of treatment in disseminated carcinoma.

Ackerman and Barnard (1966)[46] have recently performed experiments in order to assess the best method of preservation of canine kidneys for 24 hours prior to transplantation. They found that the combination of hypothermia, OHP and low pressure perfusion of the organ was a successful technique, resulting in satisfactory renal function immediately post-storage when the kidneys were transplanted into totally nephrectomised dogs.

The Hazards of Hyperbaric Oxygenation

These can be divided into hazards to patients and hazards to personnel, with particular application to personnel working in medical compressed air chambers.

HAZARDS TO PATIENTS

Oxygen toxicity

The fundamental basis of oxygen toxicity is inhibition of enzyme systems within the cell[47, 48]. Clinically, the signs and symptoms of oxygen toxicity usually appear initially in the nervous and respiratory systems. Since the basic disturbance is at cellular level, probably all systems are involved.

Neurological effects

Paul Bert in 1878 in animal studies found that exposure to more than three atmospheres of oxygen caused convulsions[49]. Donald (1947) in his extensive studies of neurological oxygen toxicity showed that there was variation between different subjects in the duration of exposure to oxygen required before symptoms occurred[50]. He also showed that the time to onset of symptoms varied on different occasions in the same subject. Donald studied a large number of subjects exposed to high pressures of oxygen in compressed air and schematically documented the signs and symptoms of oxygen toxicity as shown in Fig. 14.

It seems unlikely that serious neurological oxygen toxicity will develop in healthy individuals who are exposed to oxygen at pressures of 2-2·5 atmospheres absolute for 2 hours or less. In a series of 230 patients treated at 2·5 atmospheres of oxygen, only four had convulsions and these patients were suffering from severe toxaemia before treatment[15].

Pulmonary effects

Lorrain Smith in 1899 in animal studies was the first to demonstrate that inflammatory changes, similar to pneumonia, were caused in the lungs by breathing oxygen at high partial pressure. He showed that the higher the partial pressure of oxygen used, the sooner the inflammatory changes appeared. It seems unlikely that pulmonary oxygen toxicity will present any serious problem with the relatively brief and intermittent exposures to hyperbaric oxygen used in the treatment of patients[51].

Pulmonary atelectasis

Pulmonary atelectasis results from absorption of alveolar gas from the closed cavity formed when a bronchus is blocked with mucus or other foreign body. Absorption of gas and subsequent atelectasis is greatly accelerated when air is replaced by oxygen as the respired gas. It is therefore unwise to expose patients with acute chest infections to hyperbaric oxygen except as a life saving measure as for treatment of clostridial gas gangrene[52].

Aural atelectasis—otitic barotrauma

The middle ear is a gas-containing cavity separated from the external meatus by the tympanic membrane and communicating with the pharynx via the Eustachian tube. Should the Eustachian tube remain blocked (as from catarrh) during an increase in ambient pressure, the gas in the middle ear is absorbed and drum retraction occurs. This is accentuated by the increased pressure on the external surface of the drum. If oxygen replaces air as the respired gas, aural atelectasis and barotrauma will develop more quickly since the nitrogen of the air is replaced by oxygen. Oxygen has a higher absorption coefficient in blood than has nitrogen.

The initial symptoms of aural atelectasis are discomfort and deafness. Large decreases in pressure in the middle ear may result in rupture of vessels in the mucosal lining and bleeding into the cavity. Excessively rapid pressurisation of a hyperbaric chamber could cause rupture of an ear drum.

In a series of 230 patients, earache of varying severity developed in 47 per cent. In only five (2 per cent) was this so severe that the patients had to be decompressed[13].

Decompression causes little ear discomfort, since it is much easier for gas to escape from the middle ear to the pharynx than to enter the middle ear from the pharynx. Extremely rapid decompression from a high pressure oxygen environment possibly could cause drum rupture. This has never occurred, however, in a large series of patients on the rare occasions that emergency decompression has been required[15].

HAZARDS OF HYPERBARIC OXYGENATION

1. HAZARDS TO PATIENTS

Oxygen toxicity

Pulmonary atelectasis

Aural atelectasis, further complicated by possibilty of barotrauma

Pain in sinuses or teeth cavities

Nausea or vomiting on decompression

11. HAZARDS TO MEDICAL PERSONNEL in Compressed Air Chambers

Decompression sickness

Type I — Bends

Type II — Pulmonary chokes, Cardiovascular, Neurological

Type II after short exposure

Rupture of bulla—Bleb formation
Air Embolism

Avascular necrosis of bone

Inert gas narcosis

Increased work done in breathing, increased airway turbulence

Fire

Fig. 13.

Pain in the sinuses or tooth cavities

This complication of hyperbaric oxygenation and change of pressure is rare and arose only on two occasions in a series of 230 patients[15].

Nausea or vomiting after decompression

This is an uncommon complication of decompression. It is probable that the patient swallows gas whilst at pressure and expansion of the gas occurs on decompression, causing gastric distension. It seems wise not to recommend swallowing or gum chewing for relief of earache on compression; forcibly expiring against a closed mouth and pinched nose seems to be just as effective[15].

