ANESTHESIOLOGY

Carbon Footprint of General, Regional, and Combined Anesthesia for Total Knee Replacements

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EDITOR'S PERSPECTIVE

What We Already Know about This Topic

- Health care produces greenhouse gases both directly (electricity and gas) and indirectly from emissions associated with consumption of goods and services
- For anesthesiologists to reduce their workplace carbon footprint, they must understand the sources and amounts of the greenhouse gases produced as they care for patients in the operating room

What This Article Tells Us That Is New

- The carbon footprint in carbon dioxide equivalent emissions associated with general anesthesia (n = 9), spinal anesthesia (n = 10), and combined (general and spinal) anesthesia (n = 10) for total knee replacement surgery in Melbourne, Australia, were similar
- Single-use equipment, electricity for the patient air warmer, and pharmaceuticals were major sources of carbon dioxide equivalent emissions across all anesthetics
- Sevoflurane was a significant source of the carbon dioxide equivalent emissions of both general anesthesia and combined anesthesia
- Washing and sterilizing reusable items contributed substantially to the carbon dioxide equivalent emissions of both spinal and combined anesthesia
- Oxygen use was an important contributor to the carbon footprint of spinal anesthesia

ABSTRACT

Background: Health care itself contributes to climate change. Anesthesia is a "carbon hotspot," yet few data exist to compare anesthetic choices. The authors examined the carbon dioxide equivalent emissions associated with general anesthesia, spinal anesthesia, and combined (general and spinal anesthesia) during a total knee replacement.

Methods: A prospective life cycle assessment of 10 patients in each of three groups undergoing knee replacements was conducted in Melbourne, Australia. The authors collected input data for anesthetic items, gases, and drugs, and electricity for patient warming and anesthetic machine. Sevoflurane or propofol was used for general anesthesia. Life cycle assessment software was used to convert inputs to their carbon footprint (in kilogram carbon dioxide equivalent emissions), with modeled international comparisons.

Results: Twenty-nine patients were studied. The carbon dioxide equivalent emissions for general anesthesia were an average 14.9 (95% CI, 9.7 to 22.5) kg carbon dioxide equivalent emissions; spinal anesthesia, 16.9 (95% CI, 13.2 to 20.5) kg carbon dioxide equivalent; and for combined anesthesia, 18.5 (95% CI, 12.5 to 27.3) kg carbon dioxide equivalent. Major sources of carbon dioxide equivalent emissions across all approaches were as follows: electricity for the patient air warmer (average at least 2.5 kg carbon dioxide equivalent [20% total]), single-use items, 3.6 (general anesthesia), 3.4 (spinal), and 4.3 (combined) kg carbon dioxide equivalent emissions, respectively (approximately 25% total). For the general anesthesia and combined groups, sevoflurane contributed an average 4.7 kg carbon dioxide equivalent (35% total) and 3.1 kg carbon dioxide equivalent (19%), respectively. For spinal and combined, washing and sterilizing reusable items contributed 4.5 kg carbon dioxide equivalent (29% total) and 4.1 kg carbon dioxide equivalent (24%) emissions, respectively. Oxygen use was important to the spinal anesthetic carbon footprint (2.8 kg carbon dioxide equivalent, 18%). Modeling showed that intercountry carbon dioxide equivalent emission variability was less than intragroup variability (minimum/maximum).

Conclusions: All anesthetic approaches had similar carbon footprints (desflurane and nitrous oxide were not used for general anesthesia). Rather than spinal being a default low carbon approach, several choices determine the final carbon footprint: using low-flow anesthesia/total intravenous anesthesia, reducing single-use plastics, reducing oxygen flows, and collaborating with engineers to augment energy efficiency/renewable electricity.

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Climate change has become a considerable health-care threat of the 21st century,[1] yet health care itself produces greenhouse gases directly (electricity and gas), but also from indirect emissions associated with consumption of goods and services.[2,3] The Australian healthcare system is responsible for approximately 7% of the total Australian greenhouse gas emissions.[4] Within hospitals, the intensive care unit[5] and operating rooms[6] are the most demanding of natural and financial resources. Operating rooms require

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This article is featured in "This Month in Anesthesiology," page A1. This article is accompanied by an editorial on p. 937. This article has a related Infographic on p. A15. This article has an audio podcast. This article has a visual abstract available in the online version. Presented at the Australia and New Zealand College of Anaesthetists Annual Scientific Meeting in Melbourne, Australia, April 30 to May 4, 2021.

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large amounts of medical equipment, produce much waste,[7] and have large energy requirements.[6,8] As climate change has become an environmental (and health) emergency,[1] health systems need to investigate ways in which high-quality health care can be delivered while minimizing the environmental impact.

MacNeill *et al.*[6] studied three hospitals, one each in Canada, the United States, and the United Kingdom, finding that anesthesia could have greater carbon dioxide equivalent emissions than (1) all surgical equipment and procurement, and (2) all operating room–associated energy requirements including heating, ventilation, and air conditioning.[6] Multiple studies have focused on the surgical side of carbon dioxide equivalent emissions for different operations (*e.g.*, hysterectomies,[8] cesareans,[9] and cataracts[10]). The carbon dioxide equivalent emissions associated with the anesthetic gases desflurane and nitrous oxide are significant.[11] Similar to the United Kingdom hospital in the study by MacNeill *et al.*,[6] we observed minimal desflurane and nitrous oxide use in our hospital, although we recognize variability in Australian anesthetic practice.[12] There are calls for studies to investigate the effects of general *versus* regional anesthetic choice upon carbon dioxide equivalent emissions,[13] as this could be important even in the absence of desflurane or nitrous oxide.

We asked what was the carbon footprint of the anesthetic component of a total knee replacement, a common operation for which there is clinical equipoise between alternate anesthetic approaches. We aimed to quantify the carbon dioxide equivalent emissions of general anesthesia, spinal anesthesia, and combined general and spinal anesthesia.

Materials and Methods

This prospective, nonrandomized, single center life cycle assessment was performed and follows the observational study Strengthening the Reporting of OBservational studies in Epidemiology checklist (www.strobe-statement.org.). The hospital ethics committee gave study approval (HREC/2018/Western Health/64), deeming that patient consent was not required (observational study not requiring patient data). We considered that 10 patients to each group (general anesthesia, spinal, and combined [general and spinal] anesthesia) provided an adequate convenience sample. We enrolled patients who were having elective total knee replacements consecutively, only excluding patients due to researcher unavailability. Life cycle assessment is a scientific method used to quantify the environmental footprint of a product or service throughout an entire life cycle.[14] Previous studies have examined the carbon footprint of anesthetic equipment, which we have incorporated.[15–17] Our study focused on the carbon footprint of anesthesia as climate change is becoming increasingly important. Appendix 1 and previous reviews[13,18] contain further information about life cycle assessment methods.

Using the International Organization for Standardization (Geneva, Switzerland) ISO-14040 standards,[14] we defined our study's *functional unit* as all anesthesia for a total knee replacement in a hospital in Victoria, Australia. The ISO-14040 standards[8] life cycle assessment *system boundary* defines inclusions/exclusions (fig. 1). We did not include data for heating/ventilation/air conditioning, or any surgical equipment. Electricity consumption for anesthesia devices was estimated (not measured) from manufacturer data[19] or from previous publications.[20,21]

We obtained patient anesthetic start and stop times. General anesthetics could be either volatile gas anesthetics or total intravenous anesthesia, with all cases requiring an airway device (laryngeal mask/endotracheal tube). Spinal anesthetics were delivered with sedation and by definition required no airway device. We present carbon dioxide equivalent emissions as total data, not per hour. For many items (drugs, plastic syringes, spinal anesthetic trays and gowns, inhalational induction), considerably more were used during the first hour of anesthesia than subsequently.

