Respiratory gas analysis has now become a standard monitoring technique in anaesthesia: in theatres, intensive care unit, and for the transfer of ventilated patients. The AAGBI Recommendations for Standards of Monitoring during Anaesthesia and Recovery (2007) recommend as essential components during an anaesthetic an oxygen analyser with an audible alarm and a carbon dioxide analyser; a vapour analyser is also essential whenever a volatile anaesthetic is delivered. There are also requirements to monitor ambient anaesthetic agent concentrations in hospitals to conform to COSHH standards. An appreciation of the concentrations in hospitals to conform to recommendations to monitor ambient anaesthetic agent concentrations in hospitals to conform to COSHH standards. An appreciation of the current systems available and their design allows the user to utilize the best monitor for each situation.

Oxygen analysis
Oxygen analysis can be performed in inhaled and exhaled gases and from blood samples. In theatre, gas analysis usually takes the form of a paramagnetic cell. This works on the principle that oxygen along with nitric oxide is a strongly paramagnetic gas and is attracted into a magnetic field by the virtue of having unpaired electrons in their outer electron ring. Most other gases in anaesthesia are only very weakly attracted into a magnetic field. In older cells, a dumb-bell and torsion wire system was used; however, modern systems use a switched electromagnetic field and pressure transducer (Fig. 1). The electromagnetic field is generated at approximately 110 Hz. This creates a pressure differential between the reference sample (usually clean air) and the patient’s sample. A sensitive transducer detects the pressure fluctuations of approximately 20–50 μbar and converts them to a DC voltage, which is directly proportional to the concentration of oxygen.

Blood gas analysis is usually performed using a gas bench measuring the partial pressure of dissolved oxygen and CO2. This is usually by means of a Clarke electrode for oxygen, a Severinghaus electrode for CO2, and a glass electrode for pH. Attempts at continuous intravascular oxygen and CO2 monitoring have been made, for example Paratrend 7; however, their routine clinical use is still some way off. Clarke (polarographic) sensor
This system uses a noble metal (platinum, gold, or palladium) cathode and a silver/silver chloride anode, in a potassium chloride or potassium bromide electrolyte buffer (Fig. 2). This buffer is kept within a cellophane compartment around both electrodes. An external current is required to drive the cathode reaction, hence the name polarographic.
At the platinum cathode (positive), the following reduction is generated in the presence of oxygen:

\[ O_2 + 2H_2O + 4e^- = 4OH^- \]

At the silver anode (negative), the following oxidative reaction occurs:

\[ 4Ag^+ + 4Cl^- + 4e^- = 4AgCl \]

Therefore, current flows in the presence of oxygen and the current strength is directly proportional to the concentration of oxygen present, in the range of voltages used. The Teflon membrane is utilized as it allows dissolved oxygen through, but retards other gases. Temperature is factored into the output equation. A concentration gradient exists between the dissolved oxygen in the measured substance (usually blood) and the electrolyte solution because of the consumption of oxygen. This is required to advance the response speed of the system. The thickness of the membrane should also be considered and must be compensated for as it ages.

The polarographic sensor will over-read in the presence of N2O, as silver contamination must be compensated for as it ages. Paramagnetic oxygen analysers are the most common form of oxygen analyser used in the operating theatre.

Carbon dioxide analysis can also be performed using either mainstream or sidestream capnography.
Mass spectrometry is a very accurate technique; however, at present, it is impractical for routine in-theatre use.

Key points
Respiratory gas analysis (oxygen, carbon dioxide, volatile anaesthetic agents) is a standard monitoring technique during anaesthesia.

- Paramagnetic oxygen analysers are the most common form of oxygen analyser used in the operating theatre.
- Carbon dioxide analysis can be performed using either mainstream or sidestream capnography.
- Mass spectrometry is a very accurate technique; however, at present, it is impractical for routine in-theatre use.
Carbon dioxide in solution

The Stow–Severinghaus-type sensor is used for dissolved CO₂ measurement of CO₂ in its gaseous state is described later in this article. The Stow–Severinghaus electrode (Fig. 3) utilizes a glass pH electrode to measure the partial pressure of CO₂; over the range of 1.3–12 kPa, this relationship is linear.

