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The physics of altitude and anaesthesia

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As altitude increases there is a reduction in barometric pressure. Gases such as oxygen (O₂) and nitrous oxide (N₂O) have a lower partial pressure and a decreased clinical effect. The partial pressure of volatiles and the performance of vaporisers remain the same at increased altitudes, except for desflurane. Because the density of gas decreases at higher altitudes, equipment such as flowmeters and gas mixing devices function differently.

Keywords: altitude, physics, anaesthesia

Introduction

South Africa's major cities are located at various altitudes. High altitude is defined as an elevation greater than 1 500 m, which includes most of Gauteng.[1] Globally, about 140 million people live above 2 500 m and an equal number will visit high altitudes each year.[2] Consequently, anaesthetists require an understanding of how respiratory and anaesthetic gases behave under conditions of altered barometric pressure.[3] As altitude increases and barometric pressure falls, the partial pressure and density of gases decrease. There must be an awareness of the potential for hypoxia, decreased anaesthetic effectiveness, equipment recalibration, and the accuracy of certain equipment at altitude.

Gases

Oxygen

The partial pressure of oxygen (PO_2) remains at 21% of barometric pressure regardless of altitude. As altitude increases, barometric pressure decreases by approximately 70 mmHg per 1 000 m above sea level (Figure 1). This equates to a PO_2 of 160 mmHg at sea level and 134 mmHg in Johannesburg. Saturated vapour pressure (SVP) is temperature dependent and so remains 47 mmHg at any altitude. Table I shows the fall of inspired partial pressures of oxygen as altitude increases.

To avoid vulnerability to hypoxia during routine anaesthesia (shunting, V/Q mismatching, and hypoventilation), it has been recommended that patients with normal lung function should be administered a minimum inspired partial pressure of oxygen ($PinspO_2$) of 215 mmHg.[4] For the anaesthetist, this would mean dialling a minimum fraction of inspired oxygen (FiO_2) of 30% at sea level, 35% in Johannesburg (1 700 m), 40% at 3 000 m, and 100% on Mount Everest.

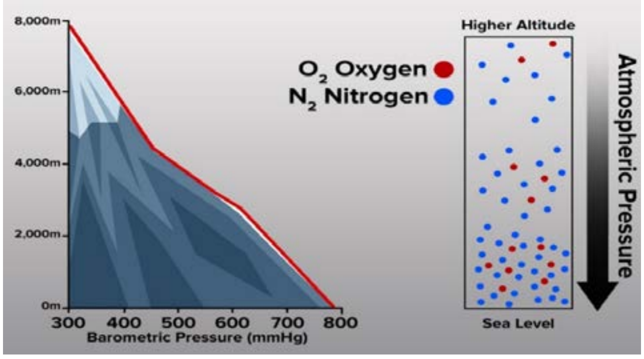

Figure 1: Fall in barometric pressure as altitude increases

Nitrous oxide

Like oxygen, N_2O is a gas at room temperature and its clinical effectiveness is dependent on its partial pressure. Because partial pressure drops with barometric pressure, N_2O's analgesic potency decreases with altitude. In his study on the analgesic effect of 50% N_2O in O_2, James et al.[5] showed that analgesic effectiveness decreased from 70% at sea level to 40% at 1 600 m, to just 19% at 3 000 m. At very high altitudes, its lack of clinical effect and the risk of hypoxia with its use in an already oxygen-depleted environment have condemned its use.[6]

Table I: Knowing your O_2 at altitude; O_2 cascade at increasing altitudes

	Sea level	**Johannesburg (1 700 m)**	**Mount Everest (8 848 m)**
P atm	760 mmHg	640 mmHg	253 mmHg
P atmO_2	21% × 760 = 160 mmHg	21% × 640 = 134 mmHg	21% × 253 = 53 mmHg
P inspO_2	21% × (760 - 47) = 150 mmHg	21% × (640 - 47) = 124 mmHg	21% × (253 - 47) = 43 mmHg
P AlvO_2	150 - (40 / 0.8) = 99 mmHg	124 - (35 / 0.8) = 80 mmHg	43 - (13 / 0.8) = 27 mmHg
P artO_2	99 - 7 = 92 mmHg	80 - 3 = 77 mmHg	27 - 1 = 26 mmHg

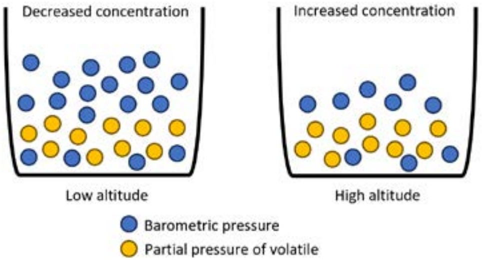

Figure 2: Effect of altitude on a volatile's measured concentration

Volatiles and vaporisers

Volatile potency is determined by the partial pressure of the vapour, also known as its SVP. Since SVP is dependent on temperature and not altitude, the partial pressure of a vapour remains constant at different altitudes. Experiments done at different altitudes with halothane vaporisers showed that, at any given setting, the output and potency remain the same; however, its measured concentration increases as barometric pressure falls (Figure 2).[7]