We examined the composition and weights of reusable and disposable consumables: gloves, gowns, syringes, airway devices, patient warming blankets, temperature probes, intravenous fluids, drugs, and gases, and associated immediate packaging. Volumes of oxygen, medical air, volatiles, and nitrous oxide use were obtained from the anesthetic machine (Aisys CS^2, GE Healthcare, USA) computer at the end of each case. Oxygen flows for sedated patients were manually recorded. We used the Andersen *et al.* study's[11] global warming potential data for anesthetic gases. We used two life cycle inventories (Ecoinvent,[22] Switzerland, and the Australian Life Cycle Inventory[23]) to obtain carbon dioxide equivalent emissions associated with devices and processes.

For reusable items, previous data were used to estimate the environmental impacts of cleaning (sterile gowns,[24] face masks, anesthetic breathing circuits, laryngoscope blades,[15] and drug trays[17]). We thus attributed the energy costs of reusable anesthetic equipment, *i.e.*, kilowatt-hour/size of item as a proportion of washer load,[25,26] and 1.9 kilowatt-hours/kg[27] items sterilized (appendix 1). The reusable anesthetic breathing circuits were changed weekly unless contaminated,[28] so their contribution to total carbon dioxide equivalent emissions was small (conservatively 25 operations per operating theater per week). Also included were the carbon dioxide equivalent emissions from carbon dioxide absorbent use (0.13 kg carbon dioxide equivalent emissions/h from Zhong *et al.*[29]). Energy requirements for liquid oxygen were 0.001 kilowatt-hours/l for oxygen gas and 0.0003 kilowatt-hours/l for compressed medical air (Ecoinvent[22] for electricity data, Australian Life Cycle Inventory[23] for carbon dioxide equivalent emissions per kilowatt-hour).

Since we knew equipment mass, we used average production data about carbon dioxide equivalent emissions/kilogram waste from the Ecoinvent[22] and Australian[23] life cycle inventories as appropriate. We assumed general waste for all disposables except for some polyvinyl chloride recycling[7] (face masks, oxygen tubing, and intravenous fluid bags), and polypropylene (spinal tray sterile wrap). Contaminated items (*e.g.*, suction tubing) were

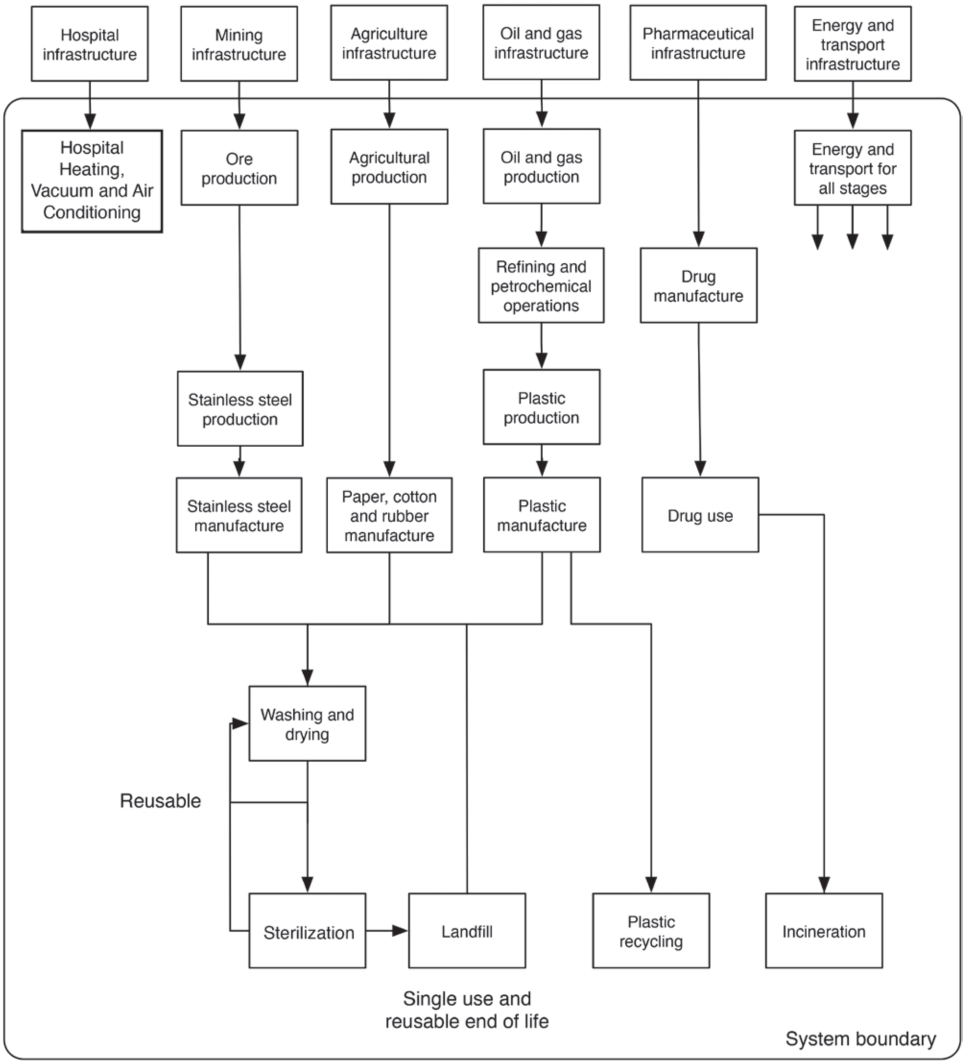

Fig. 1. System boundary.

assumed infectious/clinical waste (higher carbon dioxide equivalent emissions/kilogram, Ecoinvent), and pharmaceutical waste was assumed to undergo high-temperature incineration.

No public life cycle inventory data exist for most pharmaceuticals.[30] We used the Parvatker *et al.* study's carbon dioxide equivalent emissions data approximations for 20 common anesthetic pharmaceuticals.[31] From Parvatker *et al.*, the average/mean g carbon dioxide equivalent emissions/g drug across the 20 drugs was 340 g carbon dioxide equivalent emissions/g drug, with, for example, propofol at 21 g carbon dioxide equivalent emissions/g propofol, and midazolam 444 g carbon dioxide equivalent emissions/g midazolam.[31] Cefazolin, paracetamol, or tranexamic acid were unstudied, but we used this average 340 g carbon dioxide equivalent emissions/g drug[31] to calculate carbon dioxide equivalent emissions. We estimated carbon dioxide equivalent emissions associated with intravenous fluid manufacture from our previous morphine life cycle assessment study (including production and sterilization of 0.9% NaCl bags).[30] Some recycling was already occurring in the operating room (plastics/paper/cardboard).[7,32]

Data were modeled in SimaPro-9 life cycle assessment software (PRé Consultants, The Netherlands). We developed an inventory that quantified materials and energy used, and modeled this using the Ecoinvent[22] (version 3.5) and Australian Life Cycle Inventory[23] databases. We used Monte Carlo software algorithms (SimaPro) to obtain results and 95% CIs. We modeled our results with those for identical anesthetics being provided in China, the European Union, and the United States. We give the 95% CIs (from Monte Carlo analysis) only for the means/averages, and only for group aggregates (rather than individual components, *e.g.*, plastics or electricity use), as the same assumptions are inherent in modeling the components that make up the aggregates (producing CIs for each component is lengthy and the numbers small). The 95% CI of the mean (indirectly obtained by Monte Carlo) indicates what the variability of the results could be if the study was performed many times, and may not closely reflect the directly obtained minima/maxima results. Further details about life cycle assessment methods are contained within appendix 1.

