FIRES AND EXPLOSIONS IN THE OPERATING ROOM

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The Operating Theatre/Room (OR) is a potentially dangerous place with regard to **fires** and **explosions**, due to the presence of:

- Flammable substances
- Oxygen and/or nitrous oxide;
- Sources of ignition (flames, sparks).

This article will explain how fires and explosions develop and the precautions, which, when acted upon will help to avoid this serious and sometimes disastrous event. The patient and staff may be injured or killed by a fire or explosion.

Oxidation

The basis of all combustions and explosions is **oxidation**, which is the chemical reaction between a substance and oxygen. Atoms are broken-up and rearranged to form a new compound with the production of energy, mainly in the form of heat but often associated with light, sound, pressure and electricity. This is an **exothermic oxidative reaction**.

Oxidation can occur in a number of different ways:

- **Biological oxidation**. Glucose, like a number of other carbohydrates, is oxidised in humans consuming oxygen and producing energy (3,700kcal/kg). This happens in a very slow, and well regulated manner, at a low and almost constant temperature through a series of enzyme reactions. The end point of the reaction is the production of carbon dioxide (CO_2) and water, plus energy, which is dissipated as heat or utilized in other reactions.

- **Combustion**. Alternatively wood under different conditions may **burn**, consuming oxygen and producing exactly the same amount of heat but in a much shorter time at a higher temperature. Similarly petroleum gases contained in the cylinders for kitchen use can burn in a controlled way in a stove to boil surgical instruments.

Combustibles

These are substances capable of reacting with oxygen to produce heat at high temperatures. Many combustible materials, which include alcohol, cotton fabric, wood and rubber, are present in the operating theatre. For complete combustion to occur there is an ideal proportion of fuel and oxygen, which is defined as a **stoichiometric mixture**. For instance, the stoichiometric mixture of diethyl ether vapour in oxygen is one mole (see Appendix 1) of ether (74g) and 6 moles of oxygen (192g) or about 14 % ether vapour in oxygen. In air, the stoichiometric concentration of ether is 3.4% and in nitrous oxide it is 8%.

In practice these exact proportions seldom occur. When the concentration of fuel is more than ideal, the mixture is described as "rich", with some fuel being left either unburned or incompletely oxidised into a range of compounds (e.g. carbon monoxide, or acetaldehyde in the case of ether). When the fuel concentration is less than the ideal, the mixture is described as "lean" with some oxygen left over. Whether oxidising sugar at body temperature or burning gas in a stove at a much higher temperature, the reaction normally proceeds until either the fuel or oxygen are finished. Moreover there is a balance between the energy produced and the energy, mainly heat, which is dissipated (escapes). The reaction is at an almost constant temperature, called an **isothermal reaction**. When heat production is faster than dissipation, heat will accumulate and the reaction can enhance itself to the point of an **explosion**.

Flame

Normally a flame remains confined to a fixed point and is called a **static** flame - the candle flame, gas burner and spirit lamp are examples. Of more interest is the **self-propagating flame**, again produced in a lean (1/10 stoichiometric) air mixture inside a tube. This describes a flame, which can travel along leaving behind the products of combustion, whilst the front of the flame heats fresh mixture which in turn ignites and becomes a flame itself. The process is called **deflagration**, which is generally a mild phenomenon but can become very dangerous if it comes in contact with an explosive mixture.

A very peculiar phenomenon is the production of a cool flame by the oxidation of very rich mixtures of certain volatile agents with air. Ether can form a cool flame at concentrations around 20% to 35% when heated to as little as 200°C. There is a small zone of oxidation (not a real burning) at a low temperature and with barely visible light. The cool flame travels along the mixture, eventually dying off. However the danger is that it can act as a powerful ignition source if it encounters an explosive mixture. In addition it may remain unseen until it is too late! A classic example occurs when ether is spilled on the floor and, because it is heavy, does not spread, forming a very rich localised mixture. A faulty electric plug could then ignite the ether mixture causing a cool flame, which then travels along the floor until it reaches a place where the mixture is explosive, such as the exhaust from an anaesthetic machine, which then explodes.

