

COMMENTARIES

A short history of fires and explosions caused by anaesthetic agents

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SUMMARY

The first recorded fire resulting from the use of an anaesthetic agent occurred in 1850, when ether caught fire during a facial operation. Many subsequent fires and explosions have been reported, caused by ether, acetylene, ethylene and cyclopropane, and there has been one reported explosion involving halothane. Although some of the earlier incidents caused more consternation than injury, many of the later ones caused much death and destruction, particularly after the practice of administering oxygen, instead of air, became established. Many incidents have never been reported and many of those which have reached publication do not record essential details. The use of flammable agents has decreased significantly in recent years and although fires and explosions from non-anaesthetic causes, for example gastrointestinal gases, skin sterilizing agents and laser surgery, may continue to occur, those from gaseous and volatile anaesthetic agents may now be of historical interest only. This article reviews some of the more relevant and enlightening reports of the past 150 yr. (Br. J. Anaesth. 1994; 72: 710–722)

KEY WORDS

History: anaesthesia. Explosions

Fires and explosions have occurred in operating theatre environments for many years. Most have resulted from the use of flammable or explosive anaesthetic agents. Others have been caused by ignition of flammable gases, either those produced normally in the gastrointestinal tract or those produced in the bladder during electrosurgical procedures. Fires have resulted from the use of flammable skin cleaning agents, from swabs and drapes becoming ignited, particularly in an oxygen-enriched environment and, more recently, from tracheal tubes being burned during laser surgery. Some of these causes have resulted in fatalities to either patients or medical and nursing staff. Some incidents have been reported in detail and others only outlined, and although most explosions have been tragic, the descriptions of some of the earlier fires and minor explosions would seem to suggest that they were more entertaining than disastrous. The likelihood of explosions resulting from the use of anaesthetic agents is now very small, partly because explosive agents are used much less frequently and also because precautions against such incidents are more effective. It seems reasonable to

hope that fires and explosions caused by anaesthetic agents may now be of historical interest only.

CRITERIA NECESSARY FOR FIRE OR AN EXPLOSION TO OCCUR

Three ingredients are necessary for a fire or an explosion to occur. There must be fuel (i.e. a flammable material), an oxidant and a source of ignition. The fuel may be gaseous, liquid or solid; those most relevant to anaesthesia are the anaesthetic gases cyclopropane, ethylene and acetylene, and the vapours of volatile anaesthetic agents, especially the non-halogenated ethers, in particular diethyl ether (popularly known as “ether”). Some of the halogenated volatile agents, for example ethyl chloride and fluroxene, are highly flammable and even those which are generally regarded as non-flammable, under certain laboratory conditions, may be ignited, although some of these conditions are unlikely to be present in clinical practice. Limits of flammability vary with the percentage of oxygen present. The lower limit of flammability of any agent is significantly higher in air than if additional oxygen is present. Similarly, the range of flammable concentrations of an agent is much narrower in air than in oxygen. Fires and explosions become more common and more dangerous when oxygen is added to inhalation gas mixtures. The upper and lower limits of flammability of flammable anaesthetics used previously are shown in table I [1], and, of currently used agents, in table II [2].

The oxidant needed to provide combustion may be either oxygen or nitrous oxide. It is possible that nitrous oxide is a more reactive oxidant by virtue of its relatively unstable structure. The release of a

TABLE I. Upper and lower limits of flammability of anaesthetic agents in air, oxygen and nitrous oxide (N₂O) (vol. %)

	Lower limit in			Upper limit in		
	Air	Oxygen	N ₂ O	Air	Oxygen	N ₂ O
Diethyl ether	1.8	2.1	1.5	36	82	24
Divinyl ether	1.7	1.8	1.4	27	85	25
Ethylene	2.8	2.9	1.9	28	80	40
Acetylene	—	3.5	—	—	88	—
Ethyl chloride	3.8	4.0	2	15	67	33
Cyclopropane	2.4	2.4	1.6	10	63	30

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TABLE II. Lower limits of flammability of enflurane, isoflurane and halothane in 20% oxygen (O₂) in nitrous oxide (N₂O) and in 30% O₂ in N₂O (vol. %)

	Enflurane	Isoflurane	Halothane
20 % O ₂ in N ₂ O	4.25	5.25	3.25
30 % O ₂ in N ₂ O	5.75	7.0	4.75

single oxygen atom is more readily achieved from disruption of nitrous oxide, than from disruption of the double bond of an oxygen molecule which requires input of more energy. The increased incidence of fires and explosions which resulted from the use of additional oxygen may have been partly because of the simultaneous administration of nitrous oxide, which also became common practice when “semi-closed” breathing systems were introduced.

The source of ignition in the earliest days of anaesthesia was either an open fire, candle-light, a hot wire or rod used for cautery, or a defective electrical instrument in the airway. Mixtures of flammable gases are easiest to ignite when slightly on the “rich” side of the stoichiometric mixture and these may be ignited by a small spark. The least flammable mixtures are those near the upper and lower limits of flammability and are the most difficult to ignite; they require about five times the ignition energy necessary for ignition of the most flammable mixtures and may only be ignited by cautery or faulty electrical equipment. Sparks, usually from accumulation of static electricity or more rarely from a metal instrument hitting another instrument or a tooth, have been the cause of many explosions, particularly after oxygen-enriched gas mixtures were introduced and before antistatic materials became available. In recent years, the use of laser surgery has been a major cause of fires in the airway and these have resulted most commonly from ignition of tracheal tubes and throat packs.

ETHER

Possibly the first report of a fire occurring in an operating theatre was in Boston in 1850 [3]. Under the small heading “Caution in the use of ether and chloroform”, it reads: “A very serious accident happened in surgical practice in this city, not long since, by the taking fire of the vapour of ether. The circumstances under which the accident occurred, are these. The patient had an operation upon the face near the mouth. There being some considerable haemorrhage, the actual cautery was applied, and it was by contact with the hot iron that the ether was set on fire. Too much caution cannot be used in the application of ether, and this one instance of its inflammability in actual practice should serve as a caution to all. No lighted body should be placed near a patient, while he is under the influence of ether. There never should be a lighted lamp brought into a close, or small room, while etherization is going on”. This is a surprisingly restrained report. There is no mention of whether or not anyone died or was injured, although it is described as a “very serious accident”.

