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Quality and Patient Safety

Environmental and economic impact of using increased fresh gas flow to reduce carbon dioxide absorbent consumption in the absence of inhalational anaesthetics

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Abstract

Background: Increasing fresh gas flow (FGF) to a circle breathing system reduces carbon dioxide (CO_2) absorbent consumption. We assessed the environmental and economic impacts of this trade-off between gas flow and absorbent consumption when no inhalational anaesthetic agent is used.

Methods: A test lung with fixed CO_2 inflow was ventilated *via* a circle breathing system of an anaesthetic machine (Dräger Primus or GE Aisys CS[2]) using an FGF of 1, 2, 4, or 6 L min^{-1}. We recorded the time to exhaustion of the CO_2 absorbent canister, defined as when inspired partial pressure of CO_2 exceeded 0.3 kPa. For each FGF, we calculated the economic costs and the environmental impact associated with the manufacture of the CO_2 absorbent canister and the supply of medical air and oxygen. Environmental impact was measured in 100 yr global-warming potential, analysed using a life cycle assessment 'cradle to grave' approach.

Results: Increasing FGF from 1 to 6 L min^{-1} was associated with up to 93% reduction in the combined running cost with minimal net change to the 100 yr global-warming potential. Most of the reduction in cost occurred between 4 and 6 L min^{-1}. Removing the CO_2 absorbent from the circle system, and further increasing FGF to control CO_2 rebreathing, afforded minimal further economic benefit, but more than doubled the global-warming potential.

Conclusions: In the absence of inhalational anaesthetic agents, increasing FGF to 6 L min^{-1} reduces running cost compared with lower FGFs, with minimal impact to the environment.

Keywords: anaesthesia machine; carbon dioxide absorbent; cost analysis; fresh gas flow; life cycle assessment; mechanical ventilation; total intravenous anaesthesia

Editor's key points

- The trade-off between the environmental and economic impacts of fresh gas flow and carbon dioxide (CO_2) absorbent consumption in anaesthetic machine breathing circuits was assessed in a simulation study.
- A test lung with fixed CO_2 inflow was ventilated *via* a circle breathing system of an anaesthetic machine at various fresh gas flows to determine time to exhaustion of the CO_2 absorbent canister, with calculation of the economic costs and associated environmental impact.
- A significant cost saving may be derived by increasing fresh gas flows to reduce CO_2 absorbent consumption, with minimal adverse impact to the environment.
- High-flow anaesthesia is a viable cost-saving strategy when using a circle system for anaesthetic maintenance without inhalational anaesthetic agents in adults.

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Most modern anaesthetic machines use a circle breathing system, which facilitates use of low fresh gas flow (FGF) during maintenance of anaesthesia. Advantages of low FGF include reduced consumption of inhalational anaesthetic agents and conservation of expired heat and water vapour.[1] Disadvantages of low FGF include longer times for changes in fresh gas composition to affect inspired gas composition, accumulation of unwanted gases, and increased consumption of carbon dioxide (CO_2) absorbent.[2] When a circle system is used with total i.v. anaesthesia and an efficient heat and moisture exchange (HME) filter, the advantages of low FGF may no longer apply. Furthermore, using high FGFs confers the advantage of reduced CO_2 absorbent consumption.

Given that medical oxygen (O_2) and air are relatively inexpensive for most major hospitals, we hypothesise that the reduction in CO_2 absorbent consumption at high FGF may outweigh the associated cost and environmental impact of increased gas (medical O_2 and air) consumption during total i.v. anaesthesia. We therefore performed a laboratory study examining the relationship between FGF and time to exhaustion of absorbent canisters using two different anaesthetic machines, together with cost and environmental analyses.

Methods

A simple lung model (Fig. 1) was constructed using a 1 L test lung (SelfTestLung™; Dräger, Notting Hill, Australia) with CO_2 insufflated through the sample port of an HME filter (Thermovent® HEPA; Smiths Medical, Minneapolis, MN, USA) attached to the test lung. A second HME filter was attached to the Y-connection of the breathing circle to provide a sample port for capnography. To mimic anatomical dead space, a length of extension tubing (internal volume 90 ml) was placed between the two HME filters. The model was ventilated *via* a standard circle system with 1.8 m corrugated tubing and a 2 L reservoir bag.