Results

Between January 9, 2019, and June 10, 2019, 36 patients underwent total knee replacements in operating room 4 at Williamstown Hospital, Western Health, Melbourne. As planned for this convenience sample and dependent upon researcher availability, we obtained anesthesia data for 30 patients: 10 patients in each group of general anesthesia, spinal anesthesia, and general plus spinal (combination). We excluded 1 patient (from combined general and spinal group) as they received nitrous oxide, leaving 29 patients (discussed later). The average/mean knee replacement anesthesia duration times (and ranges) were as follows: general anesthesia, 161 (113 to 193) min, spinal, 200 (168 to 288) min, and combination, 189 (128 to 241) min. Eight general anesthesia patients received sevoflurane, one total intravenous anesthesia, and one sevoflurane/total intravenous anesthesia combination. Six general anesthesia patients were intubated, while four had a laryngeal mask placed. All 10 patients receiving spinal anesthesia had sedative propofol infusions. For the patients receiving combination anesthesia, six received sevoflurane, and three received total intravenous anesthesia, while eight were given laryngeal masks, and two were intubated.

Background Data: Masses and Types of Disposables, Gases, and Electricity Used for Reusable Equipment

Appendices 1 and 2 give background data and calculations about the masses and energy required to wash reusable equipment. Appendix 3 gives masses of pharmaceuticals, led by cefazolin, tranexamic acid, paracetamol, and propofol, which are given in larger quantities/masses than other drugs. Intravenous paracetamol was given to one or two patients per group. Note (from Materials and Methods) that propofol has a carbon footprint of only 21 g carbon dioxide equivalent emissions/g propofol,[31] so using 3-h total intravenous anesthesia propofol at 700 mg/h will have carbon dioxide equivalent emissions of less than 50 g carbon dioxide equivalent.

Table 1 gives the equipment types used including the mean, 25%, 75% (interquartile range), and minimum–maximum (range). The total masses of single-use equipment used were as follows: general anesthesia (mean, 996 g; interquartile range, 873 to 1,033 g; range, 725 to 1,392 g), spinal anesthesia (mean, 997 g; interquartile range, 934 to 1,076 g; range, 885 to 1,184 g), and combination anesthesia (mean, 1,237 g; interquartile range, 1,100 to 1,285 g; range, 1,009 to 1,687 g). For single-use equipment, the majority of waste was from total plastics: average for general anesthesia, 783/996 g (78%); spinal, 729/997 g (73%); and combination, 932/1,237 g (75%). Glass was the next most common discarded material. There were minor (less than 100 g total mass) masses of other materials discarded (copper, cotton, latex, neoprene, and steel).

Table 1 also indicates that delivered oxygen was much greater for spinal anesthesia (mean, 1,328 l; interquartile range, 1,080 to 1,545 l; range, 990 to 1,950 l) *versus* general anesthesia (mean, 197 l; interquartile range, 116 to 271 l; range, 74 to 320 l), or combination anesthesia (mean, 256 l; interquartile range, 131 to 332 l; range, 53 to 824 l). Seven patients having spinal anesthesia received oxygen flow rates of 6 l/min, and three of 8 to 10 l/min. For the nine general anesthesia patients who received sevoflurane, the range was 14 to 44 ml (range, 6 to 15 ml/h), and for the seven combined anesthesia patients, the range of sevoflurane use was 11 to 50 ml (5 to 16 ml/h). Using 6 ml/h of (liquid) sevoflurane for 3 h will have carbon dioxide equivalent emissions of approximately 6 ml × 3 h × 1.5 (density) × 130 global warming potential in carbon dioxide equivalent emissions for sevoflurane[13] = 3.5 kg carbon dioxide equivalent emissions.

Desflurane was unused, and nitrous oxide used for one patient. Both desflurane and nitrous oxide are known to have high global warming potential (2,540[11] and 265,[33] respectively), which could easily skew overall results for this 30-patient convenience sample. The one patient who received nitrous oxide had 111 l N_2O over 3.25 h. The carbon dioxide equivalent emissions for the nitrous oxide alone are 111/24.5 = 4.5 moles = 4.5 × 44 g = 200 g (0.2 kg) N_2O = 0.2 × 265[33] = 53 kg carbon dioxide equivalent emissions. Thus, compared with using sevoflurane alone, the carbon dioxide equivalent emissions from using nitrous oxide are more than 10-fold greater.

Table 2 indicates carbon dioxide equivalent emissions from anesthesia per patient anesthetic items as calculated from the types and masses of consumables used (appendices 1 and 2), and the electricity requirements for washing/sterilizing reusable equipment, patient warming, anesthetic gas scavenging, and the anesthesia machine. Note in table 2 the column heading "Carbon dioxide equivalent emissions per kg, item, ml, or l," which indicates the differing carbon intensities of materials for their entire life cycle. Cotton has high carbon dioxide equivalent emissions per kilogram due to decomposition emitting methane (*vs.* steel and plastic, which are nonbiodegradable).[22] Considerably more plastics were used than *disposable* cotton; thus, plastics contributed the majority of the carbon dioxide equivalent emissions for disposable equipment. The summary carbon dioxide equivalent emissions for each group in the last two lines of table 2 indicate the directly measured averages, and the indirectly measured 95% CIs as calculated by Monte Carlo analysis. As noted in the Materials and Methods, the 95% CIs may not be reflective of the directly measured interquartile ranges and minima/maxima seen in figure 2.

Table 1. Masses of Items Used by Anesthetists

Items	General Anesthesia: Average (Range), g/case	General Anesthesia: [Interquartile Range, 25–75%], g/case	Spinal Anesthesia: Average (Range), g/case	Spinal Anesthesia: [Interquartile Range, 25-75%], g/case	General + Spinal Anesthesia: Average (Range), g/case	General + Spinal Anesthesia: [Interquartile Range, 25-75%], g/case
Reusable items, g						
Cotton hand towel washed* and sterilized† (with sterile gown)	0	0	143	0	143	0
Plastics washed‡ (drug trays)	178 (178–178)	[178–178]	178 (178–178)	[178–178]	178 (178–178)	[178–178]
Plastics washed (anesthetic breathing circuits)§	0.1 kilowatt-hours/operation		0		0.1 kilowatt-hours/operation	
Plastics washed‡ and sterilized† (Proseal laryngeal mask, spinal tray, sterile surgical gown for spinal procedure). Note: Some spinal cases required > 1 gown (training, contamination, and so forth).	14 (0–72)	0–0	1,492 (1,227–1,828)	[1,227–1,728]	1,227 (1,227–1,227)	[1,227–1,227]
Silicone washed‡ (face mask)	78 (78–78)	[78–78]	0	0	78 (78–78)	[78–78]
Stainless steel washed‡ and sterilized§ (laryngoscope blade)‖	86 (0–123)	[31–123]	0	0	13 (0–123)	[0–0]
Single-use items,# g						
Copper**	5 (0–10)	[0–10]	1 (0–6)	[0–0]	3 (0–10)	[0–10]
Cotton	12 (0–25)	[0–23]	15 (3–28)	[6–25]	22 (11–28)	[23–25]
Glass††	161 (97–357)	[118–185]	180 (91–305)	[123–218]	186 (103–270)	[133–224]
Plastics, non–polyvinyl chloride‡‡ trash	486 (164–755)	[388–501]	451 (374–512)	[433–473]	583 (393–1040)	[482–630]
Plastics, non–polyvinyl chloride polypropylene recycled§§	0	0	42 (42–42)	[42–42]	42 (42–42)	[42–42]
Plastics, polyvinyl chloride trash	186 (89–252)	[166–222]	111 (28–236)	[92–121]	181 (98–284)	[137–250]
Plastics, polyvinyl chloride recycled‖‖	111 (91–123)	[91–123]	125 (91–151)	[123–123]	123 (91–151)	[91–123]
Rubber, latex	3 (0–29)	[0–0]	41 (28–57)	[29–57]	41 (29–57)	[29–57]
Rubber, neoprene, nitrile	30 (26–38)	[26–32]	33 (0–77)	[19–53]	42 (0–77)	[26–51]
Stainless steel##	4 (1–7)	3–6	13 (7–23)	[11–13]	13 (7–17)	[7–17]
Total, single-use items	996 (725–1,392)	[873–1,033]	997 (885–1,154)	[934–1,076]	1,237 (1,009–1,687)	[1,100–1,285]
Gases (volumes in l or ml)						
Oxygen, l	197 (75–320)	[116 – 271]	1,328 (990–1,950)	1,080–1,545	256 (53–824)	[131–332]
Compressed air, l	80 (14–273)	52–76	0	0	76 (9–193)	[42–94]
Sevoflurane,*** ml as a liquid)	24 (0–44)	0–29	0	0	16 (0–44)	[0–28]
Sevoflurane, ml/h	9.6 (6.2–14.6)	8.2–10.3	0	0	8.1 (4.8–19.0)	5.0–9.0
Sevoflurane: total intravenous anesthesia + sevoflurane: total intravenous anesthesia	8: 1: 1				5: 1: 3	

Pharmaceutical data are located in appendix 2.