A young doctor, attending the wounded at Gettysburg in 1863 during the American Civil War [4], recorded how “I was trying to secure a large bleeding vessel just above the inner end of the clavicle. The only light was 5 candles stuck in a block of wood, and held very near the ether cone. Suddenly the ether flashed afire, the etherizer flung the glass bottle of ether in one direction, and the blazing cone fortunately in another. We narrowly escaped a serious conflagration. Why did I not use chloroform, which is non-inflammable, in conditions well-known before I began to operate? I fear I must admit to gross thoughtlessness. My only consolation is that the patient suffered no harm”. What admirable honesty!

Other fires were described in 1867 [5]: “While operating at night on a mutilated finger, the lamp being three feet distant, and a sponge placed over the patient’s mouth, the air in the vicinity became saturated with the ether, ignited, setting fire to the sponge, bed-clothes, and even the face of the patient. The flames were fortunately extinguished without any injury to the patient, but not without causing great fright to those in the neighboring beds. In another instance, the same accident took place from the introduction of a red-hot iron into the mouth of a patient, from whom the sponge containing ether had just been withdrawn. The flames were fortunately at once extinguished”.

The first such incident in Britain may be the one described in a letter to the editor of the *Lancet* in 1866 [6], under the inconspicuous heading, “Dr Richardson’s apparatus” and signed with only the initials S.E.K. “Sir, Perhaps you will kindly allow this letter a place in your columns, as the striking facts I have to record warrant the necessity of great precautions in the employment of the above instrument for the extraction of teeth. I have used Dr Richardson’s Spray-producer for some little time, and can cheerfully testify to its beneficial aid in minor surgical operations, especially dental, in no case occasioning the slightest pain. The instrument I have used by day-light and gas-light, with no danger attending till the other evening, when the fright which patient, attendant, and myself experienced, determined me to operate by day-light only. A gentleman calling to have a tooth extracted, I proceeded in the usual way. Having applied a small piece of cotton-wadding over the tongue, with the view of protecting it from the fluid which I was about to direct upon the upper jaw, I began business. I should say that in every preceding instance, I have used a candle, to throw a better light into the mouth. This is held by the assistant not nearer than half a yard from the seat of operation. In this case it was done also. And now comes the terrible scene. I had scarcely used the ether (pure rectified) for twenty seconds, when suddenly a volume of flame rushed from the patient’s mouth, enveloping the three of us for a single instant. It was so soon over that the patient had not time to rise from his seat, and the assistant and myself remained in our former positions. There was no explosion: all was quiet. After regarding each other for a few moments, I ventured to inquire of the patient how he felt. I was happy to

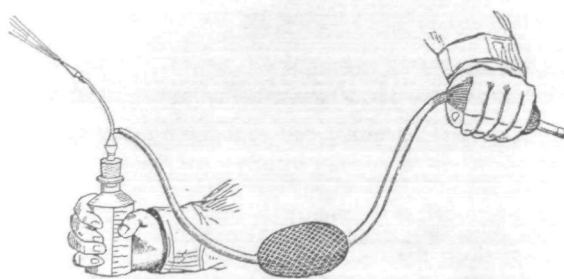


FIG. 1. Benjamin Ward Richardson's ether spray, introduced in 1866. It produced an atomized mist of ether vapour and was used widely for minor dental and surgical procedures.

see a rather ghastly smile illumine his pale countenance; but his only answer was 'what a wonderful occurrence'. There was no smell of scorching; the only injury sustained being a slight singeing of the more prominent hairs of his moustache. The assistant and myself were untouched. This was certainly an unexpected and terrible occurrence, though fortunately unattended by any untoward result. The patient's complexion was of a healthy ruddy colour on sitting down for operation; but this soon gave place to a ghost like pallor; and when I beheld the flames gushing forth from his mouth, I almost believed it was a veritable fire-demon sitting before me. He certainly did not look ethereal. The only unpleasant feeling he experienced was a sense of constriction round his neck. He is nothing the worse for it; in fact better, as he has not felt a twinge of toothache since. Now, Sir, cases like these are not to be made *light* of. The cause of the mischief might be attributed to the candle. If so, then why did the same effects not ensue in preceding instances, as the same precautions were adopted? I should esteem it a favour to be informed if any rules are laid down for operating in gas-light, as till then I shall be obliged to desist. Yours very truly, S.E.K. (October 1866)." The initials S.E.K. do not appear in the medical directories of the time. It is likely that the author was a dentist, but as there were no dental directories in those days, he has not been identified. Perhaps he was reluctant to reveal his identity as the perpetrator of this sensational disturbance.

Benjamin Ward Richardson introduced his ether spray apparatus (fig. 1) in 1866. It is a simple device, which produced a steady flow of compressed air to allow an even spray of atomized ether to be directed from the nozzle onto the area. The device became instantly and universally popular for minor surgical or dental procedures, although it had the disadvantage of causing the instruments and the skin to become thickly coated with ice, thus rendering surgery more difficult [7].

Another similar incident is described in a letter to the editor of the *Lancet* a year later [8], under the more attention-seeking heading "Danger of the ether spray", and was from George Arthur Brown, a house surgeon at Sheffield Royal Infirmary. It relates to a patient with a malignant disease of the mouth,

which had begun to bleed. The writer says that he was anxious to try the effect of Dr Richardson's ether spray in trying to stop the bleeding. A candle was held by a nurse at a distance of about 2 feet from the patient's mouth and the ether had been sprayed for nearly 1 min when "the vapour suddenly ignited, and a scene presented itself that neither I nor any that witnessed it are likely to forget. The man appeared literally to vomit forth fire, while his head seemed, and indeed was, completely enveloped in brilliant flame. The fire was however rapidly extinguished, and although the patient was terribly alarmed, and fainted, no further harm resulted to him than his having his face slightly scorched." He finishes by commenting "I may say that the bleeding was completely arrested, and has not since returned".

Despite these incidents, in a review of ether in 1870 [9], Richardson made no mention of the hazard of its flammability. A heated debate took place in the journals over the next few years about whether chloroform or ether was the safer agent, this being triggered by an increasing number of reported deaths from chloroform. Chloroform had, by this time, become a much more commonly used agent. An editorial in the *British Medical Journal* [10] urged practitioners to give ether a re-trial and another [11], reviewing all the available agents, strongly advocated the safety of ether, although no mention was made of flammability. However, one of the many contributors to this debate [12] did refer to the fire hazard: "Etherisation can, with a little caution, be used by inhaler with candle or artificial light, where the more wasteful and diffused application by the sponge would be inadmissible, from the danger of ignition". The same author, answering a question on whether or not the administration of the inflammable vapour of ether was safe at night, agreed that it was [13]: "The risk of conflagration is overcome by the use of the inhaler, which also ensures the shutting out of air".