Activation energy

Energy, usually heat, is needed to start the reaction. This is called the **activation energy**, which can be provided by an open flame, sparks, hot plate or filament. The activation energy required to start a reaction varies very much, but for ether/oxygen mixture it is very little. In practice it is the temperature of the ignition source, which is measured. The **minimum ignition temperature** for the most inflammable mixtures of anaesthetic vapours in air lies between 400 and 500°C. Note in oxygen the **minimum ignition temperature** is some 50°C lower. In contrast, a cool flame may start at a temperature as low as 200°C in a rich mixture of ether in air (20 to 35%).

Reaction Rate

The reaction rate is directly related to the size of the activation energy. Thus the higher the activation energy, the more rapid the reaction rate, and the more likely an explosion. Other factors may influence the initiation and the rate of reaction.

Temperature of the mixture

The speed of the reaction is doubled when the initial temperature is raised by 10°C (**Arrhenius law**). If the heat generated at the beginning of a reaction is only partially dissipated, the small amount of heat left behind is sufficient to raise the temperature and thus the rate of the reaction. In contrast, when, adequate heat loss occurs, such as in large rooms, the reaction may come to a halt. A self propagating flame, as described above, produced by burning ether in air inside a tube can progressively increases its temperature and pressure causing a powerful deflagration with an explosion of the tube especially if the end is closed. If the tube contains an oxygen rich mixture, a much more powerful event can be produced. Fortunately this requires the combination of a very powerful ignition and a long tube. This cannot be produced in common anaesthetic machines.

Limits of flammability

If the mixture becomes too lean it cannot ignite. The **Lower Limit** (LL) for diethyl ether is 2.1% (vapour) v/v in either air or oxygen. There is also an **Upper Limit** (UL) where there is an excessive concentration of fuel for the oxygen present. The UL for ether in air is 36%v/v and 82% in oxygen.

Nitrous Oxide

Although N_2O does not enter the biological oxidising processes, it is a powerful oxidant i.e. it strongly supports any combustion process. It is absolutely wrong to assume that it will prevent fires and explosions by dilution of oxygen. It is as effective as oxygen in producing explosive mixtures.

Implications for Anaesthesia

The conditions for flames and explosions require three essential components, a combustible substance, a source of ignition and oxygen. Despite the dangers described, in practice they rarely occur in the theatre, provided staff are careful, understand the mechanisms and take the appropriate precautions.

Flammable Substances in the Operating Theatre.

- **Diethyl Ether** burns slowly in air and is not easily ignited by a spark; mixtures with oxygen and/or nitrous oxide become explosive between approximately 1.5 and 40% v/v. Maximum detonability is approximately 15% in oxygen. Therefore hot wires and plates at 300°C, below the temperature of dull-red visible heat, are sufficient to start an invisible flame. Remember that ether vapour is denser than air and therefore sinks, spreading over the floor. Store ether in the dark to prevent auto-oxidation, which can make the simple shaking of the bottle enough to trigger an explosion. Anti-oxidants are added to "anaesthetic" or laboratory ether, reducing this risk.

- **Ethyl chloride** burns easily and explodes in oxygen or nitrous oxide or air - stoichiometric concentrations are respectively 25%, 14% and 6.5% v/v, with narrow ranges between LL and UL. Ethyl chloride is very dangerous.

- **Petroleum lubricants** - a sudden rise in pressure in a confined area such as a reducing valve or pressure gauge, can generate sufficient heat to ignite petroleum lubricants and cause an explosion.

- **Alcohol** burns very easily with an almost invisible flame, which is easily overlooked. It can easily soak drapes or swabs, which can then be ignited by a diathermy spark, especially in the presence of oxygen or nitrous oxide.

- **Natural** (generally methane or hydrogen) or anaesthetic gases inside body cavities (bowel, or alveoli) as well as swallowed ether in the stomach can explode or be ignited by the diathermy.