Desflurane

Desflurane has a high vapour pressure and boiling point near room temperature, making the output concentration delivered by a variable bypass vaporiser unpredictable. The Tec 6 vaporiser (Datex-Ohmeda) heats desflurane to 39 °C, which maintains a vapour pressure of 2 atmosphere (atm) and enables a constant, predictable output concentration of a volatile that behaves more like a pressurised gas. As ambient pressure decreases and output volume concentration remains unchanged, the partial pressure of the anaesthetic will drop. Therefore, to achieve the same potency with desflurane at altitude, the following calibration formula must be used: required dial setting (%) = desired % × (760 mmHg / local barometric pressure in mmHg).[8]

Gas analysers

Oxygen

Measurement of oxygen content in a gas mixture can be done by paramagnetic analysis, a Clark electrode, a fuel cell, or mass spectrometry. All these devices measure partial pressure and convert it to concentration (percentage). They must therefore be recalibrated at altitude. For example, if an oxygen analyser at sea level was not recalibrated in Johannesburg (1 700 m), it would read 17% (134 / 760 mmHg) instead of 21% (134 / 640 mmHg).[9]

Carbon dioxide (CO_2)

Carbon dioxide is measured by the absorption of infrared radiation by the gas and responds to its partial pressure. Fortunately, most analysers today display the output in pressure units (measured at end-expiration as the end-tidal CO_2) and not as a percentage. If percentage is used, the equipment must be recalibrated against known concentrations of CO_2 at the correct barometric pressure.[7]

Vapour analysers

Vapour analysers respond to partial pressure but are invariably calibrated in percentages. As discussed earlier, the concentration of a volatile increases as ambient pressure drops, although the partial pressure remains the same for a given dialled output setting. As a result, these analysers need recalibration at altitude to accurately show the true concentration, which is expected to be higher. Since minimum alveolar concentration (MAC) is a clinical depth of anaesthesia observed and defined at sea level, its concept is not accurate at altitude as higher concentrations are needed to maintain the same partial pressure.[7] Ideally, since partial pressure determines the clinical effect, it is minimal alveolar partial pressure (MAPP) that should be used to define MAC at altitude.[7] There should be an awareness of the increase in measured concentration of volatile required to achieve its MAPP at higher altitudes. Table II shows these concentrations for sevoflurane.[3] The MAC value conversion on most modern-day machines should be accurate if the analyser has been recalibrated at altitude.

Gas flow

Flowmeters

At low flow rates, a flowmeter device acts as a tube and so the flow of gas through it is primarily laminar. Laminar flow is dependent on viscosity, which changes with temperature but not atmospheric pressure. Therefore, at flows less than 3 L/min, provided the temperature is constant, the percentage error of the reading of these devices at altitude is insignificant.[7] At higher flow rates, the bobbin moves up the tapered tube and the resistance behaves more like an orifice that creates turbulence.

Turbulent flow is inversely proportional to the density of the gas, which drops with altitude. James et al.[7] found that at flow rates greater than 3 L/min, the percentage error of the flowmeter reading becomes significant as altitude increases. The actual flow of gas will be greater than indicated by the position of the bobbin. It is suggested that an O_2 analyser should be used when using O_2/N_2O at altitude if O_2 is used at 2 L/min and N_2O at 4 L/min, as the concentration of O_2 could be less than the safe margin of 33% as the flow of N_2O may be greater than 4 L/min with an accurate O_2 of 2 L/min.[9]

Table II: Equivalent values of MAC and MAPP of sevoflurane at various altitudes[3]

	MAC (%)			MAPP	
Agent	Sea level	5 000 ft (1 524 m)	10 000 ft (3 048 m)	(kPa)	(mmHg)
Sevoflurane	2.0	2.4	3.2	2.12	15.9

Venturi masks

These gas mixing devices tend to deliver higher concentrations of O_2 at altitude. The lower ambient pressure results in a lower pressure drop across the inlet orifice, which means less room air is entrained. The resultant gas mixture is therefore richer in oxygen. A venturi mask designed to deliver 35% O_2 at sea level will deliver 41% at 10 000 ft (3 048 m).[2]

Peak flow meters

These devices tend to underestimate peak expiratory flow by 6–8% for every 100 mmHg drop in barometric pressure.[10]

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