Another contributor wrote "the recommended method of administration of ether, by a towel folded cone-shaped, with a sponge fixed into the apex, results in a great dose of ether being distributed through the theatre... and I fancy some day we shall hear of an accident in operating by artificial light from the ether catching fire" [14]. This possibility was refuted in the next issue [15]: "If ether is administered by inhaler, rather than the folded towel, very little ether can reach the atmosphere of the room, and the conflagration anticipated is impossible"!

In 1879, a fire resulted from the use of cautery during a knee operation in Lyons [16]: "One hundred and fifty grammes of ether had been used, as the patient did not easily come under its influence. The window had been opened, the room was large, and the ether-bag was to a certain extent separated from the thermo-cautery. Suddenly the room was in flames, and the bed was enveloped in them. The ether-bag was thrown down on the floor, and the patient quickly removed. She was scarcely touched; but Dr Gros, who was giving the ether, had his hands severely burned". The article recounts an-

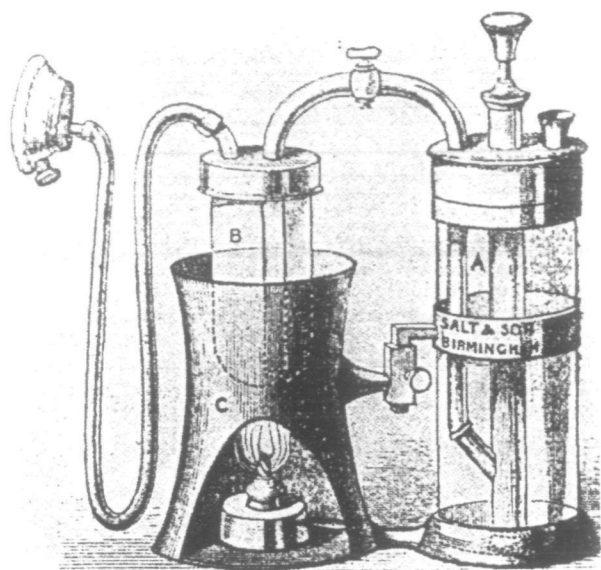


FIG. 2. Lawson Tait's warm ether inhaler, introduced in 1876. The spirit flame heated the ether vaporizing chamber, thus delivering pure ether vapour to the mask.

other incident, when an operator, at the time when the ether spray was in vogue, conceived the idea of anaesthetizing the haemorrhoids of a man "whom he was about to cauterise with the red-hot cautery. The ether spray was suspended, the red-hot iron was applied, but the dense ether-vapour took fire. The haemorrhoids were not affected; but the unfortunate patient was severely burned, as were also the hands of the assistants".

In 1882, a fire occurred during an operation by Professor Briggs at his clinic at the University of Nashville [17]: "during etherisation for the removal of a tumour of the parotid, the vapour caught fire from the flame of the alcohol lamp of the spray-producer, and the clothes of the patient were ignited. Neither the patient nor attendants were injured, the flames being speedily extinguished by the operator".

Ether was proving dangerous elsewhere also, killing a professor in Havana [18] after an ether fire in his laboratory and also a nurse, who was pouring ether from one bottle to another too near a gaslight in New York [19]. It also resulted in several explosions in an ice-making factory in Marlborough, where ether was used in the process of freezing water [20].

The use of open flames in anaesthetic machines, to warm ether vaporizers or to prevent ice forming in nitrous oxide cylinder yokes, was a potentially dangerous practice. Tait, an obstetrician and gynaecologist from Birmingham, devised his ether inhaler in 1876 [21]. It was heated by a spirit lamp and designed to deliver pure ether to the patient (fig. 2). Stanley Sykes commented "it is not known how long this machine was in use before it finally blew up". Tait was described as a "merciless, truculent and pugnacious controversialist" (perhaps capable of spontaneously igniting a flammable gas by his very presence alone), but he did incorporate a 5-foot long tubing between the inhaler and the patient, thereby delivering the ether vapour well away from the

flame. Perhaps it was not such a dangerous invention after all, as no incidents were reported and in 1880, Tait [22], writing in support of ether, stated "performing as I do a large number of abdominal sections using ether, I am free of all catastrophe, and the relief is blessed".

Many surgeons believed, as did Tait, that inhalation of cold ether caused pulmonary complications and the concept of administering warm ether was a logical way of resolving this problem. In 1891, a Spanish doctor introduced an "electro-thermo-etherizer" [23], which heated ether to 31 °C, thereby reducing the patient's heat loss.

In 1892, an incident was reported [24] in which ether was spilt near a fireplace by Dr Averill whilst he poured it from a 5-pint bottle into a phial: "The ether became ignited and a loud explosion followed. The house was shaken and the bottles in the surgery shattered, the windows also were broken and the room was totally wrecked. Dr Averill was found with his clothes in flames rolling about on the floor. His eldest son rushed into the room, and with great presence of mind, ripped the clothes off his father's body, and saved him from being burnt to death. Dr Averill, who was very badly injured about the head, face and other parts of the body, is, we are glad to learn, progressing favourably though still confined to bed. His son was burned about the hand".

In 1899, the results of an inquest into the deaths of two nurses at a workhouse in Rochdale were reported [25]: "A nurse sat with her back to the fire, taking an inventory of the bottles, and the other was counting those on one of the upper shelves, when an ether bottle accidentally fell against another bottle, and being thin at the neck, broke. There was an immediate explosion, blowing out some of the window glass and setting fire to the furniture and woodwork. The superintendant nurse was found in a semi-conscious state, while the other one managed to get out though badly burned". The coroner adjourned the inquest for a fortnight in the hope that the surviving nurse would be able to recount how the explosion had occurred. However, she died within a few days of the accident.

The first recorded explosion caused by an electric spark, rather than a fire or flame, occurred in 1903 [26] when a surgeon wrote: "While engaged in a tedious and difficult operation, my attention was taken from my work by a sudden flash of light and some quick movements on the part of the anaesthetist, and I found that the ether vapour had ignited, scorching the hairs and eyebrows of the patient, and had burned the skin of his forehead sufficiently to cause quite a marked redness. The anaesthetist reported that the patient being on the face he was unable to see the pupil properly and he had turned on the electric light in order that he might more readily note the reaction of the pupil. The blaze had resulted coincidentally with the turning on of the light... the only conclusion was that the ether had ignited from the spark in the electric light burner, when contact took place in the turning on of the light".

