THE
BRITISH HYPERBARIC
ASSOCIATION

GUIDE TO ELECTRICAL SAFETY STANDARDS
FOR
HYPERBARIC TREATMENT CENTRES

British Hyperbaric Association
Technical Working Party

Guide to Electrical Safety Standards
for
Hyperbaric Treatment Centres

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A GUIDE TO THE USE OF ELECTRICITY IN PRESSURE CHAMBERS.

1.0   INTRODUCTION

The remarkable and accelerating advance in medical electronic technology in the past decade has enabled patient care to be improved by the ready availability of electrically powered monitoring and therapeutic equipment. The stage has now been reached in some specialities where it is seen as unreasonable to deny patients access to such equipment. The adoption of electrically powered equipment in hyperbaric medicine has been hampered by its perceived potential as a fire risk in oxygen enriched atmospheres, by the need for electronic circuitry to be pressure resistant or pressure compatible and by the requirement for it to be waterproof to protect it during fire suppression measures.. The low demand for equipment to meet these conditions has meant that a generally agreed manufacturing standard has not been developed. At the same time hyperbaric physicians are under an increasing obligation to use the electronic equipment routinely available in the hospital ward for patients under pressure. There is a need therefore for some guidelines to safe practice.

1.1   Scope of Document

⇒   The effects of electricity on the human body
⇒   Wiring and earthing standards
⇒   Medical electrical equipment standards
⇒   Fire risks
⇒   Guidelines for the choice of equipment to be used under hyperbaric conditions
⇒   Use of defibrillators in pressure chambers
⇒   Use of mobile telephones

1.2   Purposes of Document

⇒   Provision of basic information on the effects of electricity on the human body.
⇒   Description of basic safety concepts.
⇒   Indication of existing applicable electrical standards and their shortcomings.
⇒   Description of the particular electrical hazards of the hyperbaric environment.
⇒   Guidance on the choice and use of equipment and possible modification.

2.0   THE EFFECTS OF ELECTRICITY ON THE HUMAN BODY

The flow of electricity in the human body has two effects.

1 -   Disruption of normal electrical activity.
2 -   Destruction of tissue.

2.1   Disruption of Physiological Processes.

For shocks of more than one second duration the hazard is related to the current flow in the body. This can be calculated from Ohm's law (equation 1).

Equation 1
$$\text{Current flow} = \text{Potential Difference} \div \text{Resistance}$$
or in units
$$\text{Amps} = \text{Volts} \times \text{Ohms}$$

The hazard increases as current rises, as voltage rises and as resistance falls.

For shocks of less than one second hazard is related more to the energy of the shock which can be calculated (equation 2, see page 5)).

2.1.1   Perception Threshold

Stimulation of receptors in the skin causes a sensation of tingling at low current and then pain at higher levels of current. The lowest current which can be perceived by a victim is termed the perception threshold.

2.1.2   "Let Go" Threshold

Stimulation of peripheral nerves causes pain and muscle contraction. Direct stimulation of muscle also causes it to contract. The lowest current causing muscle spasm is the "let go" threshold; so-called since at this level of current and greater a victim may not be able to release a conductor which has been grasped and so suffer continuous electrical shock.

2.1.3   Respiratory Effects

If the victim is held on to the conductor as described above and if current flows through the chest, the victim's breathing can be affected. At the same time, muscle spasm itself increases the body's demand for oxygen and suffocation may be a cause of death in these instances.

Electric current flowing through the respiratory centres of the brain is also thought capable of causing respiratory inhibition and hence death by suffocation.

2.1.4   Cardiac Effects

Direct stimulation of the heart muscle can disrupt the activity of the heart. The electrical activity of the muscle fibres that transmit electrical signals in the heart can be disturbed and this disrupts the co-ordination of the heart and causes ventricular fibrillation. Ventricular fibrillation occurs when the contraction of the heart muscle is so disorganised that no blood is pumped to the brain and irreversible brain damage occurs in 4 minutes or less. **Ventricular fibrillation is the most common cause of death due to electric shock.** Extensive work has been performed on the sensitivity of the heart to electric shock and this has shown that fibrillation is most likely if the shock affects the vulnerable period of the cardiac cycle: the period just before and during the upstroke of the T wave on the electrocardiogram. This is particularly important for shock duration of less than 100 ms when fibrillation may occur for current magnitudes over 500 mA if the shock involves the vulnerable period. Currents of several amperes are require to induce fibrillation if the shock falls outwith the vulnerable period.

