A brief historical review of non-anaesthetic causes of fires and explosions in the operating room

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Summary
Fires and explosions have occurred in the operating theatre for many years. Flammable inhalation anaesthetic agents were responsible for many incidents in the past, but these are no longer available in many countries. Other causes of fires and explosions still exist in the operating theatre and, from time to time, result in serious and occasionally fatal injury. Flammable gastrointestinal gases have been the cause of injury to patients during gastric surgery, laparoscopy and during examination of the large bowel with electrical instrumentation. Gases formed in the bladder during urological procedures have ignited, causing rupture. Alcohol-based skin cleaning agents have resulted in severe burns to the skin. Equipment used for storage and delivery of oxygen to patients has caused fires in a variety of ways. Adhesive skin drapes have resulted recently in two tragic deaths. The increasing use of laser therapy, particularly in ear, nose and throat surgery, and in oral surgery, has brought about a renewed awareness of the risk of fire. The relevant factors which should be borne in mind and the precautions which should be adopted when laser therapy is to be used in the airway are discussed. (Br. J. Anaesth. 1994; 73: 847–856)

Key words

Fires and explosions are rare events, but they can be devastating both in terms of structural damage to equipment and theatres, and to human lives. Their frequency has declined steadily over the past 40 yr, partly because of changing medical practice and partly because of greater awareness of contributory factors. The risk of fires and explosions from administration of flammable anaesthetic agents has largely disappeared following the dramatic reduction in their use over the past 10 yr. A short history of such “anaesthetic” fires and explosions has been documented previously [1]. There still remains a potential for serious fire from many other causes, and this article provides a historical review of these. The increasing popularity of laser surgery in a widening range of procedures may result in sporadic fires, regardless of how well precautions are publicized. Three ingredients are necessary for a fire to occur: fuel, source of oxygen and source of ignition. Gastrointestinal gases, gases produced in the bladder, skin sterilizing agents, breathing systems, nebulizers, drapes, swabs and tracheal tubes are all fuels which have resulted in fires or explosions. The source of oxygen may often be atmospheric air, but sometimes an oxygen-enriched gas mixture exists in the vicinity of the fuel. Nitrous oxide can also provide oxygen for combustion. The source of ignition may be diathermy, cautery, faulty electrical equipment, electrostatic charge (perhaps from an ultrasonic device) or laser; ignition may also result from adiabatic compression of oxygen.

Gastrointestinal gases
Flammable gases are produced at all levels of the gastrointestinal tract and have been the cause of numerous explosions. Hydrogen and methane are the most common flammable gases in the bowel, their proportions varying with diet, digestion and metabolism. The large bowel may contain 40% of flammable gases, the maximum recorded concentrations being 69% hydrogen and 56% methane. Human flatus has been shown to contain 44% hydrogen and 30% methane [2]. Hydrogen production, unlike methane, is dependent on bacterial metabolism of ingested material; its production is also increased after preoperative administration of mannitol. Methane production is independent of all of these factors [3].

The explosive range of hydrogen is 4–72% and of methane 5–15% [4], but neither is combustible in less than 5% oxygen [5]. Oxygen concentrations in the normal gastrointestinal tract decrease from 10% in the stomach to 5% in the colon, but anaesthesia using oxygen and nitrous oxide increases the concentration of both gases in the bowel [6]. Insufflation of carbon dioxide into the bowel before examination, a practice which is widely recommended [7, 8] but seldom performed, raises the lower limits of explosion to more than 50% for hydrogen and 29% for methane [5]. The concentration of flammable gases in the bowel can be reduced to 5% of normal by low-residue diet, fasting for 12–24 h and adequate preoperative bowel washout [9]. The use of mannitol as an effective and rapid method of cleansing the bowel was shown to markedly increase the hydrogen concentration in the bowel [5]. Carbon dioxide insufflation reduced the risk of explosions [3, 10].
mannitol was used, administration of antibiotics reduced the concentration of flammable gases [11, 12].

Humans produce about 200 ml of these flammable gases each day. Cows produce about 30 litre per day, so that endoscopy in the cow could be very dangerous. It has been shown that measurable although very low concentrations of flammable gases are eliminated from the lungs of animals [13] and their peritoneal cavities may contain hydrogen at a partial pressure of 2.7 kPa [14]. Humans eliminate 0.02 ml of hydrogen in expired gas every 1 min, a concentration too small to be important [15].

**PYLORIC STENOSIS**

Pyloric stenosis, a condition less commonly seen nowadays, allows more prolonged degradation of stomach contents and an increase in the amount of flammable gases present. Several sensational incidents have been reported [16-21] and were summarized in a highly entertaining review in 1954 [22].

