FIRE AND EXPLOSION HAZARDS IN OPERATING THEATRES

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(With an appendix by W. W. MAPLESON)

The normal risks of anaesthesia and surgery are not the only ones which patients face in operating theatres. The possibility of fire or explosion is ever present and constitutes almost as much risk to staff as to patients. In recent years the incidence of serious explosions has been very low; this has been achieved principally by regulations governing the building and maintenance of premises and apparatus rather than by knowledgeable decisions by medical and nursing staff. To try and obviate human fallibility and ignorance, some of these regulations have led to expensive expedients which have been quite disproportionate to the magnitude of the risks. For example, it was estimated in 1969 that, since the inception of the National Health Service, a quarter of a million pounds had been spent on spark-proof switches in locations where sparks in fact presented no hazard and in which no instance could be cited of an explosion having been caused.

THE COMPONENTS OF EXPLOSIONS

Fires and explosions can only occur when three components are assembled simultaneously: a gas which supports combustion (usually oxygen, but also nitrous oxide in anaesthetic practice), a flammable material and a source of ignition. The elimination of any one of these is the aim of safety precautions in this field.

Oxygen

Not only can this not be eliminated, but it is frequently present in concentrations above the normal atmospheric value, thus making any conflagration much more violent than otherwise and in some circumstances rendering some otherwise safe materials a hazard. Particularly dangerous are stoichiometric mixtures in which the proportions of oxygen and a flammable agent are exactly those needed to produce complete combustion. In the circumstances of anaesthetic practice, flammable mixtures of anaesthetics with air will burn but not detonate. Oxygen enrichment has two effects: the range of concentrations of anaesthetic agents which will ignite is increased and, when they are ignited, the speed of propagation, allied to the rapid increase in pressure leads to a chain reaction so rapid that detonation of all the mixture occurs. Mixtures of nitrous oxide with oxygen support combustion even more strongly than oxygen alone and even pure nitrous oxide mixed with flammable anaesthetic agents will detonate (Macintosh, Mushin and Epstein, 1963).

Flammable agents

The abolition of the use of flammable anaesthetic agents has sometimes been proposed on safety grounds and has been brought about by voluntary action in some places. Whilst this will certainly eliminate the risk of anaesthetic explosions, it does not eliminate the possibility of anaesthetic techniques being a critical factor in promoting a fire. It is not a remedy which it has been thought prudent to try and introduce compulsorily. Not only would it be regarded as an infringement of professional freedom but, on a global view, the use of flammable agents is still extensive and training in their use must continue.

There are, however, circumstances in which, by custom, anaesthetists have accepted a restriction on the use of flammable agents. In some x-ray departments, the possibility of sparks cannot be eliminated and in such circumstances flammable agents are usually avoided completely.

It must not be overlooked that anaesthetic vapours are not the only flammable agents in the danger area. Alcoholic solutions for skin cleansing cause burns when ignited and such happenings are regularly reported by the Defence societies. Ether may be used to de-grease the skin or remove zinc oxide strangling adhesive; flammable solutions are sometimes poured on to and wiped over surfaces to sterilize them, or introduced into suction bottles to
de-bubble them. As long as such materials are to hand, inventive people will think of ways to employ them and constant vigilance is necessary. In most instances a non-flammable alternative can be found.

**Ignition sources**

Mixtures of flammable gases in oxygen can be ignited by sparks which have an energy as little as 1 μJ (Macintosh, Mushin and Epstein, 1963). The prevention of fires and explosions has concentrated predominantly on ensuring that sources of ignition and flammable agents are not in proximity. Following recommendations of a Ministry Working Party (Ministry of Health, 1956) a Zone of Risk was established. Vickers (1970) showed that this was defined unnecessarily widely and that, even in highly unfavourable circumstances of ventilation and vapour production, flammable concentrations are found in very limited areas. Present regulations allow sockets of normal construction at a height of 45 cm from the floor in operating theatres (Department of Health and Social Security, 1971a). The Zone of Risk in the U.K. is now defined as extending for 25 cm around the breathing circuit; only switches in apparatus which can be moved into this region must be of sparkless construction or enclosed in a gas-tight container.