Much higher currents cause all the heart muscle to depolarise and contract for as long as the current is applied. When this current is stopped the heart, if it has not been damaged, can start beating normally again. This phenomenon is the basis of the cardiac defibrillator.

2.1.5   Cerebral Effects

Stimulation of the brain causes unconsciousness and convulsions. This is the basis of electro-convulsive therapy. As mentioned above, electric current flowing through the respiratory centres of the brain is also thought to cause respiratory inhibition and death by suffocation.

2.2   Tissue Destruction

The tissue destruction hazard is related to shock energy which can be calculated (equation 2)

Equation 2
$$\text{Shock energy} = \text{Current}^2 \times \text{Resistance} \times \text{Time}$$

or in units
$$\text{Joules} = \text{Amps}^2 \times \text{Ohms} \times \text{seconds}$$

The hazard due to energy release increases with increasing current, with increasing resistance as long as current flows and with increasing shock duration. Current is calculated from Ohm's law for this calculation and so energy release also depends upon voltage (equation 3).

Equation 3
$$\text{Shock energy} = \text{Potential Difference} \times \text{Current} \times \text{Time}$$
or in units
$$\text{Joules} = \text{Volts} \times \text{Amps} \times \text{seconds}$$

2.2.1 Electrothermal Burns

These can occur at points on the path that electricity takes through the body where resistance is high or where current flow is high. The skin has the highest resistance and so there is commonly a burn at the points where the current enters and leaves the body. This need not be the case, however, and all the organs along the current path may be affected including muscles, neurovascular bundles and tendons particularly in the narrow parts of the limbs where resistance is highest such as the wrists and hands. Muscle damage causes release of myoglobin into the blood stream and this in turn may be a factor precipitating renal failure after electric shock. Major tissue damage is followed by hypovolaemia, cardiovascular shock and severe illness. Even where superficial tissue damage seems trivial, however, internal injury may be significant enough to cause damage to peripheral nerves or result in long term muscle contracture.

2.2.2 Arc Burns

These are burns caused by the intense heat given off by an electric arc and involve exposed skin. They are usually of minor importance and can be regarded in the same way as other cutaneous burns. They may be rendered more significant, however, if clothing catches fire or if the eyes are involved.

2.2.3 Mixed burns

These burns occur when the flash of an arc and the passage of an electric current are associated and are usually due to accidents involving high voltages.

2.3 Alternating Current (AC)

It is a peculiarity of electric shock that disruption of physiological processes are most efficiently induced by a changing electric current and voltage rather than by one which is constant. Alternating electric current (AC) is therefore more dangerous than direct current (DC) and this is most marked for AC currents of 10-300 cycles per second (Hz). At these frequencies and for shocks of more than 2 seconds in duration AC shock is twice as dangerous than DC. At lower frequencies, the potency of AC falls back to that of DC. As frequency increases the disruption of electrically mediated physiological processes becomes less important and the effects of electric shock are seen more as both internal and external burns and are related to energy levels.

Table 1 Effects of Alternating Currents from 15 to 100 Hz

Effects of Externally Applied Alternating Current	Current (mA)	
	Men	Women
No sensation	0.4	0.3
Pain	1.1	0.7
"Let go" threshold, mild muscle spasm	16	10
Severe muscle spasm, breathing difficult	23	15
Ventricular fibrillation		
3 second shock	80	80
0.3 second shock	800	800
Tissue destruction		>300

The effect varies with the current path and the duration of the shock.

2.3.1 "Let go" threshold

The let go threshold has been defined in 2.1.2. Because of the effects described in 2.1.2 and 2.1.3 death may result and safety standards are based on this current, which is very much less than that required to cause ventricular fibrillation, for shocks longer than 10 seconds.

2.3.2 Ventricular fibrillation threshold

With AC. there is a marked decrease of the threshold of fibrillation as the duration of shock is prolonged beyond the length of one cardiac cycle. A level of current below that which produces fibrillation may increase the excitability of the heart muscle and this produces extrasystoles during which fibrillation threshold is much reduced.

2.4 Direct Current

Direct current may be defined as a current with a frequency of less than 0.1 Hz and with an AC ripple of less than 10% of the associated root mean square (r.m.s.) voltage. Up to 2 mA there is usually no effect but at approximately 2 mA slight pain is felt on switching the current on or off (the equivalent level for 50/60 Hz is about 1 mA and the sensation continues while the current flows). There are usually no harmful physiological effects up to 20 mA even though pain might be appreciated. Although these levels of electric shock are unlikely directly to cause short term ill effects they may cause the victim to move involuntarily and this sudden movement can precipitate a non-electrical or secondary accident.

