Research Support

Support was provided solely from institutional and/or departmental sources.

Competing Interests

The McGovern Medical School at the University of Texas Health Science Center at Houston, Houston, Texas, has filed a patent application for an airway device on behalf of Dr. Jiang. Dr. Jiang is a consultant of Vyaire (Chicago, Illinois). The other authors declare no competing interests.

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Carbon Footprint of Anesthesia: Comment

To the Editor:

We read with interest the report by McGain *et al.*,[1] comparing the carbon footprint of general *versus* regional anesthesia. The use of life cycle assessment, quantified as carbon dioxide equivalent emissions, allows thorough analyses to compare the greenhouse effect of different materials.[2] Life cycle assessment is very complex and sensitive to its underlying assumptions. It is therefore somewhat surprising that the authors did not include the carbon dioxide equivalent emissions for the production of volatile anesthetics, and in addition used outdated geochemistry values instead of the more recent and more accurate ones.[3,4] The two existing synthesis routes increase the carbon dioxide equivalent emissions of sevoflurane by 100% (acetone pathway) and 700% (tetrafluoroethylene pathway; table 1).[5] Omitting these emissions significantly underestimates sevoflurane's environmental impact.

The time frame used by the authors needs to be considered as well. The global warming potential compares the cumulative heat trapping of 1g of a substance to that of 1 g of carbon dioxide during a defined period. The commonly quoted global warming potentials of sevoflurane are those during a 20- and 100-yr period, 702 and 195, respectively.[3,6] To compare the greenhouse effect of different molecules, global warming potential during a 100-yr period is most frequently used, and was used by McGain *et al.* However, the global warming potential during a 100-yr period represents an overly optimistic view, because 99.8% of the total heat absorption by sevoflurane occurs in the first 10 yr after emission, and its effects thus materialize in the first few years.

To illustrate how sensitive a life cycle assessment is to its assumptions, let us consider the impact of 9.6ml liquid sevoflurane, the hourly consumption reported by McGain *et al.* (table 1). The carbon dioxide equivalent emissions varies from 1.9kg to 80.9kg CO_2, depending on the use of older (2011) *versus* recent (2021) global warming potential values; global warming potential during a 20-yr-period *versus* a 100-yr-period; inclusion or exclusion of the production emissions; and least *versus* most wasteful production process. The value reported by McGain *et al.* may therefore underestimate the carbon dioxide equivalent emissions of sevoflurane by a factor of 46.

Competing Interests

Dr. Kalmar has received lecture support, travel reimbursements, equipment loans, or consulting fees from AbbVie (Chicago, Illinois), Getinge (Gothenburg, Sweden), and MEDEC (Aalst, Belgium). Dr. Hendrickx has received lecture support, travel reimbursements, equipment loans,

Table 1. Calculated Carbon Dioxide Equivalent Emissions of 1 h of Sevoflurane Anesthesia, Dependent on Used Global Warming Potential Values and Production Pathway

			Production Emissions		
				Included	
		Global Warming Potential Value	Not Included	Pathway No. 1	Pathway No. 2
Global warming potential during 100 yr	2011	130	1.9	3.7	15.0
Global warming potential during 100 yr	2021	195	2.8	5.6	22.5
Global warming potential during 20 yr	2011	440	6.3	12.7	50.7
Global warming potential during 20 yr	2021	702	10.1	20.2	80.9