The anaesthetic machine was connected to hospital piped medical gases and set to deliver an O_2/air mixture with fresh gas O_2 concentration of 30%. Fresh gas flows of 1, 2, 4, and 6 L min^{-1} were studied. The lung model was ventilated with the anaesthetic machine ventilator set to volume-control mode, ventilatory frequency of 12 bpm, tidal volume of 500 ml, and inspiratory-to-expiratory ratio of 1:1.5. End-tidal CO_2 (ET_{CO_2}) and inspired CO_2 ($Insp_{CO_2}$) partial pressures were monitored *via* the capnography module of the anaesthetic machine and recorded every 5 min. Three runs were performed at each FGF, and the entire study was repeated using two different anaesthetic machines: the Dräger Primus® (Dräger, Lübeck, Germany; hereafter DG for short) and GE Aisys CS^2® (GE, Chicago, IL, USA; hereafter GE for short). The endpoint for the study was time to exhaustion of the CO_2 absorbent, defined as $Insp_{CO_2}$ >0.3 kPa for 15 min, which we consider to be a reasonable threshold for changing the absorbent in clinical practice.

CO_2 inflow was from a cylinder regulated by a ball rotameter, which was calibrated daily using a digital flowmeter (VT MOBILE; Fluke Biomedical, Cleveland, OH, USA) and adjusted to deliver a flow of ~250 ml min^{-1}. Throughout all runs at FGFs of 1, 2, and 4 L min^{-1}, ET_{CO_2} remained between 5.1 and 5.6 kPa. For the longer runs at FGF of 6 L min^{-1}, ET_{CO_2} remained between 5.1 and 6.4 kPa. As the capnography waveform and ET_{CO_2} values produced by our model were representative of those observed during ventilation of healthy patients in clinical practice, we believe our model was a reasonable approximation for the purposes of this investigation.

The CO_2 absorbent was refreshed before each run. With the DG machine, a pre-packaged canister was used (Infinity ID CLIC™ Absorber; Dräger, Lübeck, Germany). The total weight of the canister was 1052 (10) g, with the empty plastic container weighing 112 (5) g. With the GE machine, a reusable canister was manually filled with 775 (5) g of absorbent pellets (Medisorb™ CO_2 Absorbent; CareFusion, San Diego, CA, USA), weighed using an electronic scale.

Economic analysis was performed using acquisition costs for medical O_2 and CO_2 absorbent for the Sydney Local Health District. We estimated the cost of medical air, which is produced on-site by electric compressors (ZT18; Atlas Copco,

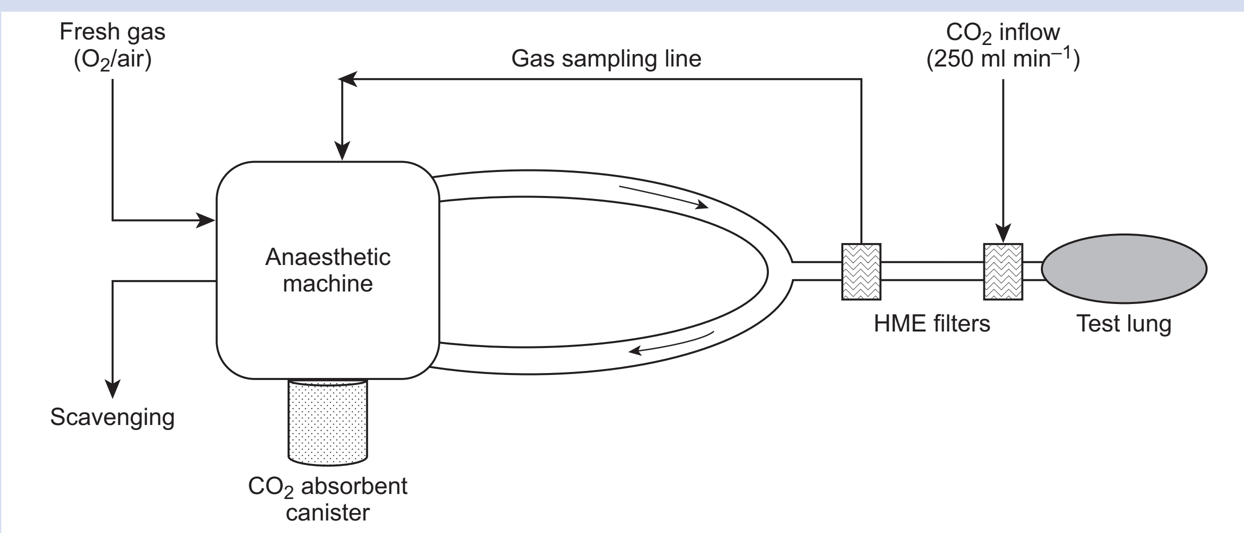

Fig 1. Schematic of experimental set-up. HME, heat and moisture exchange.