*Laundered cotton data taken from Carre's Royal Melbourne Institute of Technology (Melbourne) study within Overcash.[24] †Energy required to sterilize equipment obtained from McGain *et al.*[25–27] ‡Energy required to wash (thermally disinfect trays) taken from McGain *et al.*[17]

§Circuits changed weekly. Total 6.2 kilowatt-hours per wash load[17,28] with minimum of six circuits within and used for 25 operations. No energy attributed to spinal anesthetic as unused. ‖Stainless steel laryngoscope handles were wiped down with an antiseptic wipe between patient use. #Minimal paper/cardboard was disposed of within the operating room as the cardboard packets were routinely separated from the drug ampoules before entry into the operating room. No mattresses were used for heavy/obese patient transfers as most such patients are electively preferentially operated upon elsewhere in our health service. **Copper was found in the temperature probe. ††Glass arose mainly from drug ampoules. ‡‡Plastics, non–polyvinyl chloride were, from inspection and reference to our previous study of operating room plastics,[32] almost entirely polypropylene and polyethylene/polypropylene combinations (syringes). One plastic reusable ventilator circuit (436 g) was found to be leaking (thus discarded) for a general anesthesia + spinal patient, considerably increasing the maximum mass of plastics. §§Non–polyvinyl chloride recycling (of polypropylene) was occurring in the operating room.[7] ‖‖Polyvinyl chloride recycling of intravenous fluid bags was occurring in the operating room.[7] ##Stainless steel was contained within needles. ***Desflurane was not used for any cases. Nitrous oxide was used in one general anesthesia + spinal combination case, but this case was removed as the effect of nitrous oxide upon the total carbon dioxide emissions for the combination group excessively skewed the data.

Table 2. Carbon Dioxide Equivalent Emissions from Anesthesia per Patient

Item (Equipment, Gases, Energy)	Carbon Dioxide Equivalent Emissions per Kilogram, Item, Milliliter, or Liter	General Anesthesia		Spinal		General Anesthesia + Spinal	
		Average Kilogram Carbon Dioxide Equivalent Emissions per Patient	% Total	Average Kilogram Carbon Dioxide Equivalent Emissions per Patient	% Total	Average Kilogram Carbon Dioxide Equivalent Emissions per Patient	% Total
Average anesthesia duration		161 min (2.7 h)		200 min (3.3 h)		189 min (3.2 h)	
Electricity directly associated with anesthesia (Victorian electricity = 1.12 kg carbon dioxide equivalent emissions/kilowatt-hour							
Patient air warmer (3M, USA) 0.8 kilowatt-hours/h (product information) = 0.9 kg carbon dioxide equivalent emissions/h use		2.46 kg carbon dioxide equivalent	20%	2.96	21%	2.86	19%
Anesthesia machine 0.08 kilowatt-hours/h[18] = 0.09 kg carbon dioxide equivalent/h use		0.24 kg carbon dioxide equivalent	2%	0.30	2%	0.29	2%
Reusable equipment: electricity for washing, sterilizing (Victorian electricity = 1.12 kg carbon dioxide equivalent emissions/kilowatt-hour)[29]							
Washing plastic trays[17]	0.16 kg carbon dioxide equivalent emissions/tray[17]	0.16	1%	0.16	1%	0.16	1%
Washing[17] and sterilizing plastic, cotton, silicone, and stainless steel (sterile surgical gown and towel for spinal, combined anesthesia)	3.0 kg carbon dioxide equivalent emissions/kg washed[17] and sterilized[23–25]	0.49	4%	4.52	29%	3.96	24%
Single-use Items (Australian Government National Greenhouse Accounts Factors)[29]							
Copper	11.9 kg carbon dioxide equivalent emissions/kg	0.06 kg carbon dioxide equivalent	0%	0.01 kg carbon dioxide equivalent emissions	0%	0.05 kg carbon dioxide equivalent emissions	0%
Cotton	27.2 kg carbon dioxide equivalent emissions/kg	0.35	3%	0.44	3%	0.64	4%
Glass	3.6 kg carbon dioxide equivalent emissions/kg	0.58	4%	0.65	4%	0.65	4%
Plastics, non–polyvinyl chloride	3.3 kg carbon dioxide equivalent emissions/kg	1.72	13%	1.60	10%	2.07	12%
Plastics, non–polyvinyl chloride recycled	1.8 kg carbon dioxide equivalent emissions/kg	0.12	1%	0.07	< 1%	0.07	< 1%
Plastics, polyvinyl chloride	2.6 kg carbon dioxide equivalent emissions/kg	0.49	4%	0.30	2%	0.46	3%
Plastics, polyvinyl chloride recycled	1.1 kg carbon dioxide equivalent emissions/kg	0.12	1%	0.12	1%	0.12	1%
Rubber, synthetic and natural	2.0 kg carbon dioxide equivalent emissions/kg	0.02	< 1%	0.14	1%	0.16	1%
Stainless steel	6.8 kg carbon dioxide equivalent emissions/kg	0.03	< 1%	0.09	1%	0.09	1%
Gases							
Oxygen	0.0021 kg carbon dioxide equivalent emissions/l	0.41 kg carbon dioxide equivalent	3%	2.76 kg carbon dioxide equivalent emissions	18%	0.53 kg carbon dioxide equivalent emissions	3%
Compressed air	0.00051 kg carbon dioxide equivalent emissions/l	0.04	< 1%	0		0.04	
Sevoflurane global warming potential = 130)[11]	0.196 kg carbon dioxide equivalent emissions/ml liquid	4.70	35%	0	0%	3.14	19%
Pharmaceuticals, total	Variable carbon dioxide equivalent emissions[27]	1.20	9%	1.26	8%	1.26	8%
Average and range of all carbon dioxide equivalent emissions (kg carbon dioxide equivalent)		13.3 (8.1–20.8)	100%	15.4 (11.7–19.0)	100%	16.7 (10.6–25.7)	100%
95% CI of carbon dioxide equivalent emissions		11.4–17.9		13.7–18.3		14.6–23.6	

Carbon Dioxide Equivalent Emissions: Effects of Anesthetic Duration

As table 2 and figure 3 indicate, the average/mean duration of spinal and combined anesthesia were approximately 40 and 30 min more (*i.e.*, 20% longer) than general anesthesia. The increased duration for spinal/combined anesthesia is at least partly due to increased time to undertake the spinal anesthetic. The longer spinal and combined anesthetic duration increased the carbon footprint of electricity for the patient air warmer and scavenging by 0.8 and 0.6 kg carbon dioxide equivalent emissions, respectively. Further, because spinal anesthesia was 20% longer than general anesthesia, this added approximately 2.76 × 0.2 = 0.6 kg carbon dioxide equivalent emissions to oxygen use for the spinal anesthetic. A spinal anesthetic of 20% shorter duration would thus have approximately 1.4 kg carbon dioxide equivalent less emissions. The effects of anesthetic duration had a much lower magnitude of effect upon the carbon footprint of other anesthetic activities.