Calculated carbon dioxide equivalent emissions (kg/h) caused by a 9.6 ml/h sevoflurane consumption[1] depend on the global warming potential value that is used (global warming potential during 100 yr *vs.* global warming potential during 20 yr; 2011 *vs.* 2021 geochemistry report data); and whether production emission is included, and if so, which one (acetone [No. 1] *vs.* tetrafluoroethylene [No. 2]).[3,5,6]

consulting fees, and meeting organizational support from AbbVie, Acertys (Aartselaar, Belgium), Air Liquide (Paris, France), Allied Healthcare (St. Louis, Missouri), Armstrong Medical (Coleraine, UK), Baxter (Deerfield, Illinois), Dräger (Lübeck, Germany), General Electric Healthcare (Madison, Wisconsin), Getinge, Hospithera (Anderlecht, Belgium), Heinen und Lowenstein (Bad Ems, Germany), Intersurgical (Wokingham, UK), MDoloris Medical Systems (Loos, France), MEDEC, Micropore (Elkton, Maryland), Molecular Products (Louisville, Colorado), NWS, Philips (Brussels, Belgium), Piramal (Mumbai, India), and Quantium Medical (Barcelona, Spain). The other author declares no competing interests.

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Carbon Footprint of Anesthesia: Comment

To the Editor:

We read with great interest the recent article by McGain *et al.* entitled "Carbon Footprint of General, Regional, and Combined Anesthesia for Total Knee Replacements."[1] We congratulate the authors for their meticulous analysis of the factors that contribute to carbon emissions including less commonly included factors such as variable electricity sources, and for sharing their established sustainable practices with the Anesthesiology community.

However, carbon emissions are only one consideration when evaluating environmentally sustainable practice. The authors' life cycle analysis does not include the carbon-free (but still harmful) impact of single-use plastics. As plastic does not readily degrade, it releases a negligible amount of carbon after reaching the landfill, thereby limiting its life cycle carbon contribution to its production process. Yet significant environmental harm occurs at plastic's life cycle endpoint through landfill use, breakdown into microplastics,[2] and the release of volatile organic compounds,[3] all of which are not accounted for in carbon equivalents. Solely focusing on carbon emissions can lead to false conclusions being drawn about the sustainability of disposable plastics (1.1 to 3.3 kg CO_2/kg, from the authors' article) and resterilized reusable equipment (3.0 kg CO_2/kg), with medical industries marketing single-use equipment as "carbon friendly."[4]

We posit that the total environmental impact of resterilizing and reusing equipment is eclipsed by the short- and long-term harm of single-use disposables. We applaud the authors' commitment to reusable equipment, from anesthesia circuits to spinal kit trays, and encourage the reporting of any available safety data associated with this practice to assist others in reducing their reliance on single-use plastic.

Competing Interests

The authors declare no competing interests.

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Carbon Footprint of Anesthesia: Comment

To the Editor:

We read with interest the article by Mc Gain *et al.*[1] presenting the comparative carbon footprint of two general and regional anesthesia techniques. As the authors point out, the results cannot be systematically extrapolated to other countries because of the different energy sources used in each country. An important point is the use in this study of reusable breathing circuits changed once a week, as is the case in several countries,[2–5] which considerably reduces costs and greenhouse gas emissions compared to North American practices that require changing circuits (mostly single-use) between each patient even when a filter is used.[6,7] It is conceivable that this would have had an impact on the results of the same study conducted in North America.

However, several recent studies have demonstrated, *in vivo*, that bacterial or viral contamination of an anesthesia circuit was very low and did not increase with the time of use,[8–11] when effective hydrophobic heat and moisture exchange filters were used, with a rigorous technique of filter change and cleaning of the anesthesia station.[11] In an effort to reduce operating room waste, which represents 25% of hospital waste,[12] it may be time to revise our recommendations to allow for safe and sustainable practice.

Competing Interests

The authors declare no competing interests.