2.4.1 Muscle spasm

Unlike AC there is no definable "let go" threshold since only the making and breaking of current leads to painful and cramp-like contractions. As mentioned above, however, the effects of electric current are most marked during changes of current and voltage and it is possible for a victim to experience sudden muscle spasm and pain on releasing a DC conductor which is sufficient to cause it to be grasped again. The victim may be unable to let go because of this and secondary accidents may be precipitated. Safety levels for DC, therefore, are not based on the muscle spasm threshold.

2.4.2 Heart dysfunction

At DC current levels higher than 20 mA there is an increasing likelihood of disturbance of heart function such as irregular beating and it is this effect that determines DC safety levels. At 150 mA the likelihood of death due to ventricular fibrillation is 5% and at 175 mA it is 50%. Information derived from electrical accidents seems to indicate that the danger of ventricular fibrillation generally exists only for longitudinal currents. For transverse currents (from hand to hand) animal experiments have, however, indicated that a higher threshold may exist. In turn, longitudinal current is most dangerous when the feet are positive (table 2). For shocks that last for longer than the cardiac cycle, the threshold of fibrillation for DC is several time higher than for AC (cf tables 1&2). For shocks of less than 200 ms the threshold for fibrillation is the same for both types of current.

Table 2. Effects of Direct Current

Effects of Direct Current for 2 second shocks from left hand to feet with the feet positive (rising current; downward current is 50 % less lethal)	Current (mA)
Light stitching pain when switching on and off	2-3
Warm sensation, increasing risk of burns	10-300
5% risk of ventricular fibrillation	150
50% risk of ventricular fibrillation	300
Internal burns, unconsciousness	>300

2.5 The Electrical Impedance of The Human Body (a)

The effects of electricity on the body described above depend upon the current and voltage generated by an electric shock and these in turn depend upon the electrical impedance of the body. Simply, this can be thought of as consisting of two components; the impedance of the skin and the internal impedance of the body.

2.5.1 Skin Impedance

The impedance of the skin depends on the voltage, frequency, shock duration, surface area of contact, pressure of contact, the degree of skin moisture and temperature. For touch voltages of up to about 50 V impedance varies widely because of these factors both within and between individuals.

At voltages of 50 V to 100 V skin resistance reduces considerably and becomes negligible when the skin breaks down.

Skin impedance is made up of both resistive and capacitative elements. At the moment voltage is applied the capacitative element is not charged and so skin impedance is negligible and the initial electrical impedance of the body is approximately equal to its internal impedance alone.

Again, because of the capacitative element of skin resistance, skin impedance decreases as current frequency increases

2.5.2 Internal Impedance

Internal impedance of the body is largely resistive and depends principally on the current path although when the area of contact becomes very small, internal impedance is reduced.

2.5.3 Total body impedance

Values for total body impedance and the resistance of the different current paths through the body are tabulated fully in IEC 479 and the 5th centile figures only are tabulated here (table 4). The initial impedance of the human body for a hand to hand or hand to foot current path with large areas of contact is not more than 500 Ω for the 5th centile of the population. It is less than the minimum values tabulated since capacitative elements are not charged and it limits the permissible current peaks of short impulses.

Impedance decreases with the frequency of AC and for sinusoidal frequencies greater than 5000 Hz total body impedance approaches the value for internal resistance.

Table 4 Electrical Impedance of the Human Body (a)

Touch Voltage	Total Body Impedance not exceeded by 5% of the population (Ω)	
	ac. (50-60Hz)	dc.
25	1750	2200
50	1450	1750
75	1250	1510
100	1200	1340
125	1125	1230
220	1000	1000
700	750	750
1000	700	700
minimum value	650	650
Initial impedance	500	500

These values were measured with electrodes of large surface area and represent a worst case condition since the contact area in most electric shock accidents is small.

At 50 volts, wetting the contact area with fresh water lowers impedance by 10-25% and if wetting is with conductive solutions such as saline there may a 50% lowering.

A value of 500 Ω has been taken as the impedance of the human body for calculating permissible body current (c).

2.6   Intra-cardiac Electrical Conductors: "Microshock" (1)

Ventricular fibrillation can be induced by currents less than the perception threshold if the current is led directly to the heart muscle. If the source of an electric current lies in or near the heart the current density is very much higher than for an equivalent shock delivered across the limbs. Very much lower total current is therefore required to generate a significant effect. Intra-cardiac conductors may be wires or catheters filled with an electrically conductive fluid such as saline or blood.