It is likely that this will be the subject of international agreement and a draft Standard (International Electrotechnical Commission, 1975) is in existence. It is noteworthy that this introduces two levels of risk. An anaesthetic breathing circuit which encloses a mixture containing oxygen, nitrous oxide or flammable anaesthetic is described as an “enclosed medical gas system”. For the purpose of this code, the enclosed system is assumed to extend for a distance of 2 cm around it to allow for leaks. Equipment for use in an enclosed medical gas system must not be capable of producing sparks having an energy greater than 1 μJ, nor a surface with a temperature exceeding 150 °C. Such equipment will be termed “Anaesthetic proof, Category G” and marked APG. An outer zone, extending from 2 cm to 25 cm (the existing Zone of Risk limit), is assumed to be intrinsically safer because the gases will be diluted with air; equipment for use in this zone will be allowed to generate sparks up to 200 μJ and be described as “Anaesthetic proof” (AP). Any equipment outside the 25 cm limit (most operating theatre equipment, in fact) can be of the freely ventilated type of construction. Thus foot-switches would not need to be gastight or “explosion proof”.

Since the free spread of flammable concentrations of anaesthetic agents outside breathing circuits is very limited, it is clear that it is within the breathing circuit and air passages that most hazards arise and where the more spectacular explosions must have originated. The obvious dangers of using cautery and diathermy in the airway need no stressing; bulbs in endoscopes must in any event have “cool” surfaces, to avoid tissue damage, and are likely to be much less than 150 °C, which is the minimum temperature for auto-ignition of an ether–oxygen mixture. They should be powered by controlled low-voltage sources. Batteries are to be preferred to transformers on other safety grounds also.

The most unpredictable source of ignition is a spark associated with the discharge of a static electrical charge. Static sparks can be avoided by preventing the build up of the electrical charges; this depends on applying a group of related precautions. Like a chain, the omission of any link is equally disastrous. The patient, the breathing circuit, the machine and any individual who can touch them must all be at the same electrical potential, which is achieved in practice by ensuring that none of them are electrically insulated from ground.

**Antistatic precautions**

The floor

Although antistatic floors are, by definition, electrically conductive, they have quite a high electrical resistance in order to reduce electrocution risks. The average resistance of the floor should not exceed 20 MΩ between two electrodes 4 in² in surface area and placed 61 cm apart (Department of Health and Social Security, 1971b). The maximum likely electrical capacity of a person or clothing is of the order of 200 pF. If fully charged, 95% of the charge stored on such a “capacitor” would be dissipated in approximately 0.01 s through a resistance of 20 MΩ.

The patient

Cotton clothing and bedding should be used and the metal table covered with an antistatic rubber mattress. Only a cotton sheet should be interposed. The table should have metal feet, and any rubber pedals or stabilizing feet must be of antistatic rubber.

Clothing and footwear of staff

Provided that cotton theatre clothing is worn, the only matter of apparent importance is footwear. The situation with regard to this matter is confusing.
HTM1 (Department of Health and Social Security, 1971a) recommends that theatre footwear and overshoes should comply with BS 2506. This, however, is concerned only with rubber footwear and is not applicable to Dunlop antistatic shoes or to wooden clogs, in both of which rubber is not the relevant material. The former are manufactured to satisfy the method of testing of antistatic footwear which is specified in another Standard (BS 2050) to which BS 2506 refers. Tests conducted in the Department of Medical Physics at the University Hospital of Wales have shown them to be satisfactory (P. L. Jones, personal communication, 1976) and it is a pity that they are not marked in the manner recommended by BS 2506.