Table 1 Mean (standard deviation) time to exhaustion of CO_2 absorbent canisters, hourly cost, and environmental impact at various fresh gas flows for DG and GE anaesthetic machines. CO_2, carbon dioxide; DG, Dräger Primus; FGF, fresh gas flow; GE, GE Aisys CS^2; GWP_{100}, 100 yr global-warming potential.

FGF (L min^{-1})	DG			GE		
	Time to exhaustion (h)	Cost (AU\$ h^{-1})	GWP_{100} (kg CO_2 equivalent h^{-1})	Time to exhaustion (h)	Cost (AU\$ h^{-1})	GWP_{100} (kg CO_2 equivalent h^{-1})
1	10.3 [0.3]	1.46	0.13	8.2 [0.4]	1.60	0.14
2	13.1 [0.6]	1.16	0.13	11.2 [1.1]	1.17	0.13
4	34.7 [1.2]	0.45	0.12	22.9 [1.3]	0.59	0.13
6	205.3 [29.7]	0.10	0.14	133 [22.2]	0.12	0.14
15	—	—	—	—	0.06	0.33
18	—	0.08	0.40	—	—	—

Antwerp, Belgium) and intercoolers (FD120; Atlas Copco, Milan, Italy), from their respective power ratings, the local cost of electricity, and the estimated equipment acquisition cost. Unless otherwise stated, all costs are reported in Australian dollars (AU$).

Environmental analysis was carried out using a life cycle assessment (LCA) cradle-to-grave approach. Life cycle assessment is an analysis of the environmental impacts of all systems and material flows involved at any stage throughout the life of a product or service,[3] and is a robust method for assessing the environmental performance of a product. The procedure for conducting an LCA is standardised in ISO 14040 and consists of four main stages: (i) definition of goal and scope, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation and evaluation.[4] The impact category relevant to our current study is the 100 yr global-warming potential (GWP_{100}) given in kilograms of CO_2 equivalents. Our LCA accounts for the global-warming impact arising from the production, transport, and disposal of the CO_2 absorbent canister, medical O_2, and air. The canister is composed of absorbent material (a soda lime mixture of calcium hydroxide and sodium hydroxide) and the container itself is composed of polypropylene. The production of calcium hydroxide covers all equipment and total heating energy for production. The production of sodium hydroxide is assumed to be through electrolysis and covers brine production. The production of O_2 is assumed to be through an air separation plant and covers the electricity for the production process, cooling water, and waste heat and infrastructure. The production of air is assumed to include a compressor and electricity consumption. Transport of absorbent canisters is assumed to be by sea freight from their country of manufacture, and then by road to the institution. Disposal of the canisters and materials is assumed to be *via* landfill and is included in the scope of the study. Impact assessment for each of the production processes was performed with SimaPro (PRé Consultants BV, Amersfoort, Netherlands) using its inbuilt life cycle inventory database (ecoinvent 2.2).

All data processing was performed in Excel 365 (Microsoft Corporation, Redmond, WA, USA) and descriptive statistics were reported. Details of the economic and environmental analyses are described in the Supplementary material.

Results

The mean time to CO_2 absorbent canister exhaustion and the associated cost and environmental impact at various FGFs are shown in Table 1. The mean time to CO_2 absorbent canister exhaustion increases non-linearly with increasing FGFs for both DG and GE anaesthetic machines (Fig. 2a). A plot of FGF against the reciprocal of time to exhaustion, which represents the fraction of CO_2 absorbent canister being consumed per unit time, reveals a linear relationship (Fig. 2b). This linear relationship is consistent with previous studies.[5,6] At FGF of 6 L min^{-1}, it took more than 5 days (GE) or 8 days (DG) for exhaustion of the absorbent.