Carbon Dioxide Equivalent Emissions: Averages, Ranges, and Components

Using Monte Carlo modeling, we found that the carbon dioxide equivalent emission means/averages were similar for all three approaches, and that the 95% CIs overlapped considerably, resulting in difficulty in making group comparisons. For general anesthesia, the mean was 14.9 kg carbon dioxide equivalent emissions (95% CI, 9.7 to 22.5); spinal anesthesia, 16.9 kg carbon dioxide equivalent emissions (95% CI, 13.2 to 20.5); and combination anesthesia, 18.5 kg carbon dioxide equivalent emissions (95% CI, 12.5 to 27.3). Figure 2 provides graphical contextualization of the means, interquartile ranges, and minimum–maximum ranges of the carbon dioxide equivalent emissions for the three anesthesia approaches. Figure 2 indicates that the interquartile ranges are relatively close, but there are considerable *intragroup* outliers. The range for spinal anesthesia was less than for general or combination anesthesia as there was a more standard approach (spinal procedure, propofol infusion, no variability in [unused] anesthetic gas use, minor variation in oxygen delivery/hour).

Table 2 and figure 3 indicate that electricity for the patient air warmer was responsible for at least 2.46 kg carbon dioxide equivalent (16%) emissions of all anesthesia approaches. Total single-use plastics, glass, and so forth were responsible for 3.5 (general anesthesia), 3.4 (spinal), and 4.3 (combination) kg carbon dioxide equivalent emissions, respectively (20 to 25% total, with the majority from single-use plastics). All pharmaceuticals beyond gases were responsible for 1.2 to 1.3 kg carbon dioxide equivalent emissions, 7 to 8% total for all three approaches. For general anesthesia, sevoflurane (global warming potential = 130 times carbon dioxide)[11] for 9/10 patients was the principal contributor; average 4.7 kg carbon dioxide equivalent emissions (32% total), range 2.7 to 8.6 kg carbon dioxide equivalent emissions. The patient who received total intravenous anesthesia represented the minimum 8.4 kg carbon dioxide equivalent emissions in the general anesthesia group. For the combination anesthesia group, sevoflurane contributed an average 3.1 kg carbon dioxide equivalent emissions (17% total), range 0.6 to 10.0 kg carbon dioxide equivalent

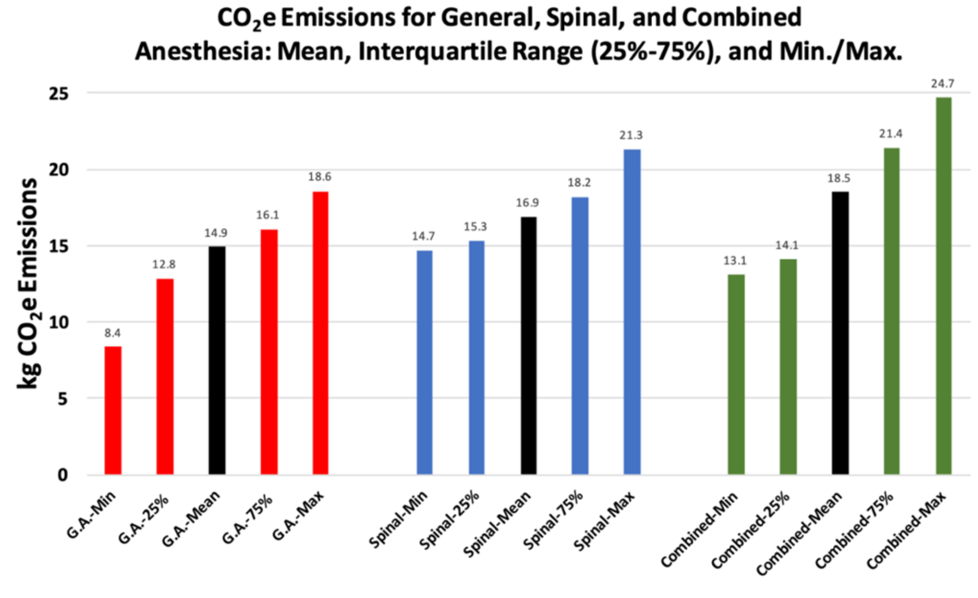

Fig. 2. Carbon dioxide equivalent emissions for general, spinal, and combined anesthesia: mean, interquartile range (25%–75%), and minimum/maximum.

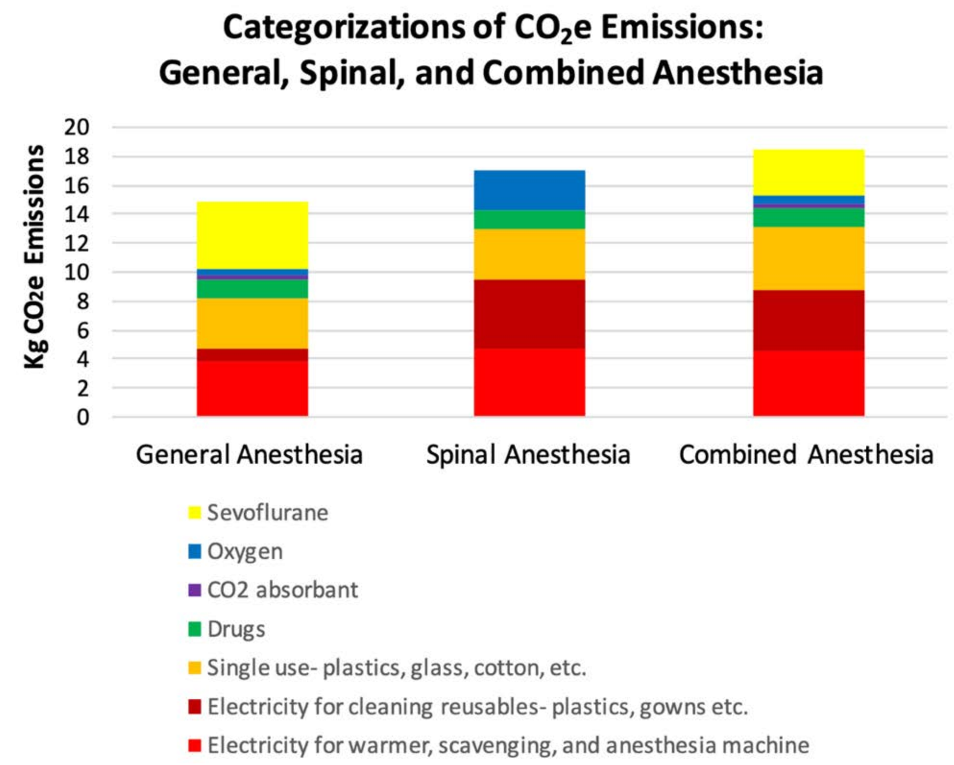

Fig. 3. Categorizations of carbon dioxide equivalent emissions: general, spinal, and combined anesthesia.

emissions. For spinal and combination anesthesia, washing and sterilizing reusable gowns, plastic spinal trays, and so forth contributed 4.5 kg carbon dioxide equivalent and 4.0 kg carbon dioxide equivalent emissions, respectively (coal was 75% of electricity for Melbourne, with 1.1 kg carbon dioxide equivalent emissions/kilowatt-hour).[23,34] Oxygen use was also important to carbon dioxide equivalent emissions for spinal anesthesia (2.8 kg carbon dioxide equivalent emissions, 16% total) as O_2 flow rates were 6 to 10 l/min, compared with 0.5 to 3 l/min for general and combination anesthesia approaches.