One of these reports [18] described how a man, sitting with his wife in the darkness of the cinema, had lit a cigarette in his cupped hands and had belched violently: “To his alarm and astonishment, and of those seated near, there was a flash and a sharp explosion; the cigarette was blown from his lips across several rows of seats; his moustache was singed, and his lips and fingers burnt”. He left the cinema in pain and confusion, and subsequently underwent surgery “depriving him of an exciting party trick”.

Another incident [21] described how a man playing bridge was offered a light for his cigarette by his playing partner sitting opposite. As he leaned forward, he felt an uncontrollable urge to belch, and being in refined company, he attempted to do so discreetly through his nose. He enlivened the proceedings by producing two fan-shaped flames from his nostrils, and when he subsequently attended his doctor, a witness observed “he looked just like a dragon, Doctor”. Perhaps the dragon killed by St George may also have suffered from pyloric stenosis, as perhaps did all the ancient dragons which roamed the earth, breathing fire with every eructation. The source of ignition in these prehistoric creatures could have been sparks from gnashing teeth (not dissimilar as perhaps did all the ancient dragons which roamed the earth, breathing fire with every eructation. The source of ignition in these prehistoric creatures could have been sparks from gnashing teeth, which were the source of much anxiety when cyclopropane was used in dental anaesthesia), or from pawing the rocky ground: there were no antistatic precautions in those days.

It is surprising that more explosions during gastric surgery have not been reported. One unpublished fatal incident occurred around 1935 when a surgeon stubbornly ignored the warnings of his anaesthetist, who was administering ether for a gastrectomy. He opened the stomach with diathermy and the resulting explosion destroyed the theatre and killed the patient. It may have been the flammable gases in the stomach which caused the explosion, but the induction had been stormy, and it was possible that the patient had swallowed some ether vapour. There was no such uncertainty in a report in 1964 [23] which described an almost identical incident, although not fatal: the patient’s stomach was enormously dilated, and when diathermy was used to open it, a loud explosion occurred. The gases escaping from the stomach ignited and burned with an intense blue flame for about 10 s. The anaesthetist, thinking that anaesthetic gases had been the cause, quickly wheeled his machine out of the theatre but, as he had been using only oxygen, nitrous oxide and halothane, he was almost certainly not the culprit.

**LAPAROSCOPY**

The danger of performing laparoscopy was said to lie in the possibility of instruments perforating the bowel with the release of flammable gases into the peritoneal cavity and these being vulnerable to ignition by faulty electrical instrumentation. The incidence of bowel perforation in this way is thought to be approximately 2% [24]. In the early days of laparoscopy, air was used as the insufflating gas, and while nitrogen in air might quench the explosivity of any flammable gas present, the danger of air embolism was considered too great a risk and it was superseded by nitrous oxide. This was not really logical because it too is relatively insoluble in blood and thus almost as likely to result in gas embolism; worse still, it supports combustion, indeed it is more supportive than oxygen. Carbon dioxide is the gas used today for insufflation of the peritoneal cavity, having the advantages of high blood solubility and thus less danger of gas embolus and a quenching effect on flammability.

There have been several reports of explosions during laparoscopy, the most recent being in 1978 [25], in which a patient died during electrocoagulation of the fallopian tubes. Four litres of nitrous oxide had been insufflated. When the assistant “removed his foot from the switch, the surgeon began to withdraw the forceps through the laparoscope, there was a loud bang, like the sound of a balloon bursting, and the assistant was blown backwards by the blast”. The patient had an immediate cardiac arrest from which she could not be resuscitated. Faulty coagulation forceps were thought to have caused a spark, which initiated the explosion. Post-mortem examination revealed two large rents, one on each side of the diaphragm, the muscles of the abdominal wall being completely torn from their attachments.

An earlier report in 1976 [26] described cardiac rupture and diaphragmatic rupture in another fatal case, in which the laparoscope was broken in two places and the forceps blown out of the abdomen. Nitrous oxide had been used for insufflation. The authors urged that carbon dioxide be used to insufflate the peritoneum.

There had already been much discussion in the literature on whether or not nitrous oxide was preferable to carbon dioxide, and whether or not it was possible for bowel gases to be present in sufficiently high concentrations to result in an explosion [27-32]. Normal bowel contains approximately 0-500 ml of gas, probably existing in pockets.
along the length of the small and large bowel. If by chance an electrical instrument perforated the bowel at such a pocket, an explosion could result, particularly if the tip of the instrument remained in the lumen of the bowel. If the bowel was punctured by the insufflating needle, it was estimated that the potential leak of flammable gas into the insufflated gas in the peritoneum would take some hours to even approach flammable concentrations, even in the worst theoretical conditions [33].