- **Propane, butane or other petroleum gases** for burners, stoves, lamps are very common sources of domestic and theatre disasters.

- **Modern volatile agents**. None of these (desflurane, isoflurane, sevoflurane) are inflammable; however they are expensive and not always available. Halothane, which is inexpensive and widely available, is also not inflammable, nor is the azeotropic mixture (halothane 66%-ether 34% - See Appendix 3).

Source of ignition energy

- **Extraneous flames** - any kind of open flames from candles, burners, matches, burning lamps etc. however small.

- **Hot wires and plates** - cautery, electric stoves, hot-wire spirometers, electric bulbs especially those for endoscopy or modern halogen lamps, glowing cigarette ashes.

- **Electrosurgical appliances** - these are powerful sources of ignition energy in the form of sparks, arcs or heat within the machine, the foot switch, diathermy spark, or faulty equipment. Sparks also happen in normally functioning switches, or when a live plug is pulled from a socket. Bad electrical contacts not only produce hot wires and/or arcs, but can also cause a fire themselves.

- **Static electricity** is a possible risk, though the risk is reduced in a humid environment. A fully antistatic equipped theatre is ideal but difficult to realise, small measures such as using black rubber antistatic tubing for the breathing tubing and scavenging will reduce the risk.

- **Compression energy** - gas escaping from cylinder may ignite lubricants.

Clinical practice

Keep the anaesthetic mixture confined to the apparatus:

- **Avoid open mask anaesthesia**. If an open mask technique is used and the head is not covered by drapes, and the room is well ventilated, only an area extending for some 25-30cm around any part of the patient's head should be considered dangerous. Gases passing under the towels toward the diathermy are potentially very dangerous.

- **Intubate / LMA whenever possible**. Semi-closed breathing systems (e.g. the Penlon EMO vaporiser or Tri-Service apparatus) contain the ether vapour.

- **Ensure good theatre ventilation**. In a well-ventilated room, the mixture is rapidly diluted to a safe concentration once it leaves the expiratory valve of the breathing system or ventilator.

● **Use a scavenging system** connected to the expiratory valve of the breathing system or ventilator to carry the ether mixture outside through a theatre wall.

● **The "zone of risk"** of fire or explosion was described by the Association of Anaesthetists of Great Britain and Ireland in 1971. It is defined as an "**area extending 25 cm around any part of the anaesthetic apparatus...**" This is because leakage from the apparatus is always possible, but careful maintenance of the apparatus will help to reduce leaks. Potential sources of ignition must not be put in this area.

● **Diathermy** is safe to use with ether and air providing you are not working on the head and neck or lungs. There is a risk of a fire, but if it is not used near the head and neck or lungs, the risk of a fire is very small.

● **Oxygen and ether combinations**. Oxygen may be required to maintain the patient's oxygen saturation during anaesthesia (Appendix 2),. Under certain conditions a mixture of ether and oxygen can result in an explosion, compared to a mixture of ether and air which can burn. Therefore added oxygen and a diathermy is very dangerous. **Do not use ether and oxygen with diathermy**. You must either switch off the oxygen, or switch off the ether, or ask the surgeon to switch off the diathermy. Never risk an explosion it could kill you !!

Minimize the flammability

● Use as little supplementary oxygen as needed to maintain saturation.

● If possible use non-flammable agents.

● Store all flammable substances out of the room and in a safe place.

● Gas and petroleum burners should be kept out of the theatre - **no open flames or fires.**

● Avoid nitrous oxide.

● Do not use lubricants on reducing valves, pressure gauges or other parts connected with oxygen or nitrous oxide cylinders.

● Dilute any flammable or explosive mixtures, which escape if the air in the room is changed as often as possible - **plenty of fresh air. NOTE** - air conditioners like those used for home or office do not change air, in fact they may be a source of ignition.

Prevent ignition sources

● Keep monitors, other electrical appliances and instruments 1.5m above the floor and at a safe distance from head of the patient (25cm)

● Beware of diathermy! Both the electrode and foot switches should not be allowed into contact with anaesthetic gases. Remember these may infiltrate the towels toward the surgical field.