A similar explosion was described in 1921 by Dr McCardie [27]. The patient was undergoing laryn-

gосcopy and biopsy of a vocal cord and was anaesthetized with ether and oxygen through a nasal catheter, while also receiving ether by the open method. When the surgeon inserted the electric laryngoscope, "there occurred two or three very loud reports like small pistol shots, very startling, and flames issued from the patient's mouth; in fact his mouth was on fire. The flames were 5 or 6 inches high, and very like those which occur when a Winchester quart bottle is set on fire. As soon as I realised the position, I pulled out the nasal tube and the flames instantaneously ceased". Faulty electrical equipment has regularly resulted in the ignition of anaesthetic agents. It was extremely fortunate that this incident did not have a more disastrous result.

Another incident was described in 1922 [28]: "At the close of an operation for gangrenous appendix, about six ounces of ether were poured into the abdominal cavity. Almost at once a column of blue flame leapt from the abdomen, and in another moment a second column from the mask over the patient's mouth. Apparently, ether vapour, with which the small room was well charged, ignited near the gas stove, and the flame rushed to the vicinity of the table".

Dr Henry Featherstone described an explosion in his theatre in 1931 [29], where a spirit-lamp was warming the valve on the nitrous oxide cylinder: "A pin-hole in the bag allowed a stream of mixture to impinge on the flame and the bag exploded with a deafening report. My head was 2 feet away, and I learnt a lesson which I will never forget".

An incident recounted by Stanley Sykes, in a chapter entitled "Stupidities" [30], is introduced as follows: "Surgeons hold a place of unchallenged pre-eminence in a chapter on Stupidities. The list is so long it is difficult to know where to start". He recounts an incident described in the autobiography of Ferdinand Sauerbruch, professor of surgery in Berlin [31]. "A clinic can provide nasty surprises too. A Spanish family brought their twelve-year old boy to the hospital, his lung condition making an operation necessary. The operation was proceeding normally when through a cause we were never able to trace, the glowing cautery set light to the ether vapour used as the anaesthetic. The violent explosion that followed, was repeated almost immediately as an oxygen cylinder blew up. The patient was killed on the spot, the sister and the assistant were injured, and I lost one ear-drum." This is akin to someone dropping a lighted match into a pail of petrol and saying "through a cause we were never able to ascertain, the thing blew up!" There is no mention whatsoever of the anaesthetist. Perhaps there was none, or perhaps he, or she, was well out of harm's way.

Fatal explosions began to occur more often when oxygen was added to anaesthetic systems, particularly in closed systems. Many anaesthetists were reluctant to accept that there was much of a risk and occasionally someone would be sufficiently confident to put his beliefs to the test. One such anaesthetist found himself having to justify his claim that the mixture of nitrous oxide, oxygen and ether, which he had been using, was safe [Anonymous, personal

communication]. When challenged on this by the professor of surgery, he unfortunately decided to experiment. He collected the expired gases from a Magill system into a large pail and carried it carefully into the corridor outside the theatre and, with a great flourish, flung a lighted match into it. There was a terrific explosion, which cracked all the windows in the corridor and gave everyone a spectacular fright. The anaesthetist may have been very unlucky in this escapade, because ether, which is heavier than air, would have concentrated in the bottom of the pail, displacing air out of it, to the point where the gas concentrations may have approached a stoichiometric mixture.

Explosions occurred occasionally in the absence of a flame or apparent spark. In 1925, a 16-yr-old boy died during surgery for a fractured jaw after a cycling accident [32]. He was anaesthetized with oxygen and ether. The dentist was attempting to keep the teeth dry by means of warm air, supplied through a dental syringe. On the third application of warm air, there was an explosion at the back of the mouth, which resulted in acute and uncontrollable haemorrhage, the boy dying within 10 min. The jury returned a verdict that "death was due to accident", but whether there had been a spark from hitting the teeth with the syringe or whether the "warm air" had been too hot or had been injected with too high pressure, is not known.

By 1930, Pinson estimated that "at least a hundred explosions probably occur every year with ether in this country" [33] and most of these only caused trivial burns or scorches of the lips, mouth or face. His opinion was that, after discontinuing administration of ether for 2 or 3 min, expired air would have become sufficiently dilute to be non-flammable. He had become so confident in this that, for several years, he had "continually used the ether bomb apparatus, often within 2-6 feet of an open fire, and frequently much nearer a cautery, without ignition taking place". The ether bomb, designed originally in 1921 [34] and improved in the 1923 model [35], was capable of producing very high concentrations of ether from a steel vaporizer immersed in boiling water. This fearsome concept, in common with Tait's ether inhaler, was the cause of much apprehension, but there do not appear to be any reports of untoward incidents. Perhaps the obvious potential dangers of the vaporizer made everyone especially cautious in its use.

There were many reports of serious explosions during the 1930s. Oxygen was now being used more widely than before and concentrations of ether, which would not have been in the explosive range when mixed with air, became highly explosive when delivered with a higher concentration of oxygen. The lack of antistatic precautions also played an increasing role in the production of serious explosions. In 1933, an anaesthetist died from an explosion [36] when a patient anaesthetized with oxygen, nitrous oxide and ether was turned from one position to another.

In 1935, Ironside described an explosion in the Royal Masonic Hospital [37], when he and an attendant were wheeling an anaesthetic machine



FIG. 3. The damaged steel casing of a Manley ventilator after an explosion during administration of ether.

from theatre back into the anaesthetic room to start another case. "A violent explosion occurred. The ether container broke into small pieces, and two bottles of ether on the other side of the room exploded about two seconds afterwards. The theatre attendant was knocked down, I was blown over, and so was the Sister, who was cut about the face. The patient fell off the trolley and the whole room was a sheet of flame. There were actually three explosions: the swing doors leading from the anaesthetic rooms into the theatre were blown open three times with great bursts of flame. We managed to remove the patient, and send for the Fire Brigade, and the fire was soon under control." The report does not state whether or not the patient was badly injured.