Intra-ventricular conductors are more dangerous than intra-atrial. Ventricular current as low as 20 μA has caused fibrillation in dogs. In man 0.1% of the population would be expected to fibrillate with a current of 44 μA from an intra-ventricular lead. Fifty per cent would fibrillate at 200 μA. In contrast, the right atrium, where central venous catheters might lie, are relatively insensitive and currents of 3 mA have failed to produce fibrillation.

2.7   Electrical Safety

The basic concepts in electrical safety are: **Insulation**
                                                       Earthing
                                                       Isolation

2.7.1   Insulation

The primary aim of electrical safety measures is to isolate the source of electric current. This is accomplished by effective insulation of electrical conductors and encasement of electrical equipment, by an insulating material. Equipment can be designed with high standards of insulation so that no earth is required. This is double insulated or Class II equipment.

2.7.2   Earthing

In practice, it is possible for basic insulation to break down and for the metal casing of electrical equipment to become live. At mains voltage this constitutes a serious hazard for anyone coming into contact with the live part. This hazard is avoided if a low resistance pathway to earth is provided and effective earthing is the second line of prevention of electric shock. Equipment requiring an earth for protection is class I equipment. Ideally, all conventional fixed wiring carrying mains power should run in an earthed metal conduit.

Earth loops (1)

Each item of electrical equipment is built to a certain standard of insulation which states the amount of current that can be allowed to flow to earth via the earth wire. This is termed the earth leakage current. It is also possible for electrical equipment to develop an insulation fault such the level of earth leakage from the device is increased but remains undetected. If the earth connections of a number of electrical devices are connected along the length of a cable which leads to earth it is possible that there will be a voltage gradient along the length of the earth cable. This means that if a patient is connected to earth via two electrical devices connected to earth at different potentials an unexpected electrical current will flow through the patient. This is particularly dangerous if one of the patient connected conductors lies within the heart (for instance, a pacing wire) since potentials of only 45 mV are needed to fibrillate a patient at the theoretical lower limit of 45 μA (see 2.6 microshock). In order to avoid earth loops all electrical equipment in a medical area should have an equipotential earth point.

In fact these points about earth looping are largely historical since now most external cardiac pacing equipment is battery operated and most patient connected electrical equipment is not earth referenced on the patient applied parts (see 2.7.3 Isolation, Patient isolation).

2.7.3   Isolation

Mains free supply

It is possible to reduce greatly the dangers of mains electricity by the use of an "earth free" mains supply. The system requires the addition of a 1:1 isolating transformer for every power output. The secondary winding of the transformer is not earthed in any way so that

both terminals are live. Since earth is not part of the secondary circuit earth leakage currents can only return to the transformer by its own leakage currents which are in the micro-Amp range. Such a circuit must not develop a fault which can convert it to a grounded system without warning and a line insulation monitor must be used to detect and warn of such a potentially hazardous event. Devices connected to an earth free supply must have fuses on both live lines and must be fitted with a double-pole on-off mains switch. Such a system is expensive and although theoretically safer than conventional systems it is more complex. This complexity may itself lead to hazard and earth free power supplies remain of unproven efficacy. Earth-free power systems may not prevent against micro-shock since the leakage current at which line-insulation monitor alarms may be set at 1 mA or above. Mains free supplies are used to protect equipment not designed to medical standards.

Patient isolation

It is also possible to isolate the patient from earth by only connecting electrical circuits to the patient that are isolated from earth by the use of transformers or optical coupling within the mains powered device. This approach is cheaper than the use of mains isolated power supplies and has become widely accepted. It does not, however, remove the need for effective earthing for class I equipment.

2.7.4   Fuses

These are devices that have a lower current rating than the conductor or circuit that they protect and melt when current exceeds a set value thus disconnecting the circuit. These devices should not be regarded as preventing electrical shock. Fuses prevent overheating, fire and breakdown of insulation in the circuit they protect.

2.7.5   Residual Current Protective Devices

These are active protection devices which detect earth leakage current as a difference between the supply and load currents. They respond to a pre-set level of such leakage by tripping a circuit breaker which disconnects the power supply. Typically the circuit is interrupted in 30 ms at a leakage current of 30 mA and this provides a great deal of protection against electric shock.

Residual Current Devices, however, can be a hazard to patients if connected to electrical equipment which sustains life from minute to minute if a backup supply is not immediately available. See also the requirement for Group 2 medical areas below.