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Carbon Footprint of Anesthesia: Comment

To the Editor:

Using life cycle assessments, McGain *et al.*[1] account for the carbon footprint of general, regional, and combined anesthesia techniques for total joint replacements in Australia. With the accounting of carbon emissions, we applaud the authors for demonstrating that the environmental impact of our clinical endeavors extends far beyond the four walls of the operating room. We would like to expand the focus to include an assessment of the impacts to local water systems and to shine the spotlight on ecologic economics. In contrast to life cycle assessments, ecologic economics views human systems as a subsystem of Earth's larger ecosystem. By emphasizing the preservation of natural capital, ecologic economics is very different from life cycle assessments, and most life cycle assessments are merely a mainstream economic analysis of the environment. McGain *et al.* glance upon ecological economics when they point to the water needs when sterilizing and reusing equipment (fig. 1), even though their system boundaries did not accommodate the long-term impact of the operating room on water ecology. Using ecologic economics, one begins to appreciate the extant and extent of healthcare delivery. Tradeoffs between reusable and disposable equipment are not just an issue of the carbon footprint. The sterilization of medical equipment requires a water supply to clean the equipment. Therefore, any ecologic analysis should include the specific geographic location of water sources and an appreciation that these sources are renewable.[2] Water systems are intricate and complex, and water is recycled and reused.[3] It is time that we more fully understood the ecologic impact of healthcare delivery. Thankfully, McGain *et al.* have shown us a way.

Competing Interests

The authors declare no competing interests.

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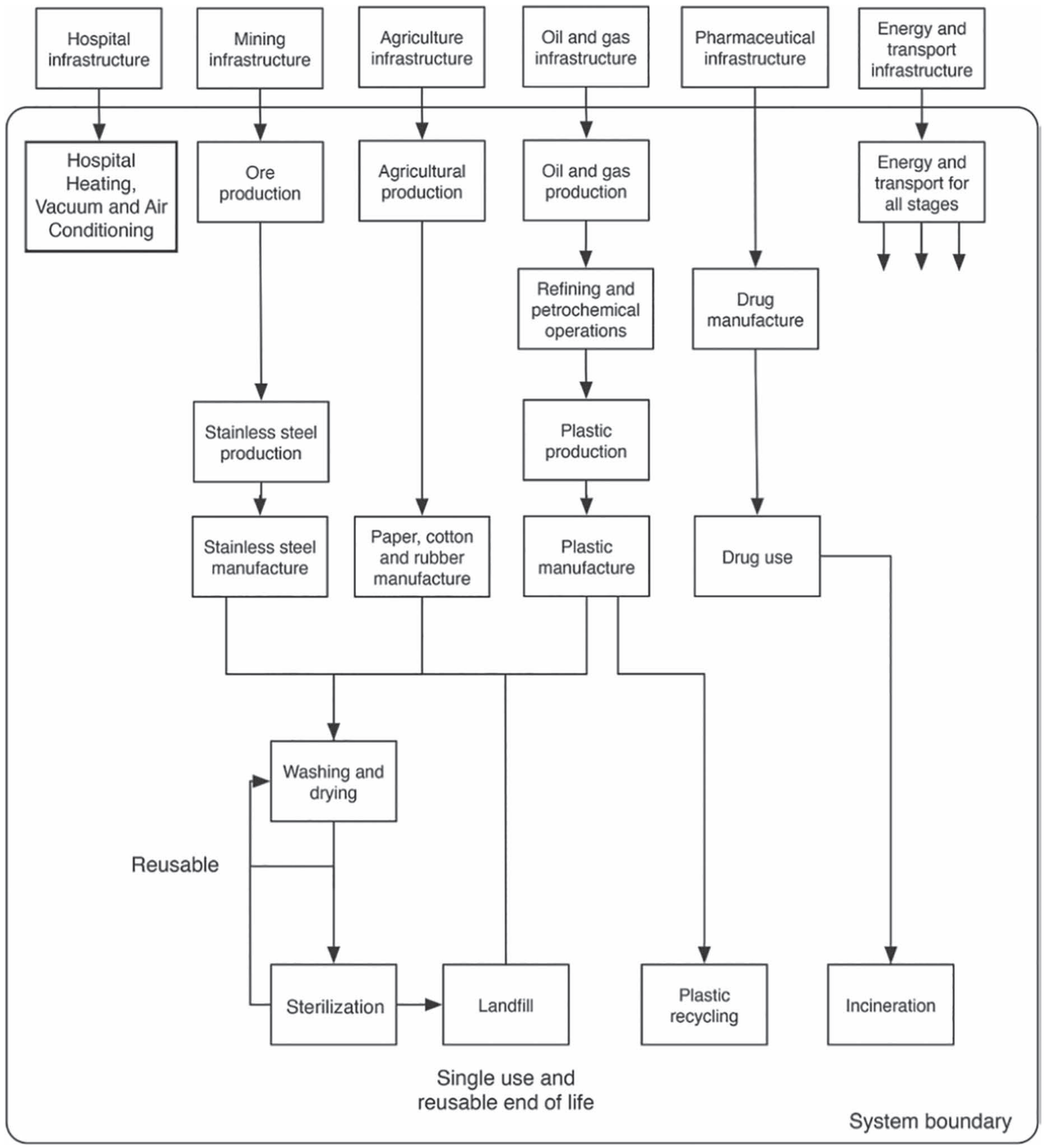