Often the exact cause of an explosion cannot be defined clearly. A fatal explosion occurred during a gastrectomy in 1935 [E. M. Smith, personal communication]. The operator was known to be obstinate, impatient and unwilling to comply with any request for caution when ether was being used. Junior staff were reluctant to assist him in theatre for fear of having their fingers cut off or their heads blown off. Their fears were fully justified when he ignored the advice of his anaesthetist once too often. When he used cautery to open the stomach, the resulting explosion killed the patient and wrecked the theatre. Anaesthesia had been induced with an inhalation agent, initially chloroform and then ether. It was reported as being a difficult induction, with the patient coughing, choking and swallowing, and therefore it is possible that the stomach may have contained ether vapour. Alternatively, if surgery was being undertaken to correct pyloric stenosis, there may have been flammable gases in the stomach, which could have been ignited by cautery.

MacIntosh described how the careless disposal of flammable agents down sinks and wash basins can be dangerous [38]. A sobering incident occurred during ophthalmic surgery in the early 1950s [J. I. Young, personal communication]. A junior nurse was told by the theatre sister to dispose of a half-full bottle of

ether which had been on the anaesthetic machine. Not knowing quite what she should do with it, but aware that it was fairly dangerous, she decided to dispose of it in what she regarded as the safest possible way. She poured it down the lavatory, pulled the chain and went back to theatre. After completing the first cataract, the surgeon, a man who hated noise, went out for a quiet cigarette. Before going back into theatre, he went to the lavatory and, after sitting down, discarded his cigarette between his legs into the pan. There was a loud bang, followed by a sheet of flame upwards out of the pan. He had a very unpleasant fright but, although severely shaken, he was not badly burned, because ether burns with a cool flame.

Ether continued to be used in Britain, although less frequently, until the mid-1980s. It had the advantages of maintaining heart rate and arterial pressure, promoting bronchodilatation and allowing jaw relaxation, thus providing easier intubating conditions than other agents.

The most recent fatality resulting from an explosion during administration of ether occurred in 1985 [39]. A 78-yr-old patient was undergoing bilateral cautery of turbinates. His trachea was intubated and the lungs ventilated artificially. Anaesthesia was maintained initially using halothane, but was changed to ether when the patient developed bronchospasm [40]. It was considered safe to use cautery, as closed circuit anaesthesia was being used with a cuffed tracheal tube. Cautery of the second side of the nose was underway when the explosion occurred [C. S. Bray, personal communication]. The patient suffered a ruptured trachea. Although it was repaired, and despite all intensive care measures, he died from renal complications 25 days later.

It was shown subsequently that there was a leak at the patient end of the double-tubing of the ventilator, near to the Y-piece [C. S. Bray, personal communication, 41]. It is likely that this would have resulted in a jet of gas mixture escaping under pressure during each inspiratory phase of ventilation and that

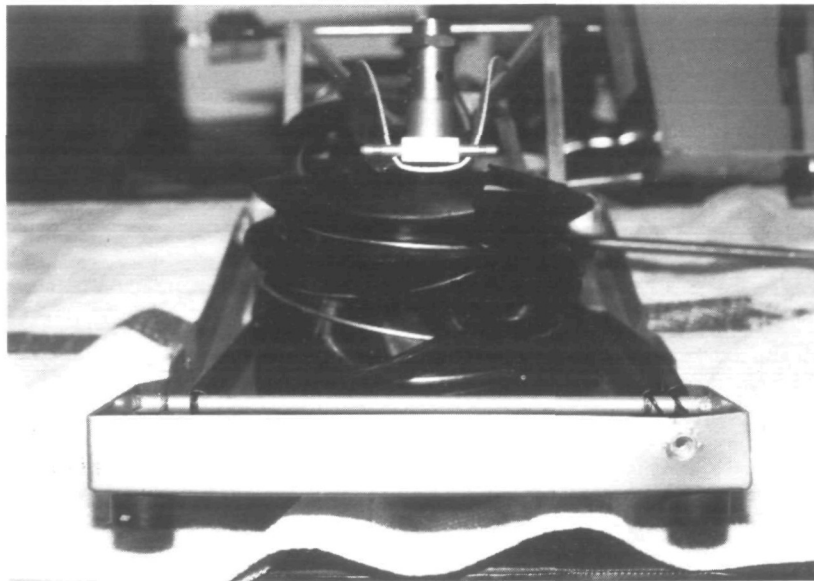


FIG. 4. Disrupted bellows of a Manley ventilator after an explosion during administration of ether.

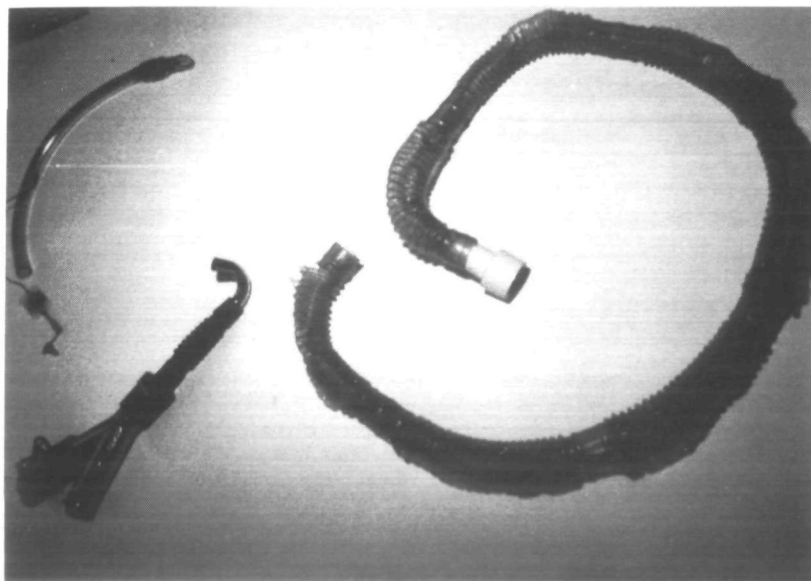


FIG. 5. Scavenging tube, ruptured in several places, catheter mount and Y-piece remnant of the double tubing from the ventilator and the blackened, but apparently undamaged, tracheal tube, after an explosion during administration of ether.

this escape would have taken place under the drapes, but near the site of operation. This gas would have been ignited by the cautery probe or its switch, which were both within the "zone of risk". There may also have been a faulty switch in the cautery handle. The apparent lack of damage to the tracheal tube makes it likely that the explosion occurred during the expiratory phase [L. Small, personal communication]. If it had occurred during inspiration, the flame and the pressure wave would have travelled towards the smaller airways, probably causing instant death. If ignition occurred during expiration, the flame would have entered the tubing and would then have travelled in both directions as a conflagration. On reaching the bellows, which would have held a reservoir of approximately 500–700 ml, detonation would have taken place. The blast would have travelled in all available directions,

back up the fresh gas flow tube towards the back-bar of the anaesthetic machine (where the high-pressure, one-way valve may have prevented involvement of the ether vaporizer), along the scavenging tubing and along both limbs of the double-tubing, towards the patient.