Laparoscopy is now performed for prolonged surgical procedures, which may last several hours. It has been shown that if nitrous oxide is being administered continuously to a patient, an increase in peritoneal nitrous oxide concentration occurs [34]. In gynaecological patients, anaesthetized with 66% nitrous oxide, there was a gradual increase in peritoneal nitrous oxide concentrations, reaching a mean value of 36 (±6.90)% after 30 min. The possibility that equilibration might continue towards the inspired concentration of 66% constitutes a further cause for concern, as it was shown that only 29% nitrous oxide was necessary to support combustion of the highest reported bowel concentration of hydrogen (69%), and 47% for the equivalent concentration of methane (56%). The results of further studies are awaited.

COLONOSCOPY

An early explosion was described as occurring “with a loud report, equally startling to the patient and the surgeon”, during fulguration of a rectal polyp [35]. Sigmoidoscopy revealed no damage, and the patient came to no apparent harm. The author’s sensible advice, to wash out any gases present, was ignored and explosions continued to occur.

In 1952 a 56-yr-old man required electrocautery of two rectal polyps [36]. His bowel was prepared with tap water enemas, the first polyp was biopsied and cauterized, and the accumulated smoke was removed by suction, but when the second polyp was being cauterized, there was “a sudden violent explosion within the bowel, causing a blue flame to shoot out of the end of the sigmoidoscope for a distance of one or two feet”, and the bang was heard in the next room. The patient screamed and began to climb off the table. Subsequent deterioration resulted in laparotomy, and resection of two feet of colon. The patient recovered.

A fatal explosion in 1979 [37] resulted during coagulation of a caecal polyp. The bowel had been prepared with mannitol, but without inert gas insufflation. After 8–10 s of coagulation, there was an explosion which caused the patient “to jerk upwards off the table”, and the colonoscope to be completely ejected. The patient collapsed; laparotomy revealed numerous lacerations of the colon and spleen, and hemiectomy was performed but, despite the transfusion of 45 u. of blood, the patient died. The authors stated that insufflation of inert gas was the only sure way of avoiding explosion of colonic gas.

Another fatal case in 1965 [38] resulted from diathermy used to open a caecostomy. “Some sparking took place at the point of the diathermy needle on cutting through the caecal wall, and immediately on entering the lumen, a loud explosion took place... but no flash or burning was noted. A few seconds later, a small puff of white smoke was noted coming from the drainage tube in the left iliac fossa”. Subsequent deterioration occurred and the patient died. Post-mortem revealed discoloration and blast marks from the hepatic flexure distally along the whole length of the bowel, with several large perforations. Most surgeons now use scalpel and scissors to open a caecostomy or colostomy.

The use of mannitol to prepare the bowel may result in gaseous distension. In 1981, opening such a bowel with electroresection resulted in a violent explosion causing a longitudinal laceration of the entire transverse colon, requiring resection; the patient recovered [12]. Another similar non-fatal explosion in 1983 was accompanied by the release of whitish-grey gas, and explosion of pieces of colon into the theatre [6]. Another in 1982 resulted from endoscopic electrocoagulation of two rectal polyps [3]. The bowel had been prepared with mannitol, after 3 days on a low-residue diet; bowel gases had been aspirated, and nitrous oxide insufflated before cautery was begun. During cautery of the second polyp an explosion occurred with rapid deterioration of the patient who required hemiectomy.

Explosions in the bladder

Flammable gases are produced in the bladder during electroresection of the prostate or fulguration of polyps. The predominant gas produced is hydrogen, in concentrations of up to 60% [39,40]. Small concentrations of other flammable hydrocarbons have also been identified, notably carbon monoxide, acetylene and ethylene. Concentrations of these gases increase if high frequency currents are used [39]. Pure hydrogen is not flammable: it only becomes so in the presence of oxygen. During cystoscopy therefore the risk of explosion should arise only if air or oxygen is inadvertently allowed to enter the bladder, and if the tip of the resectoscope or cautery is allowed to emerge from the fluid and into the gas bubble. Urologists often hear popping sounds and see sparks and incandescent particles during transurethral resection of the prostate (TURP). These phenomena are believed to be caused by the formation of flammable gases from electrolysis of tissue, particularly water [40]. In vitro studies have shown that 19% oxygen may be produced from burning of tissue [41]. In vivo samples were shown to contain about 6% oxygen.

