CASE REPORT

Efficient Breathing Circuit for Use at Altitude

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We describe a case report of a subject suffering high-altitude cerebral and pulmonary edema successfully treated with low flow rates of supplemental oxygen administered with a breathing system designed to conserve oxygen supplies at high altitude.

Key words: high altitude, breathing system, oxygen, carbon dioxide, altitude illness

The 2 principal types of oxygen delivery systems used at altitude are nasal prongs and face masks with an attached reservoir bag (nonbreathing system). Nasal prongs are typically used at night with an oxygen delivery rate of 1 L·min⁻¹. This delivery system is wasteful because most of the gas is vented into the atmosphere. Nonbreathing systems, which are frequently used for climbing at extreme altitude (eg, Poisk, St Petersburg, Russia), are based on a reservoir bag. They deliver oxygen more efficiently because fresh gas is stored during expiration in a flexible reservoir for subsequent use. Oxygen is still wasted in the dead space, but the main problem is dilution of oxygen with ambient air. As ventilation increases above the flow rate of supplied oxygen, the inhaled-oxygen concentrations fall.

These problems have been largely overcome in a novel partial rebreathing circuit based on principles designed by Fisher and colleagues.¹ The Fisher circuit contains a reservoir where ambient air and oxygen from a cylinder mix in a fixed proportion. Oxygen in the respiratory dead space is expired into the reservoir bag for gas exchange in the next breath. Because oxygen-enriched air is supplied throughout inspiration, a lower oxygen flow rate can be used. This system has been shown to deliver oxygen more efficiently than can either the Poisk circuit or nasal prongs.² The only other high-efficiency circuit

available has recently been introduced by Summit Oxygen Limited (Epping, UK; www.summitoxygen.com). This system intermittently delivers oxygen through nasal prongs that use an electronic sensor to deliver pulses of oxygen during inspiration.

A previously fit 63-year-old man became unwell on the evening of his second day at 4850 m in the Bolivian Andes. He was drowsy, responded appropriately to questions, and had a mild headache. He had marked periodic breathing and was centrally cyanosed. His pulse rate was regular at 80 beats/min and blood pressure was 135/85 mm Hg. He had mild ataxia demonstrated by a heel-to-toe walking test, but there were no other neurological signs. While sitting, his jugular venous pulse was raised to 2 cm above the sternal angle. Chest auscultation revealed fine bilateral basal crepitations but no peripheral edema. Pulse oximetry showed an arterial oxygen saturation of 62% (Ohmeda 3740, Datex Instrumentarium, Helsinki, Finland). A diagnosis was made of high-altitude cerebral edema with incipient high-altitude pulmonary edema. Because it was evening and descent was considered dangerous, we decided to give oxygen.

The patient was placed semirecumbent and connected to the Fisher circuit with a close-fitting mask (Mallinckrodt, USA). He was initially allowed to breathe air for 10 minutes when baseline assessments were made (Figure 1a). Ambient air entry was then reduced for 15 minutes. This caused a small amount of rebreathing, leading to an increase in end-tidal PCO₂ from 27 to 30 mm Hg (Datex AS/5, Datex Instrumentarium). Periodic respiration ceased, and arterial oxygen saturation increased from 72% to 78% (Figure 1a and b). Next, 500

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Figure 1. Changes in parameters in the patient with acute mountain sickness while under treatment with the Fisher circuit. **a**, Ambient air. **b**, Reduced ambient air entry with re-breathing. **c**, 500 mL·min⁻¹ of oxygen. **d**, 1.2 L·min⁻¹ of oxygen.

mL·min⁻¹ of oxygen were added for 15 minutes, which resulted in arterial oxygen saturations rising to 91% (Figure 1c). The oxygen flow rate was increased to 1.2 L·min⁻¹, causing a rise in saturation to 94% (Figure 1d). Throughout the night, end-tidal PCO₂ was approximately 30 mm Hg without further adjustment to the circuit, and the patient remained comfortable. In the morning, he descended to lower altitude and made a complete recovery.

Details of the Fisher circuit are shown in Figure 2. It contains 3 one-way valves in a triangular configuration. The crossover limb valve (C) has an opening pressure slightly greater than that produced by the retraction spring on the bellows (capacity approximately 1000 mL). During inhalation, the bellows collapse first and then gas is drawn from the reservoir bag (capacity approximately 1500 mL). During exhalation, the bellows expand with a mixture of ambient air and oxygen delivered from a cylinder. Gas flow into the bellows is controlled by varying the resistance of the ambient air tube and the flow of oxygen so that the total amount entering is slightly less than needed. Exhaled gas passes into the reservoir bag before venting. Inhaled-gas requirements above those needed for normal ventilation are supplied from the bellows. Gas therefore enters the lungs sequentially: the fresh gas from the bellows enters first, followed by the gas from the reservoir bag, which contains some exhaled carbon dioxide. The mechanics of this circuit allow efficient delivery of oxygen, thereby conserving oxygen supplies.

The Fisher circuit provides oxygen and then previously exhaled gas in sequence during inhalation. We suggest that the increased efficiency of oxygen delivery results from 3 mechanisms related to sequential gas delivery. First, the oxygen is mixed with ambient air at a

Figure 2. The Fisher high-altitude breathing circuit (components not to scale).

fixed ratio of approximately 3:1, resulting in 40% oxygen being delivered. Second, previously exhaled gas is inhaled, which has a higher oxygen concentration than in ambient air. Third, because the previously exhaled gas in effect washes out the fresh oxygen from the anatomical dead space, all the oxygen delivered into the circuit is directed to the alveoli. In contrast, when oxygen is delivered throughout inspiration, as with the Poisk and nasal prongs, the oxygen delivered at the end of inspiration is sequestered in the anatomical dead space and exhaled at the beginning of the next breath without engaging in gas exchange.

The total volume of delivered oxygen and entrained air provides for alveolar ventilation and carbon dioxide elimination. When we initially treated the patient, we provided the fresh gas from atmospheric air alone. We raised the patient's PCO₂ by slightly restricting the flow of air into the circuit and thereby increasing the volume of rebreathed gas. The small rise in end-tidal PCO₂ was accompanied by cessation of the marked temporal periodic variation in minute ventilation and establishment of a regular breathing pattern (transition between a and b in Figure 1). This was accompanied by an overall improvement in alveolar ventilation and an increase in arterial oxygen saturations. Other reports show benefits of mildly increased arterial carbon dioxide levels by improving arterial saturations³ and cerebral oxygenation.⁴ The restriction of the alveolar ventilation to the fresh gas flow with the Fisher circuit makes it suitable only for subjects at rest or sleeping. Further modifications would have to be made to the Fisher circuit before its efficiencies in oxygen delivery can be applied during climbing.

We have shown the Fisher circuit to be useful in an emergency situation as means of providing effective oxygen supplementation with flows of only $1.2 \text{ L}\cdot\text{min}^{-1}$. Although control treatment was not possible because of ethical considerations, we would not expect such marked improvement in oxygen saturations with standard circuits.

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