Figure 3 shows the distorted casing of the Manley ventilator, a particularly robust machine, figure 4 shows the disrupted bellows, with its metal plate bent upwards and figure 5 shows the scavenging tube, ruptured in several places, the catheter mount still attached to the remaining portion of the double tubing and the blackened but intact tracheal tube.

A safety information bulletin was issued in 1987 [42], reiterating the importance of using flammable agents only in machines which comply with relevant safety and antistatic requirements and in an environment which complies fully with specifications

relating to antistatic precautions. This hazard warning almost certainly resulted in further rapid reduction in the use of ether in the U.K.

ACETYLENE

Acetylene was introduced as an inhalation agent by Gauss and Wieland [43] in Germany in 1924, marketed as Narcylen. It was stored at a pressure of 1515 kPa in steel cylinders filled with a porous material containing acetone, in which acetylene was dissolved. Acetone was necessary to prevent spontaneous combustion of acetylene; special washing arrangements being required to remove acetone. A 40-litre cylinder contained approximately 5 m³ of acetylene.

Although the concept of anaesthetizing a patient with an agent as explosive as acetylene must have been somewhat frightening, many eminent anaesthetists did so and found it to have many advantages compared with ether or chloroform. Shipway, in 1925 [44], recommended that induction of anaesthesia should begin with a concentration of 70–80% acetylene in oxygen, the concentration then being decreased gradually to a maintenance concentration of 40–50% acetylene.

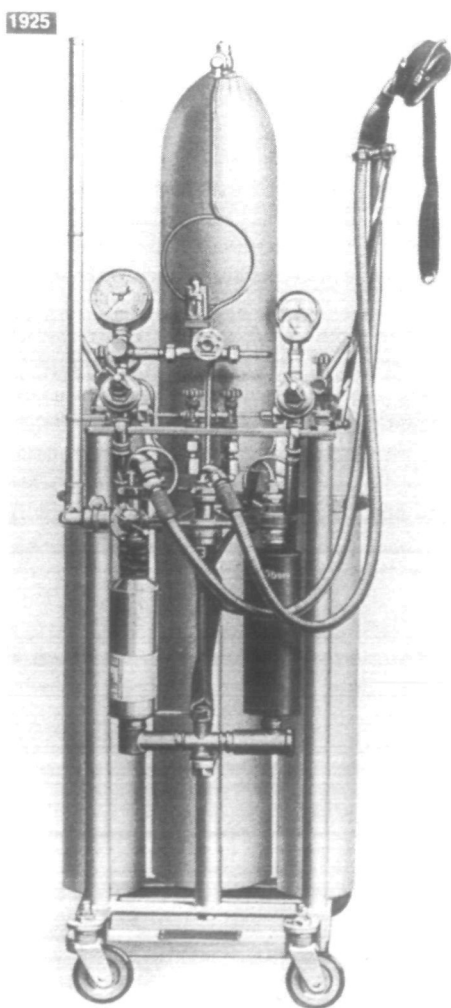


FIG. 6. A 1925 Drager anaesthetic machine, equipped with a cylinder of acetylene.

Heymans and Bouckaert used acetylene for 50 operations [45] and reported no excitation phase during induction, with the patient being anaesthetized without resistance or agitation. A concentration of 80% acetylene in oxygen induced insensibility and a degree of muscle relaxation in 3 min. Patients wakened rapidly and seemed in better condition than after cyclopropane or ether. The authors stated "the disadvantages of the method, the large size of the apparatus, the complicated technique, and the inflammability, are offset by its advantages".

This latter opinion was to be quickly disproved. Hurler [46] recorded an explosion of acetylene in oxygen caused by the use of thermocautery during laparotomy in 1925. He described graphically how the patient sustained very severe burns when a huge explosion occurred as the surgeon was withdrawing the diathermy from the peritoneum. This was followed by another explosion 10 s later, which resulted in the anaesthetic machine being knocked over. There were flames coming from in and around the mask and face. The patient's hair was on fire. Her gown and the drapes caught fire. The gas mixture in the reservoir bag then exploded. It is a vivid account of a terrifying incident. Figure 6 illustrates the Drager model anaesthetic machine involved, manufactured in 1924, with its awesome cylinder of acetylene dwarfing the machine. It was not used after 1925.

ETHYLENE

Other agents were being introduced into anaesthetic practice and although some had advantages compared with existing agents, they were all explosive. Ethylene was introduced in 1924 by Luckhardt [47] and was used for many years, particularly in North America and Germany. It was more potent than nitrous oxide and, with a lower blood-gas solubility, it allowed more rapid induction. As a lower concentration of the agent was needed, it also allowed more oxygen to be administered. Many anaesthetists used this agent and, in 1925, Hewer reported his observations after 120 administrations of ethylene at St Bartholomew's Hospital [48] and warned "any explosion with ethylene would be more dangerous than an 'ether flare', and will probably involve the death of the patient, and serious injuries to the anaesthetist".

Herb [49] reported five ethylene explosions in the Presbyterian Hospital in 1925, two occurring within 2 h of each other in different theatres. The first was caused by the assistant's gown brushing against the breathing tube in passing and the second when the tube was being changed from one machine to another.

Peterson [50] reported an ethylene explosion resulting in the death of a maternity patient and her baby in Ann Arbor, in 1929. The patient was breathing 75% oxygen and 25% ethylene from a McKesson machine and was taking three deep breaths at the beginning of each contraction, the mask then being removed, and the patient urged to bear down. Towards the end of the second stage, when the head was extending over the perineum, it

was usual to increase the concentration of ethylene until anaesthesia was produced. The article does not say at what point the explosion occurred, only that it was violent and loud enough to be heard throughout the four-storey maternity building. The anaesthetist was partly blown from her chair, but escaped injury. The gas machine was seen to be on fire, but the flames were promptly extinguished by a blanket. Immediately after the explosion the patient cried out and tried to rise to a sitting position on the table. After falling back, she developed opisthotonus, began coughing up large quantities of blood and became unconscious. Full resuscitation procedures were carried out, including tracheotomy, but she died. The fetus was delivered, dead, 30 min later.