2.8   Patient Safety

The principle underlying prevention of electric shock to patients from medical equipment is to isolate both the patient and any electrical circuit connected to the patient from earth. This means that all equipment in contact with the patient must be designed so that hazardous currents cannot flow through them, either to or from the patient, even if a fault develops. Electrical equipment connected to the patient must have an isolated power supply designed to an appropriate standard and the patient should lie on a non-conductive surface. The standards for electrical equipment connecting to endocardial leads are very much more stringent than for devices making only superficial contact with the patient. However, whenever a device is connected to the heart muscle

all other electrical equipment connected to the patient must meet the same, more demanding, standard.

The use of electrically isolated equipment does not mean that earthing can be neglected and all class I electrical equipment and earthed objects of any kind in the vicinity of a patient must be connected to earth. Ideally, there should be no potential difference between the earth points of different pieces of equipment.

2.9   Safety of Chamber Personnel

Safety of chamber personnel with regard to electric shock may be attained by preventing contact with electrical conductors at a dangerous voltage. This must be done by ensuring adequate insulation on all electrical conductors and equipment. The generation of dangerous voltages on the metal casing of electrical equipment connected to a mains supply due to a fault condition can be avoided by proper earthing of the casing. A regular preventative maintenance scheme is essential to check that earthing is still at the correct level..

2.10   Fire Risk (2,3,4)

The ignition temperature of paper is reduced by approximately 25% by compression to 6 atmospheres absolute in air and the rate at which paper burns is more than doubled. As oxygen concentration increases from 21%, ignition temperature falls and burn rate is further increased .

The risk of fire due to ignition from an electrical source in an oxygen enriched atmosphere is the single most important factor which limits the use of electrical equipment in pressure chambers. In order to avoid this risk, it is important to keep the level of electrical power used in the chamber to a minimum. Where high power utilisation in essential, such as in the use of a defibrillator, extra care and attention must be paid to avoiding the potential fire hazard.

In this context brief mention should be made of the power derived from batteries. Although the voltage levels generated by batteries are generally low the power produced can be high and shorting across battery terminals can generate large sparks. Further, the lead acid type batteries which are incorporated into a number of medical electrical devices will generate hydrogen gas during recharging and care must be taken that this does not constitute an explosion hazard. More modern lead acid batteries are sealed and may avoid this risk.

3.0   WIRING AND EARTHING STANDARDS

The wiring and earthing of any hyperbaric unit should conform with IEC Publication 364: Electrical Installations of Buildings (b). This document is currently under review and in the review Part 7 is concerned with particular requirements for special installations or locations and section 710 deals with medical locations and associated areas. The requirements of Part 7 modify or replace certain of the general requirements of IEC Publication 364. The scope of the IEC document covers medical locations in hospitals, private clinics, medical or dental practices and dedicated areas in other work places.

In medical locations, such as hyperbaric medical units, it is necessary to ensure the safety of patients to whom medical electrical equipment could be applied. This equipment may be required

to monitor, support or replace vital body functions either permanently or temporarily. The
equipment could be subjected to electromagnetic interference from the mains supply or other
sources. For every activity and function in medical locations the particular requirements for safety
have to be considered.

The standard of earthing and wiring required will depend on the function of the medical area
under consideration. This function falls into one of three groups.

Group 0   An area where no applied parts of mains supplied medical electrical equipment are
             used or are planned to be used.
Group 1   An area where medical electrical equipment is used or is planned to be used, but
             not for intra-cardiac procedures.
Group 2   An area where medical electrical equipment is used or is planned to be used for
             intra-cardiac procedures.

An applied part is defined as any part of the medical electrical equipment intentionally coming into
contact with the patient whether or not it is electrically conductive.

IEC 710 sets guidelines in the following areas:

Protection against electric shock
a)   Protection against direct and indirect contact.
b)   Protection by automatic disconnection of supply
           1) The specification of residual current protective device is detailed.
           2) In group 1 locations care should be taken that the simultaneous use of
              many items dose not trip the residual current protective device
           3) In group 2 areas protection by use of residual current detection devices
              should be used only on circuits for x-ray equipment and on circuits for large
              equipment with a rated power of more than 5 kVA.
c) Standards for information technology systems
d) Requirement for supplementary equipotential bonding in order that all the earthing
       points in any area are at the same voltage and that an electric shock cannot be
       given to a patient connected to two separate earthing points via items of medical
       electrical equipment.

Wiring Systems
Switchgear and control gear; electrical safety power supply and equipment to be
connected to emergency supply in event of primary power failure; information technology
systems power supply.