Environmental Impacts: International Comparisons

Figure 4 indicates the modeled results of our data with electricity sourced in three other countries/regions: China, the European Union, and the United States (source: Ecoinvent).[22] The carbon dioxide equivalent emissions per kilowatt-hour varies due to different energy sources. Australia and China have similar "carbon intensities" (carbon dioxide equivalent emissions per kilowatt-hour) due to their reliance on coal, while the European Union (and the United Kingdom) has large nuclear and hydro/wind/solar sources for electricity generation, and the United States is moving rapidly toward greater renewable electricity generation. Such modeling changed the carbon dioxide equivalent emissions for washing and sterilizing reusable equipment, and electricity for patient warming. We assumed that the carbon dioxide equivalent emissions due to the use of single-use equipment were identical between countries, *i.e.*, produced in China, as this is the major source for single-use items in Australia and anecdotally elsewhere.

From figure 4, as expected, the carbon dioxide equivalent emissions for all three anesthesia approaches for Australia and China are close. For the European Union and the United States, the carbon dioxide equivalent emissions for spinal anesthesia are decreased compared to Australia due to the greater predominance of renewable electricity used to clean reusable equipment/gowns. In the European Union, spinal anesthesia has a carbon footprint of approximately 60% (9.9/16.9 kg carbon dioxide equivalent emissions) that in Australia. Comparing the results of figure 2 (Australian data) with figure 4 (international modeling), the *minimum* carbon dioxide equivalent emissions for general anesthesia in Australia (total intravenous anesthesia) is less than the European Union general anesthesia *average* (8.4 *vs.* 11.9 kg carbon dioxide equivalent emissions), but the *minimum* for spinal anesthesia for Australia (14.7 kg carbon dioxide equivalent emissions) is considerably higher than the European Union *spinal average* (9.9 kg carbon dioxide equivalent emissions) due to high carbon intensity

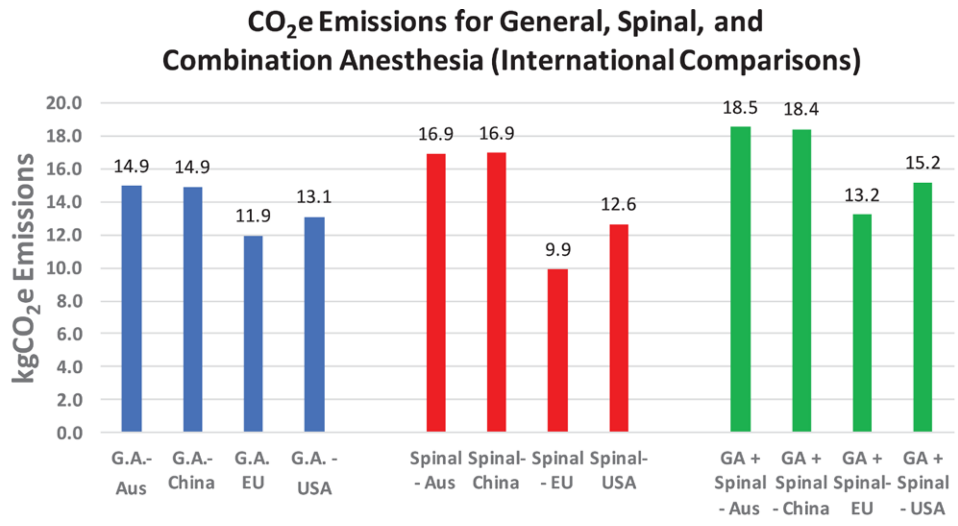

Fig. 4. Carbon dioxide equivalent emissions for general, spinal, and combination anesthesia (international comparisons).

Australian electricity required to clean reusable anesthesia equipment.

Discussion

The carbon footprints of anesthesia for a knee replacement were similar for general, spinal, and combination approaches, with significant overlap between the CIs. There was considerable *within-group* variation for general and combination anesthesia (a twofold difference in minimal-maximal carbon dioxide equivalent emissions), but only 50% difference for spinal anesthesia. The three major components of carbon dioxide equivalent emissions across all groups were (with approximations) single-use equipment (20 to 25%, mainly plastics), electricity for the patient air warmer (15%), and pharmaceuticals (8%). Carbon dioxide equivalent emissions from sevoflurane use for general anesthesia (32% total) and combination anesthesia (17% total) were considerable. Carbon dioxide equivalent emissions for cleaning reusable equipment were more than 25% total for spinal, and 20% for combined anesthesia. Oxygen use was about 15% of carbon dioxide equivalent emissions for spinal anesthesia. Importantly, the duration of anesthesia was 20% longer for spinal *versus* general anesthesia. Procedure duration contributes to carbon dioxide equivalent emissions, particularly electricity for the air warmer.

Inhalational anesthesia is known to have higher carbon dioxide equivalent emissions than total intravenous anesthesia.[35,36] For general anesthesia, the use of low flow (minimum 6 ml liquid sevoflurane/h) rather than total intravenous anesthesia increased the carbon dioxide equivalent emissions by 1.2 kg carbon dioxide equivalent emissions/h. There is, however, sparse evidence comparing the carbon footprint of general and spinal anesthesia.[13,37] Spinal anesthesia had a high carbon footprint, partially attributable to cleaning reusable equipment and compression of liquid oxygen, the carbon dioxide equivalent emissions for which were elevated due to the electricity mix of 75% brown coal for Melbourne, Australia. It is unclear internationally what standard oxygen administration is during spinal anesthesia, but flow rates of greater than 6 l/min may be atypical. For cleaning reusable equipment, we assumed worst case steam sterilizer efficiency,[25,27] recognizing that potential efficiency improvements[25,38] could reduce carbon dioxide equivalent emissions by 0.5 kg carbon dioxide equivalent emissions/h just for anesthesia alone. The modeled carbon dioxide equivalent emissions for cleaned reusables in Australia are similar to China, but double the United States, and quadruple Europe/United Kingdom, because of different energy mixes.[15]

Our small, single-center, prospective, nonrandomized, observational, unblinded study has limitations, which makes comparisons between the anesthetic groups and between countries uncertain. We did not prescribe anesthetic choice, and we limited our convenience sample to 30 patients having one operation type in Australia. We aimed to provide a life cycle assessment of three anesthetic approaches to a total knee replacement, but we caution comparison between the three groups. A prospective study powered appropriately would be a considerable undertaking and of limited benefit given the initial hypothesis posed by this study.

We acknowledge anesthetic practice variability, particularly choice of anesthetic gases with high global warming potential.[11] Use of desflurane and nitrous oxide in our small study could skew group results markedly (*e.g.*, greater than100 kg carbon dioxide equivalent emissions for either nitrous oxide or desflurane use).[13] We chose to exclude the one patient receiving nitrous oxide as the relative carbon dioxide equivalent emissions from using nitrous oxide compared with sevoflurane/total intravenous anesthesia/spinal anesthesia are very high, making intergroup comparison difficult.

Comparisons between the amount of equipment/drugs/gases are influenced by the duration of the operation. Many items have greater use in the first hour (induction, drug administration, spinal anesthesia) than for subsequent hours. Nevertheless, other environmental effects are more closely dependent upon duration (electricity for the air warmer and scavenging), carbon dioxide absorbent use, and oxygen use.

We excluded orthopedic surgery and all operating room heating/ventilation/air conditioning carbon dioxide equivalent emissions, focusing solely upon anesthesia. Anesthetic breathing circuits were changed weekly,[28,39] a practice common in Australia,[40] Germany,[41] and elsewhere. Reusable laryngoscope blades, handles, face masks, and surgical gowns were used.[15] We averaged the carbon dioxide equivalent emissions for all 20 drugs studied by Parvatker *et al.*,[31] using this average for unstudied drugs (cefazolin, paracetamol, and tranexamic acid).[31] Drugs given in relatively large quantities (cefazolin) dominated the pharmaceutical carbon dioxide equivalent emissions. Cardboard/paper was routinely separated preoperatively.