Psychological complications

Major psychological complications of hyperbaric therapy are rare. In 230 patients treated in the single-patient chamber, the incidence of apprehension (3 patients) and claustrophobia (7 patients) was surprisingly low, largely because the method of therapy was fully explained to the patient. The transparency of the chamber walls, and the intercommunication system also helped to reduce claustrophobia. Naturally, minor apprehension occurs in most patients, but this is readily allayed by compressing the patient slowly for the first treatment cycle[15].

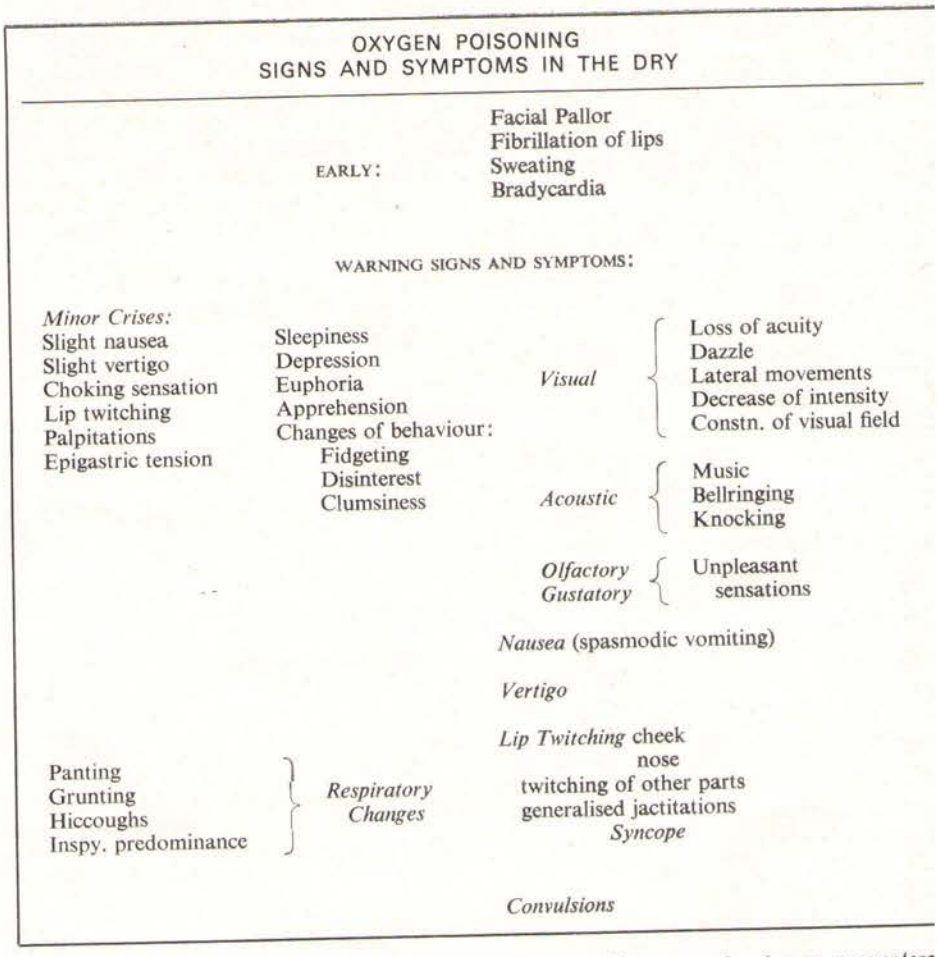

Fig. 14. Schematic representation of signs and symptoms of oxygen poisoning as encountere in a large series of exposures of conscious subjects to toxic tensions of oxygen (3 to 5 atmosphere absolute) in compressed air. Reproduced by kind permission of Professor K. W. Donald (M.D. Thesi Cambridge, 1945).

HAZARDS TO MEDICAL PERSONNEL IN COMPRESSED AIR CHAMBERS

Decompression Sickness, Types I and II

Body tissues are normally saturated with atmospheric gases at the pressure at which they are present in the atmosphere. When the ambient pressure is raised and the gases are inhaled at the raised pressure, greater amounts of gas dissolve in the tissues until tissue saturation is attained at the higher pressures. If rapid decompression is now performed, bubble formation occurs—this follows the saturation of the body with nitrogen[53].

Decompression sickness can be divided into Type I, in which bubble formation occurs in the region of a major joint, or Type II which is more serious, and consists of bubble formation in the respiratory, cardiovascular or nervous systems. Both conditions are treated by recompression of the individual in a compressed air or OHP environment.

Walder (1966)[53] describes a special variety of Type II decompression sickness which occurs after only short exposures to compressed air. Gas trapping may arise in the lungs of individuals exposed to compressed air. The gas, trapped beyond a blocked bronchus, expands on decompression, and produces a bulla which ruptures into the interalveolar septum and causes bleb formation in the loose connective tissue layer of the septum. Gas bubbles may then pass into the pulmonary venous circulation producing this special variety of Type II decompression sickness.