Fig. 1. Reduce, reuse, and recycle: Understanding the ecologic impact on water resources.

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Carbon Footprint of Anesthesia: Comment

To the Editor:

The article "Carbon Footprint of General, Regional, and Combined Anesthesia for Total Knee Replacement" by McGain *et al.*[1] provides welcome dialogue in the evidence-sparse domain of carbon equivalent comparisons between anesthetic modalities. Their paper describes prospective life cycle assessment of anesthetic components of total knee joint replacement surgery, and found similar carbon dioxide equivalent emissions for spinal anesthesia, general anesthesia, and combined spinal with general anesthesia (14.9 to 18.5 kg CO_2 equivalents per case). While it may be tempting to interpret these findings as representing environmental equipoise, there are several institutional and geographical differences that we think are relevant to consider when implementing this research locally, and to encourage thoughtful advocacy in the important task of healthcare climate work.

Western Health, the Melbourne, Australia, hospital in which this study was conducted uses a laudable range of reusable anesthetic items, including facemasks, Proseal (Teleflex Medical Europe Ltd, Ireland) laryngeal masks, laryngoscope blades, anesthesia circuits, spinal trays, drug trays, sterile gowns, cotton drapes, and cotton hand towels. Despite this, single-use products still comprised approximately 20 to 25% of all emissions for the three anesthetic modalities examined.[1] We propose that in most institutions that have not implemented reusable equipment like Western Health, the carbon emissions for all anesthesia options for a total knee replacement would be greater. Reusable equipment has a lower carbon footprint when renewable energy provides some or all of the energy, and is consistently cheaper,[1] such that hospitals that use single-use items in place of reusable items for a total knee replacement may have higher financial and environmental costs. Thus, institutional procurement will significantly affect anesthetic carbon dioxide equivalent calculations. For example, the carbon dioxide equivalent emission for using a reusable drug tray is 0.11 kg, compared to up to 0.20 kg[2] for a single-use item. A reusable steel laryngoscope blade, including sterilization, produces 0.22 kg CO_2 equivalents, compared to 0.44 kg for a single-use steel blade,[3] and a reusable laryngeal mask produces 7.4 kg CO_2 equivalents, which corresponds to 40 disposable laryngeal masks, contributing 11.3 kg CO_2 equivalents.[4] This is not accounting for other reusable items, such as anesthetic circuits, sterile gowns, cotton drapes, and facemasks.

McGain *et al.* note that geographical variation in electricity energy sourcing alters the carbon dioxide–associated equivalent emissions per kilowatt-hour; however, these differences may be greater where hospitals currently use single-use items and transition to reusable equipment in locations with a high or increasing renewable energy mix. In the study by McGain *et al.*, washing and sterilizing items contributed approximately 29% to the total carbon dioxide equivalent emissions for spinal anesthesia, and 20% for combined spinal and general anesthesia.[1] As noted by the authors, healthcare electricity in Victoria, Australia, is currently coal-driven, but will be 100% renewable energy from 2025.[5] As such, a renewable energy mix similar to the United Kingdom and Europe would translate to a fourfold reduction in carbon dioxide equivalent emissions for cleaned reusables. These considerations should compel clinicians to advocate for adopting reusable equipment and to continue to ensure governments make steady gains toward an increasingly renewable energy mix for healthcare electricity.