Our estimated costs of medical O_2 and air were \$0.40 and \$0.028 (1000 L)$^{-1}$, respectively. The GWP_{100} values associated with the production of 1 kg of medical O_2, air, CO_2 absorbent, and polypropylene were 0.70, 0.23, 0.73, and 3.53 kg CO_2 equivalents, respectively. Combining these results with the time to CO_2 absorbent exhaustion, we calculated the hourly running cost at each FGF (Fig. 3) and the hourly emissions in CO_2 equivalents (Fig. 4) associated with each FGF.

Increasing FGF is associated with a significant decrease in running cost with minimal net changes to environmental impact. Compared with FGF of 1 L min^{-1}, increasing FGF to 4 L min^{-1} was associated with a 69% and 63% reduction in the running cost, and 6% and 5% reductions in the global-warming potential for DG and GE, respectively. Further increasing FGF to 6 L min^{-1} was associated with 93% and 92% reductions in running costs and resulted in 9% increase and 0.2% decrease in global-warming potentials compared with FGF of 1 L min^{-1} for DG and GE, respectively.

For comparison, we also calculated the costs and environmental impact associated with the hypothetical case, where CO_2 elimination from the circle system was entirely attributable to FGF. Removing the absorbent canister from the circle system, we found that FGFs of 18 and 15 L min^{-1} were required to keep $Insp_{CO_2}$ below 0.3 kPa for DG and GE, respectively. This extreme case is associated with around 20-fold reduction in the running cost compared with FGF 1 L min^{-1} with CO_2 absorbent present (from \$1.46 h^{-1} and \$1.60 h^{-1} to \$0.08 h^{-1} and \$0.06 h^{-1} for DG and GE, respectively). However, the global-warming potential was also more than doubled for both

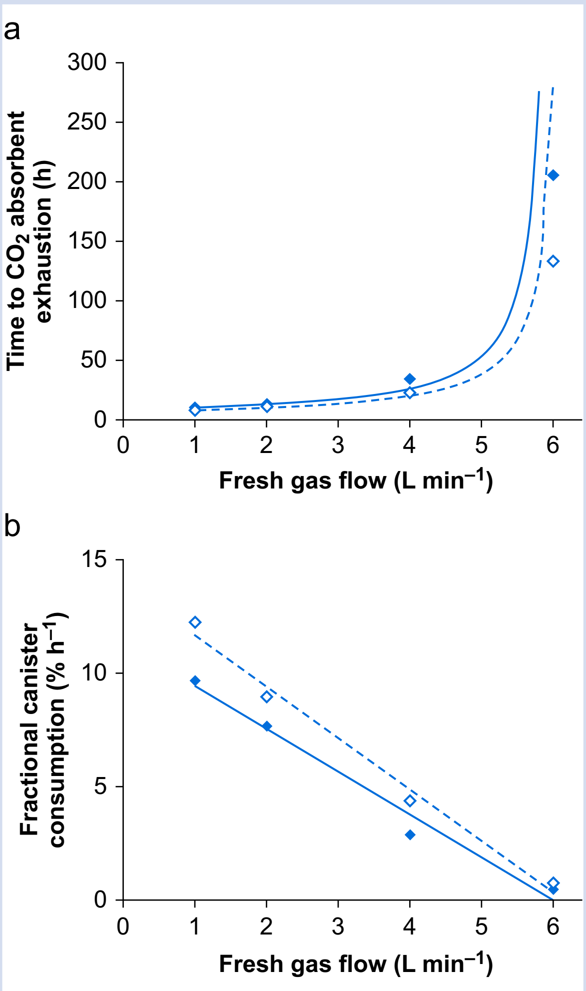

Fig 2. Impact of fresh gas flow on (a) time to exhaustion of CO_2 absorbent and on (b) CO_2 absorbent canister consumption rate for DG (◆) and GE (◊) anaesthetic machines. CO_2, carbon dioxide; DG, Dräger Primus; GE, GE Aisys CS[2]

cases (from 0.13 and 0.14 to 0.40 and 0.33 kg CO_2 equivalent h^{-1}, respectively).

To assess the generalisability of our economic analysis, we approached colleagues from tertiary hospitals across the UK and USA to obtain international cost data. Because of sensitivity of commercial information, we were only able to obtain approximate costs for medical O_2 and the Dräger CO_2 absorbent canister. To obtain a lower bound estimate of the reduction in running costs, we assumed an inspired O_2 fraction of 100% and used the highest cost for medical O_2 together with the lowest cost for the CO_2 absorbent canister that were obtained. We also extracted relevant cost data for Germany from a 2012 study.[7] Compared with our Australian data, similar trends in running cost reduction were found for UK, USA, and Germany (see Supplementary material).