Henderson [51] recorded 18 explosions with ethylene and 19 with ether in 1930, including one in which "the anaesthetist was literally blown to pieces by a cylinder, which was not attached to an anaesthetic machine". He was apparently manipulating the valve of the cylinder when the explosion occurred [52]. Henderson also described another explosion which occurred at the end of a major procedure, when the mask was removed from the patient's face and, as it was about to be laid on the machine, the explosion occurred, demolishing the reservoir bag.

Williams [53], in 1930, warned of the intra-operative and postoperative hazards of ethylene anaesthesia, but Griffith [54] used it exclusively for more than 10 years, observing that it was superior to nitrous oxide and stubbornly insisting that it was no more explosive. Sykes [55] wrote "I am happy to say that I have never seen an anaesthetic explosion. The nearest approach to it was when a gynaecologist came into the anaesthetic room and casually leaned on a 750-gallon ethylene cylinder with a lighted cigarette in his hand! I can remember my squawk of horror to this day".

CYCLOPROPANE

Cyclopropane was introduced as an anaesthetic agent in 1929 [56] and Waters and Schmidt promoted its use in clinical practice [57]. In common with acetylene and ethylene, it allowed rapid induction and could be given with a high concentration of oxygen. However, although it was an ideal inhalation agent, it was both flammable and explosive over a wide range of concentrations, including those used in clinical practice. Waters used to cause consternation among his technicians when he would wander into the laboratory smoking his pipe. However, he would have known that cyclopropane, unlike ethylene, was far heavier than air [58] and therefore would be dissipated at floor level.

Cyclopropane caused many serious explosions, with both loss of life and devastation of theatres. In 1939, there were 74 explosions in the United States, of which 13 were fatal [58]. Although many causative factors were identified, no lessons appeared to have been learnt, as fatal explosions continued to occur every year.

Walter reported two explosions with cyclopropane in an article published in 1964 [59]. One was caused

by a static spark from manual compression of the reservoir bag, resulting in the death of the patient and the anaesthetist being blown out into the corridor. The other was even more devastating and may have been the worst explosion ever. It killed two patients, two anaesthetists and two surgeons, with another surgeon losing an arm and two nurses each losing a leg.

A similar incident resulted in an explosion in 1957, in which a junior house surgeon, who was present, gave a vivid eyewitness account of what happened [A. Friedman, personal communication]: "We were doing a perfectly routine, almost minor, operation on a woman requiring diathermy to remove a non-malignant tumour of the tongue. Then the catastrophe occurred. We found ourselves lying on the floor, dazed, and our ears ringing from a tremendous explosion. We were completely deafened. We were also blinded, I suppose, by the flash, but also by the debris in the air. There was a terrible acrid smell, I remember the smell particularly, I suppose it was the burning rubber of the tube which connected the patient to the anaesthetic machine, because we later found that the explosion had actually occurred in the tube, and fortunately not inside the patient. To everyone's astonishment, who hears this story, the patient survived. If we had been operating alone, and isolated in the theatre, I suppose we would have been forced to pull ourselves together, and do what we could to resolve the situation, but there was an experienced surgeon working in the next theatre, and he came in and assessed the situation very quickly, and immediately performed a tracheostomy on the patient, and that almost certainly saved her life. She was very ill for a long time, with surgical emphysema of her neck and upper chest, but she did survive, and she turned out to be one of those remarkable people who refused to attach blame to anybody, the hospital, or the doctors, and simply passed it off lightly, saying 'Oh well, these accidents do happen don't they?' All the nursing and surgical staff experienced the shocking effect of the explosion. We were not physically injured, and the deafness and ringing in the ears and the blindness gradually wore off, but, as it happened, we were not obliged to do anything, because help came so rapidly. One of the scrub nurses burst into tears and started to shake uncontrollably, and we all felt like doing just that. It brought home to us very dramatically the real effects of shock. I felt very bruised the next day, whether from the force of the explosion or from being thrown to the floor, I don't know. We were all very lucky. We knew we were going to use the cutting diathermy, and we told the anaesthetist, who was an experienced registrar. He had quite properly turned off the cylinder of cyclopropane, but it emerged later at the enquiry that the valve on the machine was faulty, and cyclopropane had been leaking into the circuit".

A non-fatal explosion occurred in 1982 [R. Vale, personal communication] when an anaesthetic machine, with no patient attached, was being transferred from one theatre area to another, by a senior operating department assistant (SODA) who was noted for the speed and efficiency with which he discharged his duties. The machine had been used



FIG. 7. Damaged Bain circuit after an explosion caused by the presence of cyclopropane. The outer tube has ruptured at several sites and the inner tube is disrupted badly.

immediately before for the induction of anaesthesia in a child; 33% cyclopropane in oxygen and nitrous oxide were delivered through a Bain circuit. After disconnection from the patient, the system had been flushed with oxygen to remove cyclopropane. During transit, an explosion occurred. Only the SODA was in the vicinity and he suffered temporary partial deafness. It was presumed that the expiratory limb of the Bain circuit still contained cyclopropane, oxygen and nitrous oxide mixture. Figure 7 shows the damaged Bain system, with multiple holes along the outer tube and the disrupted inner tube. The SODA recalled the event as follows [H. H. Wellington, personal communication]: "It was of course a very old building dating back to 1894, and the corridor floor was almost certainly not anti-static. The Bain system had fallen to the floor after being disconnected, and as I picked it up, I must have dragged the end of the tubing along the floor for a few inches. There was a very loud bang, and I stood quite still and shocked with my eyes shut for a few moments. I couldn't hear anything at all. When I opened my eyes and looked around, I saw the machine still there, and the damage, and I realised exactly what had happened. It was all so quick. I got a terrible fright, and I was more or less deaf for a week or two after that, and then it all completely returned to normal. I suppose I was quite lucky really. It could have been a lot worse. Perhaps if the floor had been anti-static, it wouldn't have happened. One of the strange things was...the reservoir bag must have completely disintegrated, as we never found any of the bits at all. From that day on, cyclo was banned from the hospital!"

It was shown subsequently that the circuit had previously been modified and fitted to a Penlon coupling and that the conducting strip in the inner tube did not make electrical contact with the male connector on the Penlon coupling, because the conducting strip did not extend through the wall of the tube to the internal surface [L. Small, personal

communication]. An electrostatic charge could therefore have accumulated on the insulated part of the tubing and the charge could have been discharged when the attendant touched the distal end. The resulting spark would then have ignited the residual gas in the outer tubing.