The research by McGain *et al.*[1] invites us to consider how our relevant local hospital practices (product procurement and energy sourcing) impact our in-theatre carbon footprints, and to champion change to benefit our patients and our planet.

Competing Interests

The authors declare no competing interests.

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Carbon Footprint of Anesthesia: Comment

To the Editor:

We read with great interest the recent article by McGain *et al.*[1] that quantified the carbon footprint associated with the provision of spinal anesthesia and general anesthesia for total knee arthroplasty. This type of encompassing evaluation is valuable as it is not clouded by biases and highlights that meaningful carbon dioxide equivalent emission comparison depends greatly on local energy generation conditions and individual/institutional anesthesia practice standards. Examining the conduct of spinal anesthesia in the study by McGain *et al.*, there are several components that could be refined to significantly reduce the carbon burden of a neuraxial-based anesthetic.

The largest component of carbon dioxide equivalent emissions associated with spinal anesthesia is related to the electricity required for cleaning and sterilizing reusables (gowns, hand towels, among others). The significant environmental impact associated with the use of sterile gowns for spinal anesthesia mandates a thorough evaluation of this practice.[1] The risk of infectious complications associated with neuraxial anesthesia is incredibly low (0.2 to 0.3:10,000), and the American Society of Anesthesiologists (Schaumburg, Illinois) guidelines have not recommended sterile gown wearing for these procedures.[2,3] Furthermore, the requirement for sterile hand towels is questionable as alcohol-based hand rub has been shown to be an effective means to reduce cutaneous bacterial counts.[4]

The second largest contributor of carbon dioxide emissions associated with the provision of spinal anesthesia in this study is high oxygen flow rates. Given that spinal anesthesia results in complete lower extremity anesthesia, moderate to low levels or no sedation usually suffices, and therefore it may be possible to significantly reduce supplemental oxygen requirements.

Third, the development of a significant and collective environmental conscience among patients and medical providers can be harnessed to drive impactful change. As more members of society elect to purchase an electric vehicle, utilize reusable bags, or forgo plastic packaging, they may also be interested in making a similar conscientious and informed decision about the environmental impact of their anesthetic choice and practice. Practitioners are now positioned to evaluate their equipment and demand from their manufacturers equipment that has a diminished impact on the environment. In certain clinical settings (*i.e.*, busy orthopedic or obstetric practices), opportunities may exist to build a subarachnoid anesthesia kit with only the absolutely essential components, which may reduce waste and cost, although the carbon dioxide equivalent impact remains unknown.

McGain *et al.* should be commended for their description of the environmental impact of their institutional practices, and this study should serve as a rallying cry that compels us to reflect upon our own practices, motivate positive change, and improve the health of our patients beyond the operating room through data-driven adjustments to standard anesthetic delivery.

Acknowledgments

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Competing Interests

The authors are members of the ASRA Pain Medicine Green Special Interest Group, with Dr. Ip serving as the chair of this group. Dr. Schroeder has received speaking honorarium from AudioDigest and Northwest Anesthesia Seminars.