To assess the generalisability of our environmental analysis, we examined the effect of including absorbent canister transport *via* sea freight from the country of manufacture (Germany) into the bounds of the LCA, and considered shipping to Australia, UK, and USA. We found this made little difference to the overall trend in CO_2 emission at various FGFs (see Supplementary material).

Discussion

We confirmed that the time to CO_2 absorbent exhaustion is significantly prolonged by increasing the FGF within the circle systems of both the DG and GE anaesthetic machines. These results are in line with previous *in vitro* studies of absorbent consumption.[5,6,8] By combining the relationship between FGF and absorbent exhaustion time with local cost data, we have shown that there are potential cost savings when FGFs over 4 L min^{-1} are used without inhalational anaesthetic agents. Our LCA found that the combination of increased FGF up to 6 L min^{-1} with reduced absorbent consumption has little to no net impact on the global-warming potential.

Multiple mechanisms have been proposed to explain the reduction in absorbent consumption associated with increasing FGFs for circle systems.[8] Higher FGF results in dilution of CO_2-containing gas within the expiratory limb during the expiratory phase, reduction in expired gas circulating to the inspiratory limb during the inspiratory phase, and increased clearance of CO_2 *via* the effluent gas during expiration and during the pause between end expiration and inspiration. All mechanisms ultimately lead to a reduction in exposure of the absorbent canister to CO_2, thereby prolonging the time to exhaustion. In addition to these circuit factors, it is also possible that at high FGFs, CO_2-containing expired gas can access parts of the canister that would not be reached at lower FGFs, resulting in more efficient absorption. Higher FGFs can also reduce moisture content within the canister, thereby reducing clumping and thus channelling of CO_2-containing expired gas through the canister, which indirectly prolongs exhaustion time.

A potential problem with higher FGF is drying of the inspired gases. Previous studies[9] have estimated the lowest acceptable limit for absolute humidity of inhaled gas during brief (<2 h) anaesthetic procedures to be 20 mg L^{-1} and for prolonged ventilation in intensive care to be 30 mg L^{-1}. However, modern HME filters are highly efficient at maintaining the inspired humidity well above the acceptable limit across a wide range of FGFs.[10] Using a modern HME filter together with FGF of 6 L min^{-1}, it has been found that the absolute humidity within the airway was 29 mg L^{-1} after 120 min of mechanical ventilation under general anaesthesia, far exceeding the acceptable minimum.[11] Similar results were found in another study[12] using FGF of 5 L min^{-1}. Thus, high FGFs up to 6 L min^{-1} are safe in terms of gas humidity in adults when a modern HME filter is used.

Another concern regarding the use of high FGFs is the risk of desiccating the CO_2 absorbent, which can potentially lead to increased carbon monoxide production during a subsequent volatile anaesthetic procedure using the same canister. However, this concern is theoretical with modern CO_2 absorbents, which have much lower strong alkali content, and it has been shown that carbon monoxide production remains undetectable (<10 ppm), even when the absorbent is subjected to more exaggerated drying conditions compared with our study.[13]

Our study has several limitations. We only examined a single set of ventilation parameters. It is known that the ventilation pattern can affect the flow characteristics within the circle system, and thus influence the amount of CO_2 reaching the absorbent canister.[5] For example, prolonging the

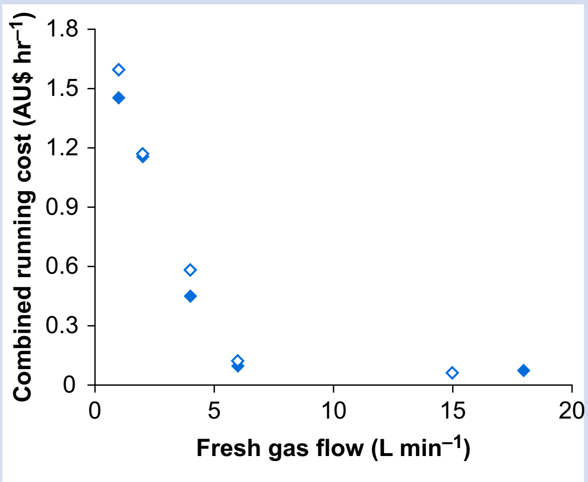

Fig 3. Hourly combined running cost (absorbent canister and medical gases) at various fresh gas flows for DG (◆) and GE (◊) anaesthetic machines. DG, Dräger Primus; GE, GE Aisys CS[2]

expiratory phase or adding an inspiratory pause (i.e. decreasing the *I:E* ratio) can both lead to greater CO_2 elimination from the circle, thus prolonging time to CO_2 absorbent exhaustion. Further studies are needed to explore the interplay between FGF, ventilatory parameters, and CO_2 production and elimination for modern ventilators.