Avoiding the use of desflurane and nitrous oxide is only the beginning of actions that anesthetists can undertake to reduce their workplace carbon footprint. The fuel efficiency of the average U.S. car is 0.40 kg carbon dioxide equivalent emissions/mile, so in our study, the average anesthetic carbon contribution (17 kg carbon dioxide equivalent emissions) is like driving 42 miles (*without* desflurane or nitrous oxide). Several activities can safely reduce the anesthetist's carbon footprint. For spinal anesthesia, reducing O_2 flows from 10 l to 6 l/min reduces driving by 1 mile/h. For general anesthesia, reducing fresh gas flow with sevoflurane by 1 l/min saves 3 miles/h. Replacing 1 l/min fresh gas flow sevoflurane with total intravenous anesthesia saves another 3 miles/h. Using the minimum plastic and glass use will reduce the carbon dioxide equivalent emissions 1 kg carbon dioxide equivalent emissions/h, equaling saving 3 miles/h. Converting from Australia's electricity mix to Europe's for spinal procedures will save 2 kg carbon dioxide equivalent emissions, equaling 5 miles/h. When combining these mentioned carbon sparing activities, you have halved the miles driven for the 3-h anesthetic.

Decreasing the carbon footprint of some activities is challenging; a minimum of pharmaceuticals and equipment are required. Further, anesthesiologists cannot change the carbon intensity of electricity, although we can advocate.[13] The use of renewable energy decreases the carbon dioxide equivalent emissions associated with cleaning reusable equipment, with promising plans locally for Victorian electricity generation.[42] For the European Union/United Kingdom/U.S. anesthesiologist, moving from single-use to reusable anesthetic equipment right now will have financial and environmental benefits.[15] Our study quantifies carbon dioxide equivalent emissions of individual areas of anesthesia practice. We encourage cognizance of one's carbon footprint, emphasizing that instigating multiple, seemingly small changes in our workplace patterns is the best path to low carbon anesthesia.

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Competing Interests

The authors declare no competing interests.

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Appendix 1: Life Cycle Assessment Methods

For this appendix, we primarily draw upon past explanations about life cycle assessment generally,[43–45] and from several previous publications from our broader group.[4,13,17,18] Life cycle assessment is a scientific method to determine the entire "cradle to grave" environmental and financial effects of processes and products.[43,45] The Society for Environmental Toxicology and Chemistry (Pensacola, Florida) defined the components of a life cycle assessment in 1991: (1) raw material acquisition; (2) processing and manufacturing; (3) distribution and transportation; (4) use, reuse, and maintenance; (5) recycling; and (6) waste management.[1] Everything we use and do has an environmental footprint, whether this is for a tangible product or a service such as an admission to hospital. Life cycle assessments have a "system boundary," *i.e.*, a limit to which one examines the environmental effects of a product or process. This system boundary is defined by local Australian and international standards.[14,19] For example, if we are examining a plastic syringe, the system boundary could be defined to include the manufacture of the plastic and ongoing maintenance of installed infrastructure, but not the actual manufacture of such installed infrastructures which are in turn used to make the syringe.

Environmental factors beyond carbon dioxide equivalent emissions, including water consumption; petrochemical use; air, water, and terrestrial pollution; and release of toxic byproducts, can be accounted for in life cycle assessment. We have focused upon carbon dioxide equivalent emissions as they are an important focus due to the increasing health concerns of climate change. In the late 1990s, standardization of how life cycle assessments should be conducted was achieved when the International Organization for Standardization released the ISO-14000 series.[20]

Functional Unit

Using the ISO-14040 standards,[20] we defined our study's *functional unit* as all anesthesia for a total knee replacement in a public hospital in Victoria, Australia. The ISO-14040 standards[14] life cycle assessment *system boundary* defines inclusions/exclusions. We did not include data for heating/ventilation/air conditioning, or any surgical equipment.

Importantly, once one has details about the components making up a process/procedure, their masses/amounts, and their origins, then one can then undertake a life cycle assessment with the relevant software and application. For example, for a general anesthetic, we obtained quantified data about (1) electricity used for cleaning/sterilizing reusable equipment, the patient air warmer, scavenging, and the anesthetic machine; (2) plastics, steel, cotton, and so forth; (3) pharmaceuticals; and (4) volatile anesthetics and oxygen use. Data related to the source/origin of the electricity, plastics, and so forth were also important. With these input data, we then turned to quantifying the outputs with life cycle inventories. We obtained the power rating for the patient air warmer (0.8 kilowatt-hours/h) from online data for Model 775, Bair Hugger, USA.[21] Anesthetic machine electricity use (0.08 kilowatt-hours/h) was obtained from Chakladar,[20] and anesthetic scavenging (0.4 kilowatt-hours/h) from Barwise.[23]

Life Cycle Inventories

Life cycle assessments make use of life cycle inventories. A life cycle inventory is a catalog of flows to and from nature, with *inputs* such as energy, water, and raw materials, and *outputs* (releases) to air, land, and water. There can be a large number of inventory flows numbering in the hundreds to thousands, in such a way that the life cycle inventory of even a simple plastic syringe requires multiple flows of petrochemical resource extraction, manufacture, transport, and use. To examine all of these details *de novo* every time a life cycle assessment is undertaken would be prohibitively exhaustive and expensive. It is ideal to obtain as much *primary/foreground* data (*e.g.*, measurement of electricity use for a hospital sterilizer) as possible in order to reduce the uncertainty of the data. Nevertheless, multiple *secondary/background* sources of information are usually required for life cycle assessments (*e.g.*, details of plastic manufacture).

Large national and international databases are the routine sources for such secondary data, such as EcoInvent[46] and the Australian Life Cycle Inventory,[47] which incorporate geographically specific average industry data. For example, the estimated carbon dioxide emission from burning coal from a defined region is obtained from such environmental databases. Such average industry data can have greater associated uncertainty than directly measured (primary) data.[27,44] Care must then be taken to ensure that the secondary data indicate the local conditions of the life cycle assessment in question (*e.g.*, local coal-fired electricity versus hydroelectric electricity used for the secondary data).

A process diagram/tree (fig. A1.1) is developed from all of the inputs that make up an output. We have included the process diagram for spinal anesthesia as an example. One can see that electricity forms a large part of the total carbon dioxide equivalent emissions as indicated by the wide red lines associated with electricity, with oxygen also being important on the right-hand side of the process diagram. Note that in this diagram, in order to be able to visualize some of the complexity of life cycle assessment methods, we have included a "cutoff" of only items that contribute greater than 1% of the final carbon dioxide equivalent emissions to general anesthesia. In reality, we included all inputs (at least several hundred) that contributed to the final carbon dioxide equivalent emissions.