Several explosions were reported in earlier times [42–44]. More recently, two incidents were described in 1975 [40]: in one case, during TURP, “an audible explosion occurred, and a tear was noted in the dome of the bladder”: suprapubic drainage was performed. The patient recovered. In the other case, an explosion occurred during resection of a tumour of the dome: the bladder mucosa was torn slightly, but further surgery was not necessary. In another case in 1979 [41] air had been allowed to enter the bladder during TURP. This had been noted and, after evacuation of the gas, resection continued. Towards
the end of the procedure, a further volume of air was accidentally introduced together with irrigating fluid: "almost simultaneously, a loud intra-abdominal bang was heard. A bladder rupture was suspected, and verified, as the irrigating fluid did not return, and small intestine was seen through the cystoscope". At laparotomy, a large intra-peritoneal rupture of the bladder was found, with peritoneal lacerations. Chips of resected prostate were spread over the peritoneal cavity. The bladder was repaired and the patient recovered. Another explosion during TURP in 1984 [45] also resulted in a ruptured bladder, when bleeding vessels near the dome were coagulated. There was no change in the patient's condition, but cystoscopy confirmed bladder rupture, and, at laparotomy, only the trigone and dome were still intact.

Skin cleaning agents

Many agents used to sterilize skin before surgery are alcohol-based and are flammable. If excess fluid is not removed before drapes are applied, or if sufficient time does not elapse to allow evaporation, then cautery or diathermy may result in ignition. A safety information bulletin published in 1984 stated "Problems have arisen when pockets of vapour form, in the vicinity of the patient, from pools of fluid which have collected on or under the operating table drapes... the fault lay with the improper use of spirit-based preparation fluid" [46].

Experimental studies have shown that antiseptic solutions in 70% alcohol will ignite at 900°C and only become non-flammable when prepared in less than 20% alcohol. Antiseptics in aqueous solution only burn at temperatures greater than 1000°C [47]. Spirit-based agents not recommended for cleaning the skin in the presence of any source of ignition include, Betadine alcholic solution (10% povidone–iodine), Hibisol (0.5% chlorhexidine), Hibitane concentrate (5% chlorhexidine), Merthiolate (thiomersal), Hydrex Hand-Rub (70% chlorhexidine) and surgical spirit (methanol, ethanol). Some of these solutions are still found in the operating theatre and may be used to scrub-up, to clean the patient's skin or to sterilize instruments. Ossicles are sometimes stored in surgical spirit. All these fluids should be in containers marked clearly with the orange and black "highly flammable" flame logo. Iodine and nobecutane may explode in atmospheres of nitrous oxide at higher under the drapes.

Minor fires have been reported by Medical Defence Societies over the past 30 yr [48]. Two fires in ophthalmic surgery may have arisen from pooling of spirit near the cautery, although an oxygen-enriched atmosphere increased the risk of fire [49, 50].

A review of such incidents [47] included one in which chlorhexidine was used to clean the skin, which ignited when diathermy was used: another described a fire when perineal warts were cauterized after the skin had been cleaned with spirit.

Benzalkonium chloride, an alcohol-based disinfectant, has caused fires in veterinary surgery [51], and in a human [52], when cautery to the cervix ignited a benzalkonium-soaked swab in the vagina. In both incidents it was thought that benzalkonium had vaporized over the operating area and had ignited.

CATGUT STORAGE FLUID

Plain catgut maintains its tensile strength for 14 days compared with 28 days for chromic catgut. Ethilon is a monofilament polyamide. These sutures must be stored in packs containing 2–3 ml of conditioning fluid. This contains 10% water and 89% isopropyl alcohol, which maintains the suppleness and flexibility of catgut for up to 3 yr, and 1% sodium benzoate and diethylenolamine. Both substances act as rust inhibitors and the latter protects sutures against the effect of cobalt-γ-irradiation, which would otherwise neutralize the alkaline pH of the fluid.

A fire occurred during an appendicectomy in 1977 [53] when a scrub nurse opened three suture packets over a kidney dish near the operating field and accidentally spilled the contents onto the drapes. When the base of the appendix was cauterized, the operating field was enveloped in flames and although quickly extinguished, the patient suffered second-degree burns of the abdomen. These suture packs do not show any fire hazard warning.

Swabs and drapes

Cotton, paper or adhesive drapes can be ignited by cautery [54, 55], especially in head and neck surgery, where oxygen and nitrous oxide concentrations may be higher under the drapes.