Blood is again separated from a buffer by a Teflon membrane; CO₂ can freely diffuse into the buffer (usually hydrogen carbonate) with NaCl and AgCl. This is in contact with H⁺ sensitive glass. The ion selective glass is designed to be H⁺ selective by manipulating its contents; they can also be made to select for Na⁺, K⁺, Ca²⁺, and Li⁺. Inside the glass electrode are KCl and a calomel (Hg/HgCl₂) reference electrode. A further Ag/AgCl electrode is in contact with the hydrogen carbonate solution to complete the circuit.

Gaseous analysis: carbon dioxide, nitrous oxide, and volatile agents

In their gaseous states, these can be measured by a number of techniques including: infrared absorption spectroscopy; photoacoustic spectroscopy; silicone rubber and piezoelectric absorption; refractometry; Raman scattering; and mass spectrometry. Most in-theatre side-sampling benches presently utilize infrared absorption.

Infrared absorption spectroscopy

Molecules containing dissimilar atoms will absorb infrared radiation and convert this energy into molecular vibration. The vibration frequency depends on molecular mass and atomic bonding within the molecule. Most molecules will absorb infrared at specific wavelengths and hence the molecule can be identified and its concentration measured. Absorption is according to the Beer-Lambert law, which states that there is a logarithmic dependence between the transmission of light through a substance and the concentration of that substance.

Usually, the generated infrared radiation is focused through a chopper wheel (Fig. 4) that has a number of narrowband filters to select specific infrared wavelengths. A reference channel and sample channel are aligned side by side, with a means of detecting the transmitted infrared (photocells or thermopiles) and amplifying and processing the signal. Pressure and temperature are integrated with the data. Alternatively, if the initial radiation is pulsed, the subsequent vibration pulse can be detected using a microphone and then amplified (photoacoustic spectroscopy).

At the wavelengths used to measure volatile agents, there are other molecules that will interfere with the absorption peaks. Carbon dioxide, nitrous oxide, alcohol, water vapour, and carbon monoxide will all absorb infrared between 3 and 12 μm. Modern gas benches look at a series of absorption peaks enabling agent identification. Carbon dioxide and nitrous oxide will broaden each other’s peaks and those of volatile agents (collision broadening). This is where the energy absorbed by one molecule is transferred to another, allowing further radiation energy to be taken up by the

Galvanic sensor, Hersch, or fuel cell

This is similar to the polarographic sensor, but the electrodes are chosen to provide their own current. The cathode is often gold or silver, and the anode is usually lead, with potassium hydroxide as the electrolyte solution. The cathode reaction is as described earlier; however, the anode reaction is as follows:

\[ 2\text{Pb} + 6\text{OH}^- \rightarrow 2\text{PbO}_2\text{H}^- + 2\text{H}_2\text{O} + \text{e}^- \]

The flow of electrons is proportional to the concentration of oxygen present. The anode is sacrificial, the system is temperature and acid sensitive, and can take a while to recover after exposure to high concentrations of oxygen (oxygen shock). They have a limited life span but can be made relatively cheaply.

Fig. 1 Schematic drawing of a Paramagnetic sensor; oxygen is drawn towards the magnet and will create a pressure difference between the limbs if the concentration is different. This can be sensed and turned into an acoustic signal.
first molecule. This is usually compensated for electronically, after looking at various predictable peaks.

In-line or mainstream infrared spectrometers can be made small enough to sit in the patient’s ventilator circuit. They shine infrared light of a specific wavelength through the plastic housing to a photo-detector. At present, they are used only for carbon dioxide. A disadvantage is that they add bulk to the patient end of the circuit; however, they are portable, do not require any gas to be taken from the circuit, and are relatively cheap.