Statistical Analyses: The Pedigree Matrix and Uncertainty

The life cycle inventory thus has inputs (such as electricity from coal) that are combined to form an output (*e.g.*, a plastic syringe). Every input in every process from secondary databases has a degree of uncertainty associated with it. This uncertainty routinely cannot be derived directly from the available information, so a standard procedure was developed to derive uncertainty factors from a qualitative assessment of the data, known as the Pedigree Matrix.[27] The Pedigree Matrix is a commonly used qualitative scoring system derived from the secondary data's reliability, completeness, temporal and geographical proximity to the process or item being assessed, and further technological factors,[27,44] with a score from 1 (good) to 5 (poor) for each factor. The Pedigree Matrix relies upon expert judgment. For example, if the secondary data for carbon dioxide equivalent emissions per kilowatt-hour of electricity produced was obtained recently from all local coal fired power stations, this would have better reliability, completeness, and temporal and geographical proximity than secondary data from an overseas-derived database that sampled one coal-fired power station a decade ago. As the Pedigree Matrix is based upon expert opinion, it is open to a perception of irregularities. The Pedigree Matrix has been updated to

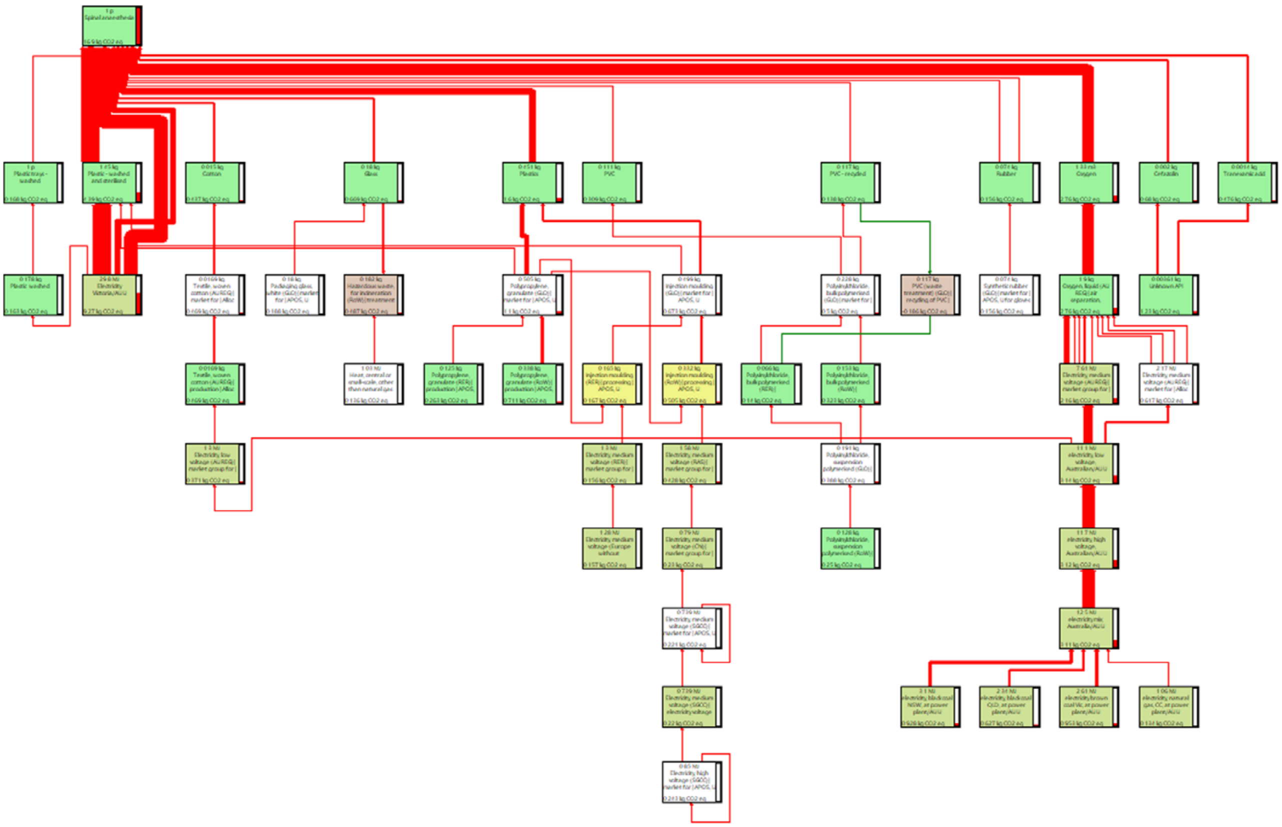

Figure A1.1. Process diagram for spinal anesthesia (as a sample).

incorporate some of these concerns with greater emphasis upon direct empirical values for each of the factors.[17,46]

There are also uncertainties associated with all life cycle assessment primary inputs that are directly measured. For example, the plastic syringes used by anesthesiologists in our study were transported from the Philippines to Australia. There is little uncertainty associated with the carbon dioxide emissions from such shipping as the distance traveled is known and the variability in fuel consumption of container ships is small. Similarly, the sterilization of the reusable plastic spinal trays in our study had little uncertainty as we had measured the sterilizer's electricity use more than 1,000 times[18] with different load types. If we had measured this sterilizer electricity use but once, the carbon dioxide equivalent emissions from such electricity use would have a greater associated uncertainty. As for secondary data from life cycle inventory databases, the Pedigree Matrix for primary input data is a qualitative scoring system.

To combine the values and frequency distributions of these hundreds of inputs to obtain outputs such as carbon dioxide equivalent emissions, we used Monte Carlo analyses (routine for life cycle assessment). Monte Carlo methods are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. Monte Carlo methods are useful when there are large numbers of inputs and where it is impractical to obtain data for each of these inputs *de novo*.[27,44]

When there is a range of possible values for a result, there are a number of approaches to how to determine the best estimate and the frequency distribution with CIs around this result. Monte Carlo methods take data points from within the frequency distributions for all inputs to develop a final output result, frequency distribution, and the plausible range, including the central tendency of the frequency distribution.[27] The greater the number of "runs" by Monte Carlo analysis, the better the estimate of the most likely value and the associated frequency distribution. A final 95% CI for a process is achieved based on the random sampling anywhere within the 95% CIs for all inputs. A Monte Carlo analysis includes at least 1,000 "runs" of random samples to reduce the chance of unusual results—that is, taking input data from the extremes of the 95% CIs. The 95% CI of the mean/average (or any other result) indicates what the variability of the results could be if the study was performed a large number of times. The 95% CI of the mean/average from Monte Carlo analysis may not be closely aligned with the directly obtained minima/maxima results. The 95% CI may lie within or beyond the minimum/maximum. This is

Appendix 2: Energy Required to Wash and Sterilize Reusable Equipment

	General Anesthesia		Spinal		General Anesthesia + Spinal	
Reusable Items	Mass, kg	Energy, Kilowatt-Hour/ Megajoule	Mass, kg	Energy, Kilowatt-Hour/ Megajoule	Mass, kg	Energy, Kilowatt-Hour/ Megajoule
Plastics washed* (drug trays)	0.18 kg	0.08 kilowatt-hours + 0.2 megajoules	0.18	0.08 kilowatt-hours + 0.2 megajoules	0.18	0.08 kilowatt-hours + 0.2 megajoules
Anesthetic circuits washed weekly†		0.1		0		0.1
Items washed* and sterilized‡ (laryngeal mask, spinal tray, cotton hand towel, polypropylene surgical gown). No sterilization of items required for general anesthesia (drug trays and circuits).	0.014 kg	< 0.1 kilowatt-hours + 0.2 megajoules	1.59	0.6 kilowatt-hours + 1.8 megajoules + 2.8 kilowatt-hours = 3.4 kilowatt-hours + 1.8 megajoules	1.36	0.6 kilowatt-hours + 1.8 megajoules + 2.2 kilowatt-hours = 2.8 kilowatt-hours + 1.8 megajoules
Silicone washed* (face mask)	0.08 kg	0.05 kilowatt-hours + 0.1 megajoules	0	0.05 kilowatt-hours + 0.1 megajoules	0.08	0.05 kilowatt-hours + 0.2 megajoules
Stainless steel washed* and sterilized‡ (laryngoscope blade)	0.09 kg	< 0.1 kilowatt-hours + 0.2 megajoules + 0.2 kilowatt-hours = 0.3 kilowatt-hours	0	0	0.01	< 0.1 kilowatt-hours + 0.2 megajoules

*Data for electricity (kilowatt-hour) for washing/drying obtained from previous study by McGain *et al.*[43] Washer and dryer electricity was 