Explosion risk
Requirements for medical electrical equipment for use in explosion hazardous atmospheres
are in IEC publication 513 (1979) and in IEC 601-1 (1988). These, however, refer
exclusively to the presence of inflammable mixtures of anaesthetic gases. There is no
guidance on oxygen enriched atmospheres.

4.0   MEDICAL ELECTRICAL EQUIPMENT STANDARDS

Medical electrical equipment for use in a hyperbaric medicine unit should comply with IEC Publication 601: 1988: Medical electrical equipment, (this title is published in Britain as BS 5724: 1989) since this is the standard which deals most closely with problems of medical electrical equipment (d).

4.1   Shortcomings of existing standards

IEC Publication 601: 1988, however, does not explicitly deal with equipment to be used in a pressure chamber. The specification requires that equipment be designed for the following environment:

1) an ambient temperature of +10°C to +40°C:
2) a relative humidity of 30% to 75%:
3) an atmospheric pressure range of 70 to 106 kPa;
4) a temperature at the inlet of water-cooled equipment not higher than 25°C.

Equipment to be used in a hyperbaric environment will be exposed to much higher pressures and may be intermittently exposed to a higher relative humidity.

As mentioned above, there are also no specifications in regard to oxygen enriched atmospheres.

4.2   Choice of Equipment

4.2.1   MLQ Forms

Purchasers of medical electrical equipment, once they have decided what is required, should satisfy themselves that the equipment is of adequate quality for the task in hand. The questionnaire used by the UK Departments of Health may prove useful for this purpose. This takes the form of forms MLQ1, MLQ2, and MLQ3. These forms provide prospective purchasers with the means of acquiring information from potential suppliers on equipment being considered for purchase. The forms are also appropriate for non-electrical equipment. In brief the forms enable purchasers to check that equipment complies with :

1)   BS5724
2)   Quality Systems for Medical Equipment 1990 (Good manufacturing practice) HMSO ISBN 0 11 321240 9
3)   All standards and regulations regarding radio-interference
4)   Quality Systems for Sterile Medical Devices and Surgical Products 1990 (Good manufacturing practice) HMSO ISBN 0 11 321241 7

Since currently accepted manufacturing norms for medical electrical equipment do not make allowance for the hyperbaric environment in terms of humidity, pressure or high oxygen content, it should be demonstrated that equipment for use in such an environment is fit for the purpose. Expert advice should be sought from manufacturers as to whether particular equipment is suitable for the environment. The therapeutic hyperbaric environment should be fully described to the manufacturer together with its associated risks as defined below.

In the absence of certification by the manufacturer of the suitability of electrical equipment, a safety case for the equipment should be made out, in collaboration with the manufacturer, which should include any necessary testing.

4.2.2   Fire risk in pressure chambers

The British Hyperbaric Association technical working party report "Guide to Fire Safety Standards for Hyperbaric Treatment Centres" should be followed.

Volatile or gaseous anaesthetic agents should not be used in pressure chambers unless ambient levels can be controlled to the exposure limits stipulated by the Health and Safety Executive. The ignition and flammability characteristics of these agents under hyperbaric conditions are unknown and it would seem wise to avoid their use in pressure chambers altogether. Intravenous anaesthetic techniques offer a safe alternative.

4.2.3   Pressure

Electrical components should be pressure compatible. They should not contain unvented gas spaces unless the casing is known to be appropriately pressure resistant. Modern solid state electronic components are very much less prone to failure than previous equipment but, for example, enclosed relay switches and capacitors may still cause problems. Cathode ray tubes, are not compatible with increased ambient pressure applications and should not be used within pressure chambers. The same is not true of liquid crystal technology which is becoming a viable low energy alternative.

Individual components can absorb gas at pressure. During decompression, off-gassing then occurs and if the component is not adequately vented it may explode.

All equipment should be designed and tested for hyperbaric conditions or be intrinsically safe with regard to them.

4.2.4   Humidity

Relative humidity levels inside decompression chambers may exceed 75%, especially during decompression and it should be assumed to reach 100% during rapid decompression. Electrical equipment for use inside chambers must be appropriate for such high humidity operation. Alternatively, atmospheric humidity monitoring and chamber humidity control should be applied so that humidity levels do not exceed the equipment specification. This is, however, predominantly a problem for high voltage equipment.

All electrical equipment and conductors used in a pressure chamber should be waterproof to a degree such that an electrical hazard is not generated in the event of activation of the fire extinguishing sprinkler or deluge system.