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Carbon Footprint of Anesthesia: Reply

In Reply:

We thank all authors for the correspondence[1-6] relating to our life cycle assessment of anesthesia for knee replacements.[7]

In response to Kalmar *et al.*[1]: We used the Intergovernmental Panel on Climate Change preferred[8] global warming potential of 100 yr, given that it is the recognized compromise between short- and long-lived greenhouse gases. The third reference in the article by Kalmar *et al.*[8] gives sevoflurane's global warming potential as 195. The fourth reference in the article by Kalmar *et al.*[9] is cited as being more recent and accurate for sevoflurane's global warming potential (130), yet we referenced that article.[7,9] We note sevoflurane's recently updated global warming potential of 144 by Andersen *et al.*,[10] with concerns that the Intergovernmental Panel on Climate Change's global warming potential for sevoflurane[8] of 195 is inaccurate. The global warming potential for carbon dioxide itself requires intermittent updating as new data arrive, leading to adjustment of the global warming potentials for anesthetic gases.[11] There are also uncertainties with all global warming potentials, particularly for trace anesthetic gases.[12] Nevertheless, we had used the most accurate global warming potential for sevoflurane (130), but acknowledge that a 10% [(144 – 130)/130] adjustment upward to a global warming potential of 144 is required now.

We did not include the carbon dioxide equivalent emissions from the production of volatile anesthetics as the article by Hu *et al.*[13] is very recent. Hu *et al.* indicated two methods of producing sevoflurane, with manufacturing method A leading to approximately fivefold greater production of greenhouse gases than the clinical use of sevoflurane itself. The lower carbon manufacturing method B produced a similar magnitude of greenhouse gases as clinical use of sevoflurane. It is unclear why Hu *et al.* found much greater carbon dioxide equivalent emissions from the manufacture of sevoflurane than estimated by Sherman *et al.*,[14] particularly as Hu *et al.* noted, "The processes described in Method-B are similar to the ones modeled by SciFinder in Sherman."[13] Neither paper had access to commercial pharmaceutical manufacturing data.

We sought production information from Baxter Healthcare (Deerfield, Illinois), a multinational supplier of sevoflurane. Baxter's February 2022 letter of response (from Jason Vollen, M.B.A., Baxter Healthcare) was as follows: "On the basis of the evidence…the majority of our sevoflurane comes from a process that most aligns with 'Sevo B' (*i.e.*, the lower [greenhouse gas] emissions' method)." We thus note the much higher greenhouse gas numbers for sevoflurane calculated by Kalmar *et al.*, but indicate that the majority of these concerns are moot. Collaborative industry research to clarify the true environmental cost of sevoflurane manufacture is urgently required.

In response to Norman *et al.*[2]: Norman *et al.* raise important concerns about single-use plastics. Our study focused upon the carbon footprint of anesthesia, although, as in all robust life cycle assessments, we obtained data (unpublished data about other environmental effects such as physical waste and aquatic toxicity, among others) about the end of life of all waste. Using more single-use plastics will evidently create more trash with attendant concerns about the ultimate resting place of such rubbish.[14]

With the rapid move toward electricity decarbonization in Australia[16] (and elsewhere), the aphorism "renewable (electricity) makes reusable (equipment) better" becomes more relevant. The combination of reduced carbon emissions, reduced plastic waste, and lower financial costs when anesthesiologists use reusable equipment[17] becomes a powerful argument to abandon single-use plastics.

In response to Gobert and Dernis[3]: Thank you for emphasizing the variability in how often anesthetic breathing circuits are changed despite studies indicating the safety of less frequent changes.[18,19] Weekly circuit changes, reusable or disposable, are certainly financially and environmentally more sound, and clinically no less safe than changing with each patient. We (and others)[20] suggest engagement with infection prevention to challenge the dominant infection prevention paradigms that (1) single use is safer, and (2) the financial and environmental costs of clinical care are simply externalities. Anesthesiologists can lead the way collaboratively just as they have for safety and quality assurance.

In response to Tsai *et al.*[4]: We have previously corresponded with Tsai *et al.* about water use required for cleaning reusable anesthetic equipment,[21] and remain in agreement that water use is an important local environmental consideration. The concerns of Tsai *et al.* about the limitations of life cycle assessment are also correct, but we note that methodologic techniques are evolving to incorporate life cycle assessment into Herman Daly's ideas about ecological economics, *e.g.*, by Pelletier *et al.*[22] Nevertheless, we remain focused upon carbon dioxide equivalent emissions as global climate change is an existential threat.