● Keep all unnecessary electrical apparatus out of the room. The oxygen concentrator can be placed at a distance from the anaesthetic machine and connected by any long tube of 1cm diameter. Alternatively it can be mounted on the wall, 1.5m from the floor.

● All equipment should be properly earthed at a single point (not the water pipe!) with cables of large diameter and not welded.

● Any patient ventilator should be flame/explosion proof.

Bibliography

To our knowledge no recent textbook of Anaesthesia deals with this topic, nor have we been able to trace the subject of explosions related to Anaesthesia in Internet. We are indebted to:

1. Macintosh R, Mushin W W and Epstein H G: Physics for the Anaesthetist (including a section on Explosions) Blackwell Scientific Publications, Oxford and Edinburgh, 1963

2. Scurr C, Feldman S and Soni N: Scientific Foundations of Anaesthesia (The basis of intensive care) 4th edition, Heinemann Medical Books, Oxford 1990.

Appendix 1- A reminder of basic chemical terms and facts

$2\ H_2 + O_2 = 2\ H_2O$ + 116kcal. That is two moles (2g) hydrogen (H_2) plus one mole (32g) oxygen (O_2) produces two moles (36g) water (H_2O) and 116kcal of energy.

Atomic weight: the weight of the atom of an element compared to the weight of an atom of hydrogen, which in effect becomes the base unit; e.g. the oxygen atom weighs 16 times the atom of hydrogen - the atomic weight of oxygen is 16. Other examples include carbon 12, nitrogen 14 and sodium 23.

Molecular weight: the sum of the atomic weights of a compound: e.g. the gaseous oxygen molecule is formed by two atoms and therefore its molecular weight is 16x2=32; nitrous oxide (N_2O): (14x2) + 16= 44; diethyl ether (C4H10O): (12x4) + (10x1) + 16= 74

Mole: the molecular weight expressed in grams: 1 mole of oxygen = 32g; 1 mole of Ether = 74g One mole of any substance contains the same number of molecules. One mole of any gas ideally occupies a volume of 22.4 litres at

Normal temperature and pressure (0^oC or 273^oKelvin: 760mmHg).

Combustion: When combustion is complete, the following reaction occurs:
1 mole fuel + b moles oxygen = products (CO_2 and H_2O) and Energy (heat, light etc).
"b" is the exact number of moles of oxygen required to completely oxidise completely one mole of fuel

Density: Ether vapour has a density of 2.56 with respect to air

Appendix 2 - The ether-oxygen dilemma

Ether is still considered a very valuable agent for inhalation anaesthesia, because it is non-toxic, efficient, and inexpensive. It is therefore rightfully still widely used in many parts of the world. However there are difficulties. As with any anaesthetic, there is impairment in pulmonary function, which may require an inspired oxygen concentration above 21% (together with assisted or controlled ventilation). Therefore oxygen supplement may be required, which increases the possible danger of fire or explosion.

Appendix 3- Azeotropic Mixture

Halothane 66% and diethyl ether 34% mixed together form an "Azeotrope" or a mixture where the molecules of the components form loose hydrogen bonds and cannot be separated by distillation in spite of different vapour curves. The halothane/ether Azeotrope can be vaporized with a halothane vaporiser and clinically useful concentrations are similar to those of this agent or around 1.5%. Induction is reasonably quick and not unpleasant and recovery more prompt than with ether. Due to the ether in the mixture, the Azeotrope retains powerful analgesic and relaxant properties and like ether it gives excellent cardiovascular and respiratory conditions. It is not explosive, can be easily transported and stored and may burn in oxygen only at concentrations over 10 %. The halothane/ether Azeotrope is an excellent anaesthetic which combines the best of the two parent substances. It is surprising that it does not have the recognition it deserves. This is possibly due to the poor development of anaesthesia relevant for developing countries whilst anaesthetists in affluent countries are submerged by a profusion of new molecules.