A fire occurred in 1972 [56] during cauterization of leucoplakia of the tongue, after nasal intubation, with a dry pack in the pharynx. Flames appeared from the mouth with each inflation. Nitrous oxide and oxygen were escaping around the uncuffed tube during each inflation and were fanning the glowing gauze into flames. The tube was disconnected, the gauze removed and little damage was done to the patient. Another fire [49] resulted from cauterization during ophthalmic surgery; the drapes began to burn and the fire spread so rapidly that the patient's forehead and eyebrow were burned before the drapes could be removed. The patient was awake, but oxygen was being blown under the drapes. A similar fire was reported in 1986 [57] and the practice of blowing oxygen under drapes was identified as dangerous [58].

Disposable surgical drapes are now being increasingly used. They have the advantages of being less expensive, more water repellent and less permeable than cloth or paper drapes, but they burn more readily. Although they may be treated with flame-retardant chemicals, when ignited the fire spreads with alarming speed. In 1983, flame-retardant paper surgical drapes caught fire during laparoscopy where they were in contact with a faulty cautery flex which had melted near its attachment to the laparoscope. Attempts to put out the fire were unsuccessful. The drapes were pulled off the patient.
while they were still burning but, within 2 min, the entire drape had ignited and the theatre had filled with smoke, making it difficult to breathe. The patient was rushed to another theatre for completion of surgery, but suffered second-degree burns of the hand, and third-degree burns of the thigh [59].

Two similar but tragically fatal fires were reported in 1992 [60]. The first occurred during cardiac surgery on a 19-day-old infant, when cautery ignited a gauze sponge and the surgical drape. Flames engulfed the infant and, in the oxygen-enriched atmosphere, were so intense that they could not be extinguished and the baby died. The second fire resulted from cautery causing ignition of drapes during emergency surgery for an adult injured in a road traffic accident. Despite immediate disconnection of the cautery, one side of the patient was engulfed in flames within seconds. The flames could not be extinguished, the drapes could not be pulled off the patient and the theatre rapidly filled with dense smoke which forced everyone to retreat. Many items of fire-fighting equipment failed to function and the patient died. Cellulose-based drapes exhibit very rapid flame propagation once ignited, even without an oxygen-enriched atmosphere: they are water repellent so that dousing the fire with water does not extinguish the flames and, being self-adhesive to the skin, will not easily separate from the skin in an emergency. All skin drapes should be made of more effective flame-resistant material.

A recent fire resulted when a space blanket on a patient ignited, after a length of tubing from an oxygen regulator burst [Kordiak AM, personal communication]. The cause of ignition was not established, but may have resulted either from heat generated by high-pressure oxygen or from a static spark from the blanket in close proximity to the oxygen leak. Space blankets are constructed of aluminium coated in plastic to improve resilience and prevent tearing: aluminium ignited in oxygen will flash-fire, but in a plastic coating burns evenly.

Fires in the presence of additional oxygen

Oxygen-enriched atmospheres predispose to more serious fires than those occurring in air. Awake patients undergoing ophthalmic surgery are often given oxygen under the drapes [49]. This has the benefit of ensuring adequate inspired oxygen when the face is covered by drapes, preventing carbon dioxide accumulation, and providing a psychologically therapeutic cool inflow of gas. Three reports in 1989 [61] described flash fires which occurred in such situations: one was caused by cautery igniting a cotton-tipped applicator during removal of an orbital dermoid in a child who sustained eyelash burns; another occurred during levator repair in a woman given nasal oxygen; the third resulted from cautery during eyelid resection, in a patient given oxygen via tracheostomy. In none of these cases was it proved that fire resulted from increased oxygen in the operating field. Nevertheless, it was recommended that drapes should be carefully placed to prevent conduits for oxygen to track towards the operating site, that oxygen should be turned off during cautery, that air, not oxygen, should be circulated, and that a low temperature cautery tip should be used.

Tracheal tubes and breathing systems

Tracheal tubes are manufactured in several materials, of which only metal is non-flammable. Red rubber, plastic and silicone tubes are all flammable, but they vary in ignitability. This may not correlate with the ease with which the flame may be sustained or spread [62]. Wolf and Sidebotham have distinguished between extraluminal tracheal tube fires, where the tracheal tube is flammable in air and has been ignited, and an intra-luminal flame, where the tube is non-flammable in air but flammable in the gas mixture contained within it. If the source of ignition perforates such a tube to ignite the gases, an intraluminal flame can develop [62].