Sidestream infrared spectrometers are most commonly used in theatre and require a sampling flow rate of up to $200 \text{ ml min}^{-1}$. However, this can be returned to the circuit. Water vapour entering the analysis chamber has to be prevented. There is a lag time for the sample to reach the analyser dependent on the length of tubing used, usually approximately $2.5 \text{ s}$ for $3 \text{ m}$ tubing. The position of sampling also matters, particularly in conditions where small tidal volumes are likely, as fresh gas flow may enter the sampling tube. In neonates, there are sampling sites on the $15 \text{ mm}$ endotracheal tube connector rather than the HME filter.

**Refractometry**

By shining beams of a monochromatic light source through a gaseous medium and focusing them on a screen, a pattern of light
and dark bands will appear at the fringe of the object. The nature of these bands will depend on the light waves arriving in or out of phase of each other, which in turn will depend on the gaseous medium’s refractive index and concentration. In the Rayleigh refractometer, a series of prisms split the light source through sampling and control tubes. The refractometer is calibrated for a particular gas and, by means of aligning the fringe patterns created by each sample, a scale can be made to give the concentration of that gas. For the anaesthetic vapours, the refractometer can be calibrated for halothane and, then by reference to conversion tables, be used with the other anaesthetic vapours. These systems are difficult to use for breath-by-breath analysis; however, they are used to calibrate vaporizer output and theatre and environmental gas exposure.

**Piezoelectric absorption**

A piezoelectric compound such as quartz can be made to resonate at a particular frequency. In the Engstrom Emma analyser, two quartz crystals are mounted between electrodes. One is coated in silicone-based oil that will absorb anaesthetic vapours; the other is not and becomes the reference. The oil will absorb the halogenated vapours and change the resonant frequency in proportion to the concentration of vapour present. There is a need to compensate for nitrous oxide, as it is minimally absorbed also. The response time is fast but individual vapours cannot be differentiated by the machine.

**Raman scattering**

When light meets an object, the light will be scattered, usually elastically, with no change in energy state. This is Rayleigh scattering and is responsible for the blue colour of the sky and colourful sunsets. However, some of the light’s energy will be absorbed and a transformational shift will occur, either by absorption of the energy or by release of the energy as a photon, with a different wavelength. This is inelastic Raman scattering. With the advent of powerful argon lasers and smaller cooling systems, portable anaesthetic monitors utilizing this phenomenon can be made. A laser beam is concentrated in the analysis chamber, the scattered light is passed through specialized optics and a series of narrow-band filters, to a photo-detector and signal processing unit. The filters allow only the shifted photons of interest through. The amount of emitted photons is proportional to the concentration of vapour or gas.

These units are still more expensive than infrared systems, but have the advantages of fast response times, no degradation of the molecule under examination, ability for multi-gas analysis, and accuracy greater than infrared spectroscopy (approaching mass spectrometry).

**Mass spectrometry**

The sample gas is drawn or injected into a low-pressure sample chamber that is attached to another chamber, at a pressure nearing that of a vacuum. The pressures are maintained by virtue of vacuum pumps. A molecular leak pathway is constructed between the two chambers. In the second chamber, the molecules are ionized, usually losing an electron. The resulting ions are then accelerated by a cathode plate, towards the second part of the chamber. Here, either fixed magnets or electro-magnets influence the ions and allow separation by the ion’s...
mass and charge. The ions are narrowband-filtered and detected by photo-voltatic receptors, and the signal amplified and processed.

In the quadrupole spectrometer, the magnetic field is a mixture of a DC field and an AC radiofrequency field. If the AC components frequency and the cathode acceleration are altered, only the ions of interest will be detected, as the others remain ‘trapped’ in the magnet. These systems are very accurate and require tiny amounts of sample. They are able to distinguish between different compounds by looking at both parent compound and predictable subsidiary peaks. These subsidiary peaks are formed by degradation of the compound, for example, nitrous oxide becomes NO, O$_2$, N$_2$, N, and O.

Mass spectrometers require powerful vacuum pumps and the sample cannot be returned to the patient owing to the ionic degradation. The response and delay times can be quite long and they are not yet cost-effective for widespread theatre use. However, they are very accurate and have a place in research.

References


Please see multiple choice questions 16–20