Measurement of gas concentrations

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Abstract

Gas analysis is one of the minimum standards of monitoring for any patient undergoing anaesthetic intervention. Side stream analysers are commonly employed to allow for measurement of gas concentrations. The systems used to measure oxygen (O_2) concentration include the paramagnetic analyser, the Clark electrode and the fuel cell. Infrared absorption spectroscopy is used to measure carbon dioxide (CO_2), nitrous oxide (N_2O), and volatile anaesthetic agents in gaseous form. Refractometry, piezoelectric absorption, Raman scattering, and mass spectrometry may also be used. The Severinghaus electrode is used to measure CO_2 concentration in solution. This article will provide an overview of the techniques used for gas analysis and their associated potential sources of error.

Keywords Capnography; carbon dioxide; gas analysis; nitrous oxide; oxygen; volatile anaesthetic

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Introduction

The ability to measure inspired and expired gases has been recognized by the Association of Anaesthetists of Great Britain and Ireland (AAGBI) as a minimum standard of monitoring. The Royal College of Anaesthetists National Audit Project 4 (NAP 4) emphasized the importance of applying these standards to any patient undergoing advanced airway management, regardless of location.

When measuring the composition of the gas mixture within a breathing circuit, the analyser can be positioned within the breathing circuit, or the analyser can remove a sample of the respiratory gases and transfer it to a remote analysis unit. These are known as main stream and side stream systems, respectively.

The most common method of measuring gas concentrations in anaesthesia is via a side stream analyser. Inspired and expired gases are sampled at a constant rate of between 150 and 200 ml/minute. Side stream systems allow for analysis of multiple gases, but are limited by their slower response time and potential for inaccuracy in the presence of condensation.

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Main stream analysers are more commonly used outside of theatre, for example pre-hospital care or the emergency department. These devices are fitted within the breathing system and provide a more rapid response time. Unfortunately, they add weight and dead space to the breathing system and are unable to measure more than one gas simultaneously.

Gas concentrations and partial pressures can also be measured in relation to blood gas analysis. Knowledge of the principles underlying these techniques is key to their understanding and interpretation.

Oxygen analysis

In modern anaesthetic machines, paramagnetic analysers are generally used to measure oxygen in its gaseous form. This system has superseded the Clark electrode and fuel cell regarding the measurement of inspired and expired oxygen. Despite this, the Clark electrode continues to play an integral role in the measurement of oxygen in the blood gas analyser.

Paramagnetic analyser

Oxygen molecules, unlike most other gases, contain unpaired electrons in their outer orbit (paramagnetic). Oxygen molecules are, therefore, attracted into a magnetic field. This attraction is utilised in paramagnetic oxygen analysers.

Contemporary paramagnetic analysers deliver the gas sample to the measuring chamber alongside a reference gas (21% oxygen). An electromagnetic field is generated at around 110 Hz, which creates a pressure differential between the two gas samples. This differential is directly proportional to the difference in oxygen partial pressures. A transducer converts this differential into an electrical signal, which is commonly converted to a percentage before being displayed (Figure 1).

Clark electrode (polarographic cell)

A platinum cathode and silver/silver chloride anode are suspended in a potassium chloride solution within a cellophane compartment. An oxygen-permeable membrane separates the electrolyte solution from the sample to be measured. A voltage of 0.6 V is applied between the electrodes (Figure 2).

At the anode, electrons are provided by the following reaction:

$$4Ag + 4Cl^- \rightarrow 4AgCl + 4e^-$$
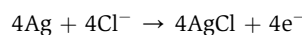
At the cathode, oxygen from the sample combines with the electrons and water to produce hydroxyl ions:

644

Datex paramagnetic analyser

Figure 1

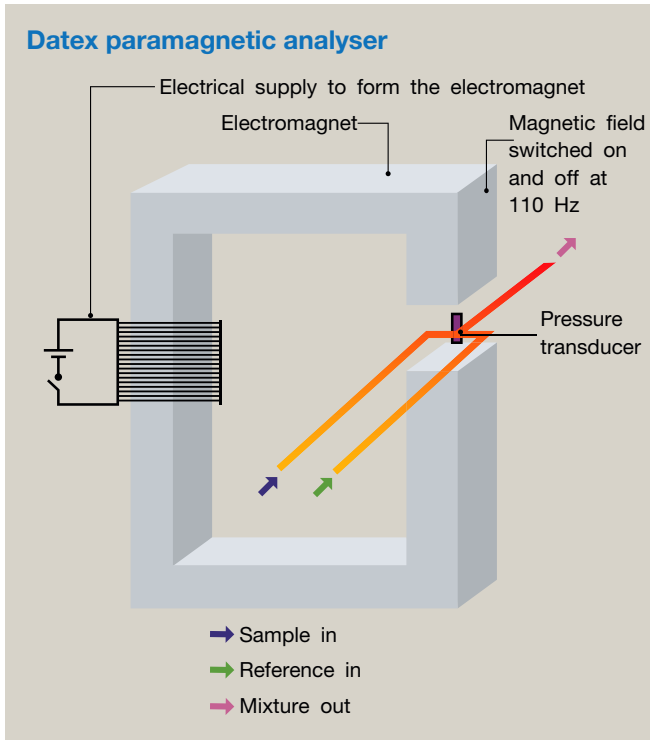## Clark electrode
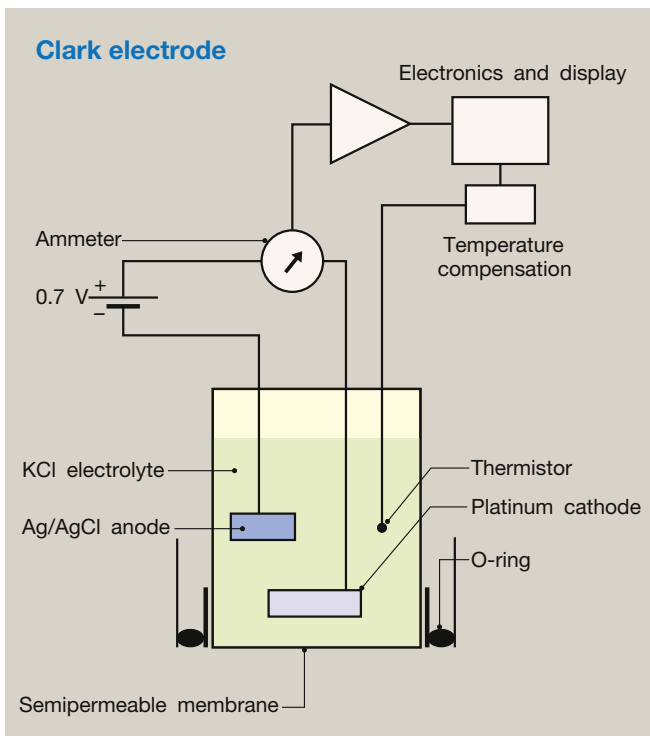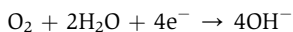

Figure 2

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

The magnitude of the electrical current generated when the cathode donates electrons (which are subsequently accepted by the anode) is proportional to the partial pressure or tension of oxygen within the measured sample.

The components of the Clark electrode are temperature and pressure sensitive and readily degradable. Regular recalibration and replacement are required to ensure accurate measurement of gases. Other limitations include its relatively slow response time, as oxygen must first diffuse across the semipermeable membrane and the system can over-read in the presence in halothane.

Fuel cell (galvanic cell)

The underlying principle of the fuel cell is similar to that of the Clark electrode, but its specific components differ. The fuel cell usually consists of a gold cathode and a lead anode suspended in a potassium hydroxide solution. Unlike the Clark electrode, it does not require a battery as it generates a current proportional to the partial pressure of oxygen.

The reaction at the cathode is the same for both the fuel cell and Clark electrode.

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$
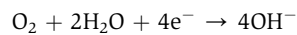
At the fuel cell's anode, electrons are produced by the combination of hydroxyl ions from the potassium hydroxide solution and the lead:

$$Pb + 2(OH^-) \rightarrow PbO + H_2O + 2e^-$$
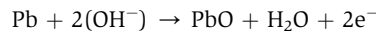
A thermistor can be incorporated into the system to allow for temperature compensation. The fuel cell's self-generating battery is depleted by continuous exposure to oxygen, resulting in a life span of around 1 year. Its response time of around 20 seconds is slower than that of the Clark electrode and the fuel cell may suffer damage when exposed to nitrous oxide (N_2O).

Carbon dioxide analysis

In anaesthetic practice, carbon dioxide is most commonly measured in its gaseous form by infrared (IR) absorption spectroscopy. However, it is also necessary to measure carbon dioxide concentration in solution for blood gas analysis. This is performed by the Severinghaus electrode.

Severinghaus electrode

A Severinghaus electrode consists of a pH-sensitive glass electrode with an outer reference electrode (usually Ag/AgCl). These electrodes are surrounded by a sodium bicarbonate electrolyte solution, which is separated from the sample by a plastic membrane permeable to CO_2. The CO_2 diffuses into the electrolyte solution, reacts with H_2O and produces H^+. It is this resultant change in $[H^+]$ that is measured by the glass electrode. This in turn is processed to display a partial pressure of CO_2.

As with other electrodes used to measure gas concentrations, the response time of 2–3 minutes is slow, as CO_2 must diffuse through the membrane before measurement can begin. If the integrity of the plastic membrane is breached, the system becomes inaccurate and regular calibration is required to ensure the electrode is maintained at 37°C to prevent these inaccuracies.

645