A plastic tracheal tube caught fire during diathermy of a tonsil tumour in 1969 [63]. Another ignited when being used for airway control through a tracheotomy, when a resectoscope was used to remove granulation tissue in the tracheostome [64]. Electrosurgery for tonsillectomy caused a further fire when a plastic tracheal tube ignited [65]. A more recent fire occurred when tracheotomy was being performed on a patient whose trachea was intubated and lungs ventilated with 100% oxygen: coagulating current was used to enter the trachea and the tracheal tube ignited with a small explosion; oxygen was discontinued, the tube was removed and tracheotomy was completed. Bronchoscopy revealed charring of the trachea around the tracheostomy site, but no damage to the airway: the tube was melted and perforated, and “the proximal lumen was full of black char” [66].

A fire in a breathing system occurred in 1961 [67] when brilliant yellowish-white flames burst up from under the drapes, followed by a muffled explosion. The anaesthetic tubing had caught fire. The surgeon had been using two diathermy probes, the second one being placed on the instrument stand. When the first probe was used, the second one was also activated, the current passing through the stand (shown to be old and non-conductive), and along the most conductive pathway available, the anaesthetic tubing, which was in contact with the stand. The fire caused black smoke to fill the tubing. The patient had smoky secretions removed from his tracheobronchial tree, but recovered.

Recommendations to reduce the risk of fire include: (1) the use of the lowest inspired oxygen concentration necessary to allow acceptable oxygen saturation levels, (2) oxygen should ideally be administered in helium or nitrogen, but not in nitrous oxide, (3) the use of non-flammable tubes with cuff inflated, so as to isolate the administered gases from the pharynx, (4) the use of saline to fill the cuff, preferably dye-coloured to allow early detection of leak [62].

Nasal cannulae

In domiciliary practice, oxygen therapy may be provided from cylinders or from oxygen concentrators. The latter equipment provides oxy-
gen, at a pressure of approximately 30 psi, to a
flowmeter. Nasal cannulae are constructed of com-
bustible plastic tubing. Three fires, and one bang,
have occurred when patients have lit cigarettes when
nasal cannulae have been in use [Kordiak AM,
personal communication]. Only local and superficial
burns to the nose have resulted from melting plastic
burning the skin. The flames did not appear to have
propagated into the nasal cavity, but back along the
tubing towards the flowmeter. Patients receiving
oxygen therapy are warned not to smoke, but
implementation is impossible. An incident describes
how a patient receiving nasal oxygen must have had
a cigarette in his mouth for some time before lighting
it, because when he eventually did, the cigarette
literally blew up. It must have been saturated with
oxygen.

Nebulizers
Three fires occurred in nebulizers in 1973 [68–70].
One resulted from a design fault in an unheated
nebulizer used to deliver 60% oxygen via CPAP to
a neonate with ARDS [68]. After 15 min, sparks
began to appear at the Venturi jet assembly and the
plastic moulding began to melt: flames then engulfed
the wingnut and flowmeter, but the device was
disconnected from the oxygen supply at the wall and
the baby was unharmed. It was thought that a static
charge had accumulated at the Venturi jet which was
not earthed adequately. It was shown that it could
retain a charge of between 16000 and 20000 V,
compared with correctly earthed models which held
charges of only 25–150 V. This model was subse-
quently redesigned. Another fire resulted when an
ultrasonic nebulizer was used to deliver adrenaline
via a tracheostomy to a patient in acute respiratory
failure [70]. Fifteen minutes after commencing
nebulizer therapy, a nurse saw whitish-orange flames
in the cup of the nebulizer, rapidly spreading to the
tubing. Immediate disconnection resulted in the fire
extinguishing itself. Scorch marks and blisters were
found on the nebulizer and similar marks were then
discovered on other used models. Nursing staff
reported that they were often aware of a “burning
candle” smell during the use of these nebulizers.
The lower part of the cup and the proximal 5 cm of
the tubing were melted and burned, the result of
converting electrical energy into high-frequency
acoustic energy which, although physically
dispersing the liquid agent into small particles, also
constitutes a potential fire hazard. The polyethylene
material of the nebulizer becomes heated, this
becoming excessive if there is insufficient liquid to
cover the upper inner surface of the cup: in this case,
the energy cannot be transmitted through the wall of
the cup, and is reflected back, causing an increase in
temperature. The manufacturers stated that the wall
of the cup was too thick and this was subsequently
modified.

Equipment used for storage and delivery of
oxygen
Cylinder explosions have occurred sporadically at
oxygen plants, in operating theatres and during
transfer of oxygen to hospital storage tanks: these
most commonly result from oil or grease coming into
contact with oxygen under pressure, particularly if a
cylinder valve is opened too suddenly, resulting in an
adiabatic increase in temperature of the small volume
of gas above. If any flammable material is present, it
may ignite.