4.2.4   High Concentration or High Partial Pressure of Oxygen (2,3)

This leads to an increase in the fire risk associated with the use of electricity. Oxygen levels in a pressure chamber should be monitored if electrical equipment is being used. The hazard is related to the level of oxygen and the available power. With very low concentrations of oxygen

combustion may not be possible. With very high levels of oxygen, an explosion risk may be present at low power levels.

Monoplace chambers which are compressed with 100% oxygen present a serious fire risk. Electrical equipment within such chambers must be intrinsically safe with respect to potentially explosive atmospheres at the maximum pressure capability of the chamber. In fact, electrical equipment for these systems can and should be limited to very low power applications. Piezo-electric pressure transducers can be used for intravascular pressure monitoring and communications systems can be self powered. Full antistatic precautions must be taken.

4.2.5   Equipment Modifications

Electrical equipment may be modified as required to become compatible with the hyperbaric environment. Equipment within the chamber can be encapsulated to resist pressure or, alternatively, enclosed spaces can be opened up if all the individual circuit components are pressure compatible.

In many instances, the main monitoring module or other working piece of equipment with the majority of electrical circuitry can remain outside, with wires passing through the hull and connecting to the patient direct or to low power signal conditioning circuitry inside the chamber. If such systems are installed, earth leakage and circuit insulation testing must be performed on the complete installation on-site.

A useful modification is the installation of inert gas purging of the enclosure of electrical equipment in the chamber. Such purging should be with the inert gas appropriate to chamber usage (helium or nitrogen) and could be used to control high oxygen levels and humidity within the equipment. Hydrogen accumulation in the vicinity of lead acid batteries during recharging could also be avoided. Once fitted, the installation of a gas purging system should be tested to ensure that adequate control of these parameters has actually been achieved.

All electrical switches must be intrinsically safe with regard to the environmental conditions.

5.0   DEFIBRILLATION IN PRESSURE CHAMBERS

Due to the perceived fire risk of the application of high energy electric current and possible sparking in a hyperbaric chamber, the provision of in-chamber defibrillation is not a widely used technique. Because of this, the Technical Working Group cannot advise that defibrillators should be routinely used under conditions of increased pressure and raised partial pressure of oxygen. Burns due to repeated defibrillation and thought to be unavoidable are not uncommon in intensive care units and should be anticipated as being equally unavoidable if defibrillation is to be used in the chamber (5).

A widely adopted alternative is to keep the defibrillator just outside the chamber which, if the need arises, is speedily decompressed while first line cardiopulmonary resuscitation is carried out. Once atmospheric pressure is attained the patient may be defibrillated with no unusual risk. This is the method advised in the United States Navy Diving Manual.

All hyperbaric treatment units should assess the likelihood of patients developing a cardiac arrest at the facility and plan accordingly. This assessment and plan should be part of the unit's operational policy.

Although the use of defibrillating equipment under hyperbaric therapeutic conditions is not a widely adopted technique, the following discussion is intended as a background for future research.

Electrical countershock therapy (defibrillation) is an important adjunct to the treatment of seriously ill patients. It is the only effective treatment of ventricular fibrillation and is also used in the treatment of other cardiac dysrythmias. Although the influence of the hyperbaric environment on the efficacy of defibrillation or countershock therapy has not been examined in people, studies on animals at pressures of up to 31 atmospheres absolute give no reason to suspect any alteration (6). Accordingly, countershock therapy might be seen as a reasonable service to provide in a hyperbaric chamber which is to used in the treatment of the severely ill.

Defibrillation involves inducing current flow through the heart of a patient at levels well above that regarded as safe in non-therapeutic situations. The energies used to do this are high, are released quickly and can generate large sparks if the resistance of the current pathway is not kept low. These two factors mean that the use of countershock always presents the twin risks of electrocution to attendants and of initiation of fire. Nevertheless, the technique is widely and safely used. The risks are considered below and suggestions are made upon which use of a defibrillator in a chamber could be based.

5.1   Risk of Electric Shock during Defibrillation

There is a risk of electric shock to personnel operating the paddles of countershock equipment if there is an electrical path from the paddles through the operator. In practice this risk is obviated by the guard on the paddle, which should ensure a long path length between hand and conductive surface, or by the use of stick-on disposable defibrillation electrodes. There is also a risk to people touching the patient during the discharge. These problems are not directly affected by the hyperbaric environment. The enclosed space, however, may make it more difficult for attendants inside the chamber to get clear of the patient. If the countershock is fired from outwith the chamber this problem may be compounded by an inadequate system of communication.

Defibrillation should not be planned to be carried out in a multiplace chamber which is too small to allow staff easily to keep clear of the patient being treated.