Despite differences in the details of their circuit designs, the results from the two anaesthetic machines tested in this study were similar. However, it cannot be assumed that our results can be generalised to other circle systems. For example, some modern anaesthesia machines incorporate a turbine that circulates gas throughout the entire respiratory cycle. The altered mixing of gases in these circuits could change the relationship between FGF and time to CO_2 absorbent exhaustion.[5]

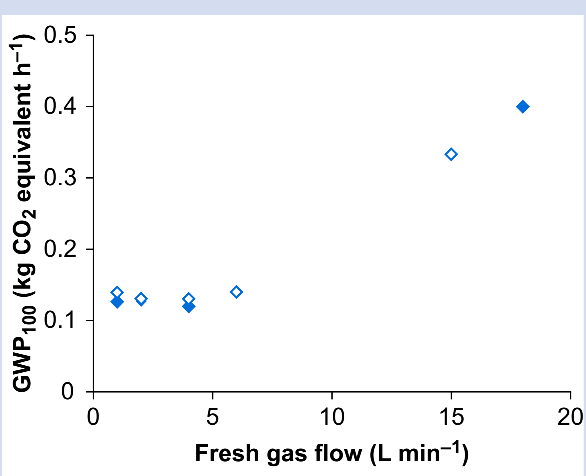

Fig 4. Environmental impact, measured as 100 yr global-warming potential, associated with various fresh gas flows for DG (◆) and GE (◊) anaesthetic machines. DG, Dräger Primus; GE, GE Aisys CS[2]

The absorbent canisters in this study were subjected to continuous ventilation until exhaustion, whereas usage patterns during clinical practice usually include pauses between cases. We are not aware of any studies examining the effects of intermittent pauses in gas flow on absorbent consumption.

Our test lung differed from human subjects in that it was not humidified and has no O_2 uptake. It is possible that moisture from the patient's expired gas may increase the humidity within the canister, thereby influencing its CO_2 absorption efficiency. However, modern HME filters are efficient at trapping moisture from the patient, and the potential impact on circuit humidity is unlikely to be significant. Furthermore, the flow augmentation effects of O_2 uptake *in vivo* are also likely negligible.

During the longer runs at 6 L min^{-1}, ET_{CO_2} drifted higher and over a wider range compared with lower FGFs. This wider range was attributed to fluctuations within the ball rotameter and was possibly related to fluctuations in ambient temperature. However, higher ET_{CO_2} will result in an underestimate of the time to exhaustion, which further supports our conclusion about the effectiveness of high FGFs. Future experiments could use mass flow controllers to deliver precise CO_2 inflow.

Economic analysis was derived using local costs and may not apply to other parts of the world. However, cost data from the UK, USA, and Germany showed that our economic analysis appeared robust and potentially generalisable to other tertiary hospitals worldwide that use piped gas supplies. Although the fractional cost saving derived from the use of high FGFs is significant, the absolute cost saving is small and represents less than 4% of the total anaesthetic cost (excluding personnel).[11] However, a change in practice to using higher FGFs could nonetheless be important as it is simple to implement, associated with no significant drawbacks, and the cost saving could be significant when considered on a worldwide scale.

Within the aforementioned limitations, we have shown that a significant cost saving may be derived from increasing FGF to reduce CO_2 absorbent consumption, with minimal adverse impact to the environment. We suggest that 'high-flow anaesthesia', with FGF around 6 L min^{-1}, is a viable cost-saving strategy when using a circle system for anaesthetic maintenance without inhalational anaesthetic agents in adults.

Authors' contributions

Study design: GZ, AA, TM, SK
Data collection: GZ, JJ, SK
Data analysis: GZ, AA, TM, JJ
Writing of first draft: GZ
Revision of paper: all authors

Declarations of interest

The authors declare that they have no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bja.2020.07.043.

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