A visiting anaesthetist from Vienna was killed in
the UK in 1951 when an oxygen cylinder exploded
as he was opening the valve. It was probably caused
by grease in the valve [71].

Some tourniquet machines are powered by
cylinders of pressurized gas. Air is obviously the
safest gas, but oxygen cylinders are frequently used.
An explosion occurred in such a machine in 1987
when an operating department assistant was badly
shocked and sustained superficial burns to the hands
and face when he opened the oxygen cylinder valve.
His clothing was peppered with debris and there
were holes in the gown and mask. The explosion was
followed by a flash fire which burned like a torch
until the cylinder was empty. There was substantial
damage to the cylinder housing and valve (figs 1, 2).
It was shown that two types of hydrocarbon grease
were present on pieces of debris and fragments from
the cylinder [72]. The subsequent hazard notice
recommended that air or carbon dioxide should be
used to drive such tourniquets and that all cylinders
should be opened slowly.

An unusual incident was recorded in 1955 [73]
when it was described how a cylinder can fracture
“leading to a sudden escape, under high pressure, of
the contents of the cylinder, which can then be
propelled forward like a jet-driven projectile”. In
the particular incident there was an old partial
fracture, about 20 cm from the base, gradually

Figure 1 The damaged and blackened oxygen yolk of an
oxygen-powered tourniquet after an explosion caused by grease
on the oxygen cylinder valve.
Non-anaesthetic fires and explosions

Figure 2 The damaged and blackened head of an oxygen cylinder after an explosion and fire caused by grease on the valve.

Figure 3 Fire and safety officers inspecting the pavement where an oxygen cylinder landed, after its base had fractured, causing it to be "jet-propelled" over the 3-m wall.

extending around the cylinder, causing it to be propelled into the air negotiating a 3-m wall eventually landing on the pavement on the other side (fig. 3).

A unique but devastating explosion occurred in 1979 when a full cylinder of 95% oxygen and 5% carbon dioxide used for cardiopulmonary bypass accidentally fell, hitting a trolley loaded with flammable substances, and exploded [74]. The explosion killed 21 people and blew out the walls of the cardiac unit.

When a gas cylinder valve is opened, a square-wave front of gas moves up at high pressure, compressing the small volume of gas in the regulating valve. Any flammable material present, for example part of a filter, dirt, fluff, oil or grease, may ignite. A fire occurred in a regulating valve in 1993 when a theatre nurse turned on a cylinder as part of a pre-use check [Kordiak AM, personal communication]. No one was injured. At the time of writing, the incident is under investigation.

Fire occurred in an operating theatre suite in 1986 when a transformer supplying the operating table overheated [75]. Dense smoke filled the corridor and two patients were evacuated until the fire was brought under control.

Leaks in breathing systems can cause flammable gases to escape and ignite. Occasionally, it is the breathing tubing itself which catches fire. In 1965 a nurse discovered a leak in a rubber connecting hose delivering oxygen from the cylinder to the flowmeter and attempted to seal it with sticking plaster [76]. Ten minutes after the start of the anaesthetic an explosion occurred and a wisp of flame 20 cm long appeared at the point where the plaster had been applied. The flame was extinguished by turning off the cylinder and no harm resulted.

Laser surgery

A laser creates small areas of intense heat which can set fire to unintended material, equipment or tissue, and burns whatever is in its path. The human eye is particularly vulnerable and the retina can be permanently scarred. If the laser beam hits a PVC tracheal tube containing an oxygen-enriched mixture, it ignites and burns like a blazing torch [77]. It can be reflected off shiny surfaces, for example retractors and forceps, and continues in a beam until it hits something. If, after dispersal, it hits a concave surface, it can re-focus, causing further harm.

The use of lasers in surgery presents such an obviously increased risk of fire that it is not surprising that there have been many fires during its use. These have included ignition of throat packs, swabs, tracheal and tracheotomy tubes, theatre clothing and patients' hair [78–82]. Almost all fires have been the result of lack of forethought and inexperience. Fewer incidents are being reported now, but it is inevitable that fires will occur sporadically from failure to adopt recommended guidelines. The study of different types of lasers and their applications is not relevant to this paper, but it may be appropriate to summarize some of the guidelines which may be applied to reduce the risk of ignition.

The use of metallic tubes is clearly desirable and several are available. Examples of chrome-carbon and stainless steel tubes are the Oswal-Hunton [83] and the Laserflex tubes, manufactured by Downs and Mallinckrodt, respectively. The former tube is all metal, whereas the cuffed version of the latter has
a PVC connector at the outer end and a PVC double cuff at the inner end. Although both tubes are composed of a spiral wire, the Laserflex is entirely flexible and can be bent to any shape required. It can thus be angled acutely away from the mouth. It has an internal lining of material which is said to ensure an airtight seal and also prevent penetration by laser. This lining becomes damaged if the tube is bent too often or is sterilized, so these tubes are not reusable. It has a reflective surface which might allow a laser beam to bounce causing harm elsewhere. However, it is claimed that the fine spiral surface disperses the beam into harmless smaller components.

The Osval–Hunt tube is more floppy, requiring an introducer for insertion, and cannot be angled out of the way. It can be sterilized or autoclaved or soaked in bactericidal solution, and reused. There is no cuffed version. It has a dull, non-reflective, "satin-matt" finish and therefore should not cause a laser beam to rebound.

Both tubes are resistant to carbon dioxide and KTP laser, but not to holmium YAG laser. If the YAG laser is deliberately aimed at either metal tube, it eventually melts the metal and penetrates. This should never be relevant to clinical practice.

Other precautions to reduce the incidence of fires include the following: all drapes and swabs should be thoroughly wet and the laryngeal inlet should be covered over by wet cottonoids to prevent the laser hitting any exposed part of the tracheal tube, and also to prevent debris and smoke from contaminating the lower airway. The least flammable conditions would be achieved by avoiding nitrous oxide altogether, by using oxygen-enriched air, with the lowest inspired oxygen concentration needed to maintain normal arterial saturation.

A cuffed tracheal tube ensures that anaesthetic gases are contained within the breathing system and do not contaminate the pharynx. An uncuffed tube results in anaesthetic gas mixtures escaping upwards into the pharynx. The common belief that enfurane, iso furane and halothane are non-flammable is only true for clinically used concentrations. Most currently available vaporizers do not deliver flammable concentrations, although some enfurane vaporizers deliver 7%. This is well above the lower limit of flammability of enfurane (5.75%) in 30% oxygen in nitrous oxide. All three agents become significantly more flammable in 20% oxygen in nitrous oxide, the lower limit of flammability for enfurane decreasing to 4.25% [84]. In a patient whose trachea was intubated with an uncuffed tube with gas escaping into the pharynx, the concentration of oxygen in this expired gas could decrease to 20%, although it would be unlikely if the inspired oxygen is more than 30%. An additional safety margin does nevertheless exist if a cuffed tube is used.

All tracheal tubes used for laser surgery of the larynx or pharynx are necessarily of smaller outer diameter, in order to allow maximum surgical access. This in turn implies a smaller internal diameter, the thickness of the metallic tube resulting in a further reduction in lumen size, which is smaller than an equivalent PVC tube. The high resistance to breathing through metallic tubes, together with their expense, may deter anaesthetists from using them, but if they revert to PVC, silicone or red rubber tubes, the risk of fire is high [85].

Miscellaneous
A fire occurred in 1990 when a methane flame was left lit in a small operating theatre [86]. The fire was restricted to the theatre, but smoke filled the whole hospital, which had to be evacuated. The person who discovered the fire did not immediately activate the alarm, but ran to someone else who did, thus losing vital time.

Ethylene oxide has been used to sterilize anaesthetic equipment, including ventilators. An explosion occurred in 1982 when a pressure valve between an ethylene oxide cylinder and the sterilizing unit failed, so that instead of delivering a pressure of 75 psi, the full cylinder pressure of 200 psi was transmitted to the sterilizer, which blew out its door with such force that it went straight through the theatre wall and ended up in the corridor [Wemyss C, personal communication].

An unusual minor explosion was reported in 1983 [87]. A 63-yr-old woman was being treated for angina with glyceryl trinitrate patches. She collapsed on admission, was found to be in ventricular fibrillation and was defibrillated. There was a loud bang, a bright flash, and a puff of yellow smoke curled upwards from the patch. Advanced cardiac support procedures were unsuccessful. At post-mortem, no damage to the patient appeared to have resulted from the presence of the patch, although there was a blackened area on its surface. Surprisingly, the bang was not thought to have been the result of the nitroglycerine content of the patch, but to arcing of the current between the defibrillator paddle and the aluminium cover of the patch. A similar incident has been described when nitroglycerine ointment had been applied to the skin [88]. The data sheet for Transderm Nitro patches now recommends that they be removed before cardioversion or defibrillation.

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