As to water, we remain committed to running hospital steam sterilizers more efficiently.[23] Kaiser Permanente (USA) has emulated our efforts and saved approximately US$300,000 per annum by more efficiently using their steam sterilizers.[24] We encourage anesthesiologists to collaborate toward a more environmentally sustainable healthcare system.

In response to Carter and Davies[5]: Carter and Davies indicate the importance of interpreting our study within the context of one's institution and practices (*e.g.*, energy use, efficiency of resource use, and behaviors). Importantly, as the life cycle carbon footprint of single-use plastic (*e.g.*, polypropylene) is less than 10% attributable to electricity, a switch to 100% renewable energy for plastic manufacture will have a much lower effect on single-use plastic's overall carbon dioxide equivalent emissions than moving to 100% renewable electricity for cleaning reusables. With Australia's movement toward 100% renewable energy,[25] the carbon footprint of reusable anesthetic equipment will decrease to levels similar to those in Europe. We encourage anesthesiologists to return to reusables where possible.

In response to Schroeder et al.[6]: Schroeder *et al.* emphasize the significant environmental impact of reusable sterile gowns in our study.[7] Schroeder*et al.* indicate the American Society of Anesthesiologists (Schaumburg, Illinois) does not recommend sterile gowns for neuraxial procedures in recent practice guidelines.[26] Nevertheless, the Australian and New Zealand College of Anaesthetists (Melbourne, Australia)[27] and the New York School of Regional Anesthesia (New York, New York)[28] recommend gown use for spinal anesthesia.

A welcome outcome of our research could be to promulgate greater understanding of regional and international variation in anesthetic practice, and the corresponding rationale. Since it is unlikely that there is a difference in infection rates from spinal anesthesia with or without a sterile gown, the focus of guidelines could shift to include protecting the patient *and* the environment.[29]

We appreciate concerns about high oxygen flow rates in our study.[7] Oxygen can be titrated to low flows *via* a facemask (4 l/min) while avoiding rebreathing,[30] or *via* nasal prongs with close monitoring. Our observational study[7] revealed surprising practice variations that could lead to large environmental footprints nationally from anesthesia. We encourage others to clarify such practice variations and begin the journey to safely reducing anesthesia's environmental footprint.

Competing Interests

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Perioperative Pulmonary Atelectasis: Comment

To the Editor:

We read the review articles by Zeng *et al.*[1] and Lagier *et al.*[2] with great interest, with their emphasis that atelectasis caused by peripheral airway closure is a common complication of mechanical positive pressure ventilation. This phenomenon was first detected during anesthesia by Hedenstierna *et al.*[3,4] and was reviewed by Milic-Emili *et al.*[5] It is well known that negative pleural pressure resolves peripheral airway closure and subsequent atelectasis. This can be achieved by synchronizing ventilation with the patient's efforts or by stimulating the phrenic nerve. However, a far simpler solution to avoid or treat atelectasis is to use negative pressure ventilation.

Before the polio pandemic in the 1950s, patients with atelectasis were treated with negative pressure ventilation in the iron lung. Its use was, however, abandoned for practical nursing reasons during and after the polio pandemic. After the introduction of positive pressure ventilation, the fight against ventilator-induced atelectasis started and is still going on.

A recent publication by Klassen *et al.*[6] clearly shows the impact of peripheral airway closure in the context of positive and negative pressure ventilation. In an excised porcine lung, the driving pressure during positive pressure ventilation needed to be twice as large as during negative pressure ventilation to reach the same tidal volume. Moreover, the leakage from deliberate damage to the visceral pleura was five times larger during negative pressure ventilation. This demonstrates that positive pressure ventilation caused peripheral airway