5.2 Fire

5.2.1 Ignition Temperature

Ignition temperature is reduced and the rate of spread of fire is increased under the hyperbaric conditions commonly used therapeutically. This subject has been reviewed (2).

5.2.2 Monoplace Chambers

DEFIBRILLATION SHOULD NOT BE CARRIED OUT IN MONOPLACE CHAMBERS COMPRESSED WITH OXYGEN.

In the event of defibrillation being required, the chamber should be decompressed and the patient removed to some distance from the chamber on the trolley. Prior to defibrillation the patient drapes or gown should be removed as oxygen may be trapped within them.

5.2.3 Fire Risk Factors during Defibrillation

Fires triggered by the use of countershock in intensive care units are not unknown and have been attributed to oxygen enrichment around the patient while an igniting spark was produced from the paddles. From study of such accidents the following comments have been made which are directly applicable to defibrillation in a pressure chamber (7,8):

Sparking is made more likely when the paddles are tipped off the skin thus reducing the area in contact with the patient:

Sparking is more likely if inadequate pressure is applied to the paddles since this increases impedance.

Sparking is more likely during repeated countershocks if gels with high initial impedance (>40 Ω) are used. These heat during use, liquefy, impedance rises further and sparks may be generated.

An ECG electrode may become the target of an arc generated at a defibrillator paddle:

    if there is too much gel under the ECG electrode so forming a conductive bridge;
    if saline pad impedance is greater than 10 Ω:
    if the ECG electrode becomes saturated with conductive gel;
    if the ECG electrode is poorly insulated on its outer surface (button snap-on type):
    if saline solution or gel gets on the ECG electrode's outer surface.

To reduce the risk of sparking it would seem wise to use large surface area stick-on electrodes and to avoid the use of defibrillator paddles in a hyperbaric chamber.

5.2.4   Defibrillator Electrode Impedance Testing

The problems described in 5.2.3 are related to poor contact at the electrode and impedance testing of electrodes prior to application of countershock should be routine. Many defibrillators have built in indicators of impedance.

5.2.5   Location of Equipment

Since current standards for medical electrical equipment do not consider the hyperbaric therapeutic environment and since defibrillating equipment generates high energies at high voltage, it is likely that only the patient applied electrodes and leads would be permitted within a chamber and that the body of the equipment be held outside. Current could be transmitted to the patient through extension leads via a suitable electrical penetrator in the chamber hull. Such a penetrator would not be used for any other purpose and should transmit only countershock leads. The entire countershock system would have to be the subject of a planned preventative testing and maintenance programme.

The wiring system described would be very much longer than usual and would, of course have to conduct both high current and high voltage. The effect of faults developing along such a current path needs to be examined and further research is required.

Defibrillator technology is by no means static (9) and it may be that a unit is developed that can be compressed and used in the chamber under hyperbaric conditions. This would avoid the undoubted problems of conducting high electrical energies though the chamber wall.

5.2.6   Oxygen Concentration during Defibrillation

The risk of ignition and fire during defibrillation is due in large part to raised levels of oxygen. Research remains to be carried out on the ability of sparking discharges from a defibrillator to cause ignition in the levels of oxygen likely to be encountered in a therapeutic hyperbaric pressure chamber.

5.4   Summary and Research Required

Direct current countershock therapy or defibrillation is a commonly used and lifesaving medical technique. It is not without risk, however, and the technique has caused electrocution and fire at atmospheric pressure on the open ward.

The risk of fire in particular is amplified by the hyperbaric environment and research remains to be done to study the effect of defibrillator fault conditions at differing atmospheric pressures and concentrations of oxygen.

Because of these points the British Hyperbaric Association cannot advise that defibrillators should be routinely used under conditions of increased pressure and raised partial pressure of oxygen.

6.0   ELECTRICAL INTERFERENCE FROM MOBILE PHONES

Many hospitals have banned mobile phones from their premises as it is possible for them to interfere with medical electric equipment. Tests have shown that mobile phones can disrupt the normal function of electric infusion devices, can increase background interference on an electrocardiograph, can cause errors in data display and can change the operating mode of programmed equipment. Mobile phones do operate in pressure chambers at pressure but should not be used if there is a risk of interference with medical electric equipment being used to treat a patient. There is unlikely to be any problem if mobile telephones, with a power rating of up to 4 Watts, are kept more than 10 metres away from medical electrical equipment (10). This also applies to cordless telephones and two way radios. Operators should be aware that ambulant patients or patients in transit can be connected to medical monitoring equipment and infusion devices.

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