CURRENTLY USED INHALATION AGENTS

It is believed commonly that halothane, enflurane and isoflurane are non-flammable in the concentrations used in clinical practice. This is not entirely the case. The lower limits of flammability of these agents have been assessed for two different gas mixtures (30% oxygen in nitrous oxide and 20% oxygen in nitrous oxide [2]), as shown earlier in table II. The lower limits of flammability of all three agents, when used with 30% oxygen in nitrous oxide, cannot be obtained from vaporizers currently in use in the U.K., assuming they are placed outside a circle system (VOC). However, any vaporizer suitable for use inside a circle system (VIC) can provide concentrations of anaesthetics above the lower limits of flammability. Furthermore, if the inspired oxygen concentration is allowed to decrease towards 20% in nitrous oxide, the lower limits of halothane and enflurane decrease to within the clinically used range.

An explosion during administration of halothane for dental anaesthesia in 1976 [60] has never been explained satisfactorily. The machine in use was a 1956 McKesson and 20% oxygen and 80% nitrous oxide was administered from the vaporizer, which was set at "full", which was quoted by the manufacturers as delivering approximately 2%. It is not stated whether or not the machine incorporated a circle system or if the vaporizer used was within such a circle. The incident is described as follows: "After induction of the tenth case of the morning, after about forty-five minutes' continuous anaesthesia, a loud bang occurred: simultaneously a spark

and a blue flame were seen inside the halothane vaporiser. The flame did not appear at the nose-piece. The patient was unharmed, and there was no damage". The probable source of ignition was stated as being static charge on the glass vaporizer, resulting either from the gas flow or from the trolley being wheeled about 8 m between dental surgeries after each case.

ACTION TAKEN TO REDUCE THE RISK OF FIRE AND EXPLOSION

In 1937, the American Society of Anesthesiologists set up a committee to investigate the hazards of fire and explosions and its subsequent report [61] analysed 230 explosions, which included 36 deaths and 89 injuries. Deaths were mostly caused by ether, ethylene and cyclopropane, especially when given with oxygen. Injuries were also caused by acetylene and ethyl chloride. Most of these accidents were shown to have occurred in circumstances where the normal safety regulations recommended by the appropriate authority had been disregarded. The report deplored the lack of knowledge of physics and chemistry among medical and particularly anaesthetic staff, and it highlighted the poor standard of practice of safety measures known to reduce the incidence of fire and explosion. Suggestions made in 1930 [51] regarding the need to introduce conductive rubber and the benefits of humidification, had been ignored. Fresh guidelines were laid down. These included the recommendation that all anaesthetic equipment should be made of conductive material, that humidification of operating theatres should be not less than 60 %, that flooring in operating theatres should be of appropriate resistance and conductivity, that all personnel and equipment in the theatre should be in conductive contact with the floor and that all materials capable of generating static electricity should be eliminated from theatre.

In the U.K., a working party was set up in 1956 by the Ministry of Health [62] to review the causes of explosion in operating theatres. Thirty-six explosions had occurred in the 7-yr period up to 1954, all of which were considered to have been avoidable. During these years, flammable agents were being used in about 0.8 million anaesthetics per year (30 % of the total number). The main cause of explosion was stated to be static electricity and the next most important cause was diathermy apparatus. The report defined a "zone of risk" between floor level and 4.5 feet above floor level and it was recommended that sources of ignition should not be introduced into this zone while flammable agents were being used. Other recommendations included specification for operating room flooring, adoption of antistatic materials which would allow dissipation of static charge without creating a spark and the use of spark-proof switches in operating theatres.

It was subsequently shown that the definition of zone of risk was too stringent [63] and, in 1971, the Association of Anaesthetists of Great Britain and Ireland [64], after reviewing the evidence, recommended the following: (1) the zone of risk should be defined as the area within 25 cm of any part of the

breathing system; (2) full antistatic precautions should be used in operating theatres and anaesthetic rooms if flammable anaesthetic agents are to be administered, but only one labour ward in a maternity department needs to be provided with antistatic precautions: it should not normally be necessary to lay an antistatic floor in recovery areas or intensive care units; (3) antistatic floors should not normally be provided in x-ray departments, radiotherapy treatment rooms or plaster rooms; (4) in areas where no antistatic flooring is provided, precautions to be adopted should include the use of a breathing system of antistatic rubber, wearing of conductive shoes and damping down of the floor in the vicinity of the breathing circuit.

Specific requirements for equipment to be used in the proximity of flammable gas mixtures are incorporated into British Standard 5724 [65]. Equipment to be used in, or within, 5 cm of the gas system, has more stringent requirements (category APG) than equipment to be used between 5 and 25 cm from the gas system (category AP).

Implementation of the safeguards recommended by the working party of 1956, albeit at enormous expense, of which some may have been unnecessary [66], was followed by a dramatic decrease in the incidence of explosions, so that only one explosion was reported to the Ministry of Health in 1961 and none was reported in 1962 [67]. Other factors contributing to this improvement may have included improved air-conditioning in operating theatres, reduction in the use of ether and cyclopropane and the introduction of halothane, new i.v. anaesthetic agents and new neuromuscular blocking agents. Since then, the use of ether and cyclopropane has been reduced further (in some countries they are not used at all), other inhalation agents have become available and the use of i.v. opioids to supplement anaesthesia has reduced the need to use high concentrations of potentially explosive inhalation agents.

A further working party [68], set up by the Ministry of Health, reviewed the antistatic requirements for those areas where anaesthesia is administered and issued its report in 1990. Recommendations included the following: (1) for new buildings, antistatic facilities should only be provided if the Department of Anaesthesia and the Health Authority have agreed that flammable agents might be used; (2) for existing buildings, if flammable agents are to be used, antistatic recommendations for materials used for anaesthetic equipment, set out in Hospital Technical Memorandum 1 [69] and for flooring (HTM 2 [70]) must be implemented and no electrically powered equipment should be used within the zone of risk, unless marked as suitable for use with flammable agents; (3) in general, any anaesthetizing area where antistatic facilities are not provided should be clearly marked with a sign indicating this: if a decision has been made to abandon the use of flammable agents and consequently not to provide antistatic facilities, management should ensure that all relevant staff are informed, that each anaesthetizing area has a warning sign, that all anaesthetic equipment capable of

delivering flammable agents has been removed or suitably modified, that pharmacy staff are informed of the decision and that heads of departments ensure that unsuitable equipment and flammable agents are not re-introduced.

Even though the risk of fire or explosion seems now to be so remote as to be almost negligible, vigilance is still essential if future incidents are to be avoided.

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