Avascular necrosis of bone

This insidious condition may not present until months or years after working in compressed air, and may follow only one exposure[53]; the bone lesion consists of an area of aseptic necrosis, often close to a major joint.

At present there is anxiety that this condition will arise in personnel working in the medical compressed air chambers. The aetiology is not clear but the condition is probably secondary to nitrogen bubbles occluding blood vessels in the bone[53]. Symptoms arise when the area of dead bone causes collapse of the overlying articular cartilage.

Inert gas narcosis

This hazard has nothing to do with decompression, but is important to surgeons operating in high-pressure air environments. The condition is said to be due to the effect on the brain of the high partial pressure of nitrogen a results in a progressive narcosis[53]. T card sorting test[55] which was carried o on men at different pressures of co pressed air suggests that whenever a sk involving complex mental operations undertaken after some time of exposu to compressed air at 2 atmosphe absolute or greater it cannot necessar be assumed that it will be carried out adequately as at normal pressure. T applies particularly if a new unrehears situation arises.

Increased work of breathing; increa airway turbulence

The mechanics of breathing are alte at increased pressure. An increase pressure is accompanied by an incre in the density of the gas respired. As ambient pressure rises and gas den increases, so the Reynolds number increase for any given part of bronchial tree; thus, the ratio of tur lent flow to laminar flow increases[56].

Even in normal individuals this p duces an increase in the work of mov gas through the airways. With nor

airways, the effects on resting ventilation are negligible, even at very high pressures[9]. In patients with pulmonary disease, however, there is a possible danger that pressurisation may precipitate respiratory failure. Individuals with respiratory disease should not, therefore, work in compressed air.

The fire hazard

Fire is the main hazard to be guarded against by workers in hyperbaric medicine.

It is known that in oxygen the *"increased risks of fire are due to a roughly one thousandfold rise in ignitability and a five-fold rise in burning rate, coupled with an ineffectiveness of most conventional fire-proofing agents, and of smothering as a means of extinction"*[57]. From a series of 45 experiments upon the effects of igniting clothing (mounted on a brass dummy or on dead pigs) in gas environments with oxygen partial pressures ranging from 0·2 to 1 atmosphere it was concluded[57]:

1. The risks of igniting the clothing of a man are greatly increased in these environments.
2. Fires in oxygen rich environments are of a fundamentally different character from those in air. (Flash fires occur in oxygen).
3. Igniting the clothing of a man in these environments may lead to fatal damage within 5 to 20 seconds of onset.

The increased risks of fire apply to compressed air environments as well as oxygen environments. From a series of experiments in which washed denim squares and pigskin clothed in washed denim squares were ignited in compressed air from 1 to 5 atmospheres, and oxygen at one atmosphere, it was tentatively concluded that "the fire risks to man in compressed air environments (over this pressure range) are greater than in air at one atmosphere but less than in oxygen at one atmosphere"[58].

It cannot be stressed too strongly that workers in the hyperbaric field should be aware of the increased fire risk and should ensure that they are acquainted with all the necessary precautions to minimise the risk as far as is practicable and to reduce the risks of setting fire to personnel.

Recommended precautions are the rigid exclusion from the chamber of all unshielded inflammables and ignition sources and the scrupulous earthing of all components[59].

Further experiments have shown that fires in oxygen rich environments can be controlled by a dense water spray and that the effects of fires in hyperbaric chambers can be reduced by the following precautions[57].

(i) Occupants should wear a tight fitting single layered garment of light weight, open-meshed material, proofed with a 10% pick-up of Borax/boric acid. This overall should conform as closely as possible to the body to avoid creating tracks for the spread of a flash fire.

(ii) An extinguisher system should provide water spray of at least 5 ml/min/cm^2 throughout the envelope of the occupant's movements, within 2 seconds of operation.

(iii) The extinguisher system should be automated to respond to a flash fire within that envelope and should have a manual override that can be operated from the inside and the outside of the chamber.

(iv) An open-ended hose, supplied from the ring main, should be provided, to be used to douse those areas such as the crutch that are shaded from the general spray.

Conclusion

The physiological basis of hyperbaric oxygen therapy has been briefly discussed. The patient can be treated in a single-person chamber compressed with oxygen, or in a compressed air chamber, inhaling oxygen via a mask or endotracheal tube. High pressure oxygen therapy is indicated in clostridial gas gangrene and carbon monoxide poisoning. It has proved valuable in the treatment of surface infections, including burns, skin ulcerations and skin lacerations, and in chronic osteomyelitis. It is a valuable adjunct to plastic surgery and is being used successfully in the surgical management of cyanotic heart disease. OHP therapy seems beneficial in the treatment of acute vascular injuries. Results of radiotherapy in conjunction with OHP are encouraging and OHP therapy appears to be effective in resuscitation of the new-born. The possible future therapeutic indications for OHP and the hazards of hyperbaric oxygenation have been discussed.

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