Clogs, however, are another matter. No Standard exists and because of their construction they fall outside the terms of both BS 2506 and BS 2050 and therefore outside the recommendation of HTM1. Clogs are rendered conductive by the inclusion of a conductive pathway between insole and sole, either of metal or conductive rubber plug: testing of clogs after a period of use has shown that in many instances the plug shrinks and fails to make contact with the floor (P. L. Jones, personal communication, 1976). Because of the small area of the antistatic surface, clogs also present an insuperable problem in antistatic testing since BS 2050 requires measurement over one square inch, and not per square inch. This is a point which, on the face of it, is of some importance since, on testing, large numbers of clogs in regular use are not found to be antistatic at all. At the same time it has to be admitted that no unfavourable consequences seem to have ensued from their widespread use and attempts to produce a spark from insulated personnel in theatres have failed, no doubt as a result of the control of humidity. In theory, however, antistatic footwear is an essential link in the safety chain and in the absence of adequate humidity and appropriate clothing could be important. Similar strictures apply to overshoes; plastic ones are relevant to cleanliness but, if sound, defeat the aims of antistatic precautions. Cotton overshoes are to be preferred.

The anaesthetic machine and circuits

These are undoubtedly the most critical part of the whole exercise. Within the breathing circuit are dry gases, often highly oxygen-enriched and enclosed in volumes which, if ignited, produce detonations of sufficient power not only to rupture the patient's lungs, but to injure other people in the vicinity. All non-metal parts of the apparatus and breathing circuit, including the castors, should be of antistatic rubber to BS 2050 (an exception is the endotracheal tube, but as this is always moist it is unable to hold a static charge). If the floor is of recommended construction this will ensure that no part of the apparatus can be at a different potential from that of the patient or anyone able to touch the circuit. It is recommended by HTM2 (Department of Health and Social Security, 1971b) that the conductivity of the floors should be tested every 3 months.

Other materials

There has been a steady increase in the use of insulating plastic materials in operating theatres, and questions are sometimes raised concerning their safety from an antistatic point of view. They include pillow covers, bowls, catheters, cannulae and syringes, themselves wrapped in plastic, and special draping materials. Plastic pillow covers should always be covered with a sheet of cotton or linen. Particular concern is often expressed about plastic endotracheal suction catheters, which are removed from a plastic packet and can be introduced directly into the air passages during the administration of an explosive anaesthetic. Consideration of the circumstances of use suggest that the risk of static sparks is infinitesimal. Certainly there are no recorded instances of incidents which could be related to such articles (Dobbie, personal communication, 1972). The objects themselves have an electrical capacity which is too small to hold sufficient charge; it would require either friction or rapid separation to generate the charge, and these factors are not usually found in these circumstances. An even greater measure of safety can be achieved if the materials are wetted before bringing them into the Zone of Risk.

Extent of antistatic precautions

Although there is a general consensus that it must be possible for flammable agents to be used, the cost of these precautions cannot be overlooked. Antistatic floors are somewhat more expensive than some otherwise acceptable alternatives; antistatic rubber has a somewhat limited life and is less convenient in other ways. It is important to have a clear policy, therefore, as to the locations in which this additional expense is justified. Restriction of antistatic precautions to a limited number of operating theatres and anaesthetic rooms within a suite is a policy fraught with difficulties; it would prevent the safe interchangeability of equipment within this area.
and would require a degree of flexibility in the use of theatres which is not usually achievable. The whole of all main theatre suites should, therefore, be uniformly protected.

In maternity departments with a designated operative delivery room, only this area need have full precautions: if any of several rooms may be used indiscriminately, the problems of interchangeability re-emerge.

X-ray departments have already been referred to as areas in which antistatic precautions may be unnecessary because other sources of ignition cannot be eliminated. There remain areas which are relatively infrequently used for operative work involving general anaesthesia, and even less frequently for the administration of flammable agents. These areas include casualty theatres, fracture clinics, electro-convulsive therapy wards, etc. In these locations the expense of full antistatic precautions is difficult to justify, particularly as a very acceptable degree of safety can be assured with a few simple precautions. Non-conductive materials can be rendered temporarily conductive by wetting them; thus as long as the anaesthetic machine conforms to the recommendations outlined above, and staff and patients are appropriately shod and clothed, a high degree of safety can be assured if the floor is wetted over the area in which anyone can touch the breathing circuit whilst a flammable agent is being employed. This can be most reliably achieved by spreading a damp sheet. Recovery areas are not a practical problem because of the rapidity with which expired gases become non-flammable after administration ceases (Vickers, 1970).

OTHER FIRE HAZARDS

Drapes and packs

Leakage of oxygen-enriched gases can render some surgical materials much more flammable than expected. Gupte (1972) reported the ignition of a pharyngeal gauze pack during intra-oral diathermy attributable to leakage of oxygen-nitrous oxide mixture around the endotracheal tube during positive pressure ventilation. Cameron and Ingram (1971) reported the vigorous ignition of surgical drapes when oxygen-enriched gases were being vented beneath them.

Nebulizers

Two fires have been reported in connection with nebulizers of different kinds. A venturi jet through which dry oxygen was flowing was inadvertently not earthed because of a design fault. The jet was shown to be able to hold charges of up to 20 000 V (Webre, Leon and Lawson, 1973). The plastic venturi nozzle melted, but as Bruner (1973) pointed out, it is difficult to see how static electric discharges could provide sufficient energy for this. No better explanation was forthcoming despite considerable experimental investigation.

A fire arising in an ultrasonic nebulizer has also been reported (El-Naggar, Collins and Francis, 1973). These devices convert electrical energy into high frequency acoustic energy at powers which constitute a potential fire hazard. The energy from the ultrasonic crystal is coupled by water and a flexible cup to the liquid to be nebulized. In this instance, because of a design fault, the polyethylene cup of a Bendix nebulizer was of a greater thickness than one-quarter of the wavelength of the acoustic wave; this caused the plastic to heat up excessively, and in the presence of 60% oxygen it ignited.

Laparoscopy

Some concern has been raised about the use of nitrous oxide for laparoscopy on the grounds of explosion risk (Robinson, Thompson and Wood, 1975). No explosion has actually been reported and what few measurements of i.p. hydrogen and methane concentrations have been made have been far below the flammable limit (Drummond and Scott, 1976). The credibility of the risk thus depends on the credibility of the theory which postulates it. In essence, Robinson and colleagues argue as follows: approximately 0.5 litre of hydrogen is produced in the gut in 24 h, and in one-third of individuals a few hundred millilitres of methane are produced also. Since hydrogen is very diffusible, high concentrations must also exist in the peritoneal cavity. Nitrous oxide supports combustion and therefore a flammable mixture may occur during laparoscopy.

There are several weaknesses in this line of argument. First, whatever the theoretical tension, it is a routine finding on x-ray that there is normally no free gas in the peritoneal cavity and that the presence of even small quantities indicates serious pathology. Only when a gas is introduced into the peritoneum will hydrogen and methane start to diffuse into it. Second, although hydrogen may be highly diffusible, its passage across the bowel wall will depend on its solubility, which is low. Professor Mapleson, in an Appendix to this paper, shows that, taking “worst case” assumptions, the rate of transfer of hydrogen...
is such that it would take some hours to achieve a flammable mixture.

There remains the possibility of a rapid escape of flammable gases from a perforation of the gut. The quantity of gas in the gut at any one time ranges from 0 to 500 ml in different subjects (International Commission on Radiological Protection, 1975). Small detonations have occurred during diathermic opening of the bowel, but only in association with bowel obstruction or other pathology. How frequently the large bowel is perforated by laparoscopic diathermy is not known. Steptoe (1976) alleges an incidence of perforation of 2%, but he does not distinguish between different parts of the bowel, nor give any direct evidence. Rapid combustion of 40 ml of hydrogen would increase the temperature enough to increase the intra-abdominal pressure by about 150 cm H₂O (14.72 kPa); this increase is likely to be transient, but nevertheless is not one to be viewed with equanimity. The hazard of diathermy penetration of the large bowel in mistake for the fallopian tube needs therefore to be weighed against the cardiovascular hazards of carbon dioxide in choosing the gas for laparoscopy.

**SUMMARY**

A high degree of safety from fires and explosions exists in operating theatres in the U.K. and this is reflected in the extremely low number of fatal and non-fatal accidents which occur. This has been achieved by safety precautions which in some respects have been over-careful and over-expensive. Antistatic precautions applied to the breathing circuit seem to have been the crucial factor in achieving this level of safety.

**APPENDIX**

**Diffusion of gas through the wall of the large intestine into a gas-filled cavity at laparoscopy** (by W. W. Mapleson)

The concentration of a “foreign” gas, such as hydrogen, in the inside and outside surfaces of the gut wall are \( \lambda P_L/P_B \) and \( \lambda P_C/P_B \) where \( \lambda \) is the gut-wall/gas partition coefficient for the gas, \( P_L \) and \( P_C \) are the partial pressures of the gas in the large intestine and in the abdominal cavity, \( P_B \) is the barometric pressure and concentration is in \( \text{cm}^3 \text{gas (BTPD)/cm}^3 \text{tissue} \). It follows that the concentration gradient of gas through the gut wall is given by

\[
\frac{\lambda}{t} [P_L/P_B] - [P_C/P_B]
\]

where \( t \) is the thickness of the gut wall. Therefore the rate of diffusion of the gas through the gut wall is given by

\[
V_G = \frac{A}{t} \lambda [P_L/P_B] - [P_C/P_B] D
\]

where \( A \) is the area of gut wall through which diffusion occurs and \( D \) is the diffusion coefficient for the gas in the gut wall.

Values for the variables may be estimated as follows:

- \( \lambda = 0.019 \) for hydrogen, 0.028 for methane (Morrison and Billett, 1952)
- \( D = 5.2 \times 10^{-5} \text{cm}^2 \text{s}^{-1} \) for hydrogen, 2.2 \( \times 10^{-6} \text{cm}^2 \text{s}^{-1} \) for methane (Kety, 1951, interpolating for methane on the basis of molar mass)

and, for the “worst” case in which the whole of the inside of the large-intestine wall is in contact with hydrogen and the whole of the outside with laparoscopy gas:

\[
P_L = P_B
\]

\[
P_C = 0
\]

\[
A = 3500 \text{ cm}^2 \quad \text{(International Commission for Radiological Protection, 1975)}
\]

\[
t = 0.10 \text{ cm} \quad (\text{I.C.R.P., 1975, assuming the density of gut wall tissue = 1.05 g cm}^{-3}).
\]

Whence

\[
V_G = 2.1 \text{ cm}^3 \text{ min}^{-1} \quad \text{for hydrogen,} \quad 1.3 \text{ cm}^3 \text{ min}^{-1} \quad \text{for methane.}
\]

Therefore the time required to transfer 400 cm³ (the amount required to produce a concentration of 5% in a typical laparoscopy gas volume of 8 litre) is 190 min (> 3 h) for hydrogen and 310 min (> 5 h) for methane.

However, the rates of diffusion calculated are extreme upper limits which would apply only if the whole inside surface of the wall of the large intestine were in contact with hydrogen or methane and the whole outside surface were in contact with the laparoscopy gas. Furthermore, part of the gas diffusing into the gut wall will be carried away by the blood perfusing the gut wall.

**REFERENCES**


—— (1971b). Anti-static Precautions: Flooring in Anaesthetising Areas; *Hospital Technical Memorandum No. 2. London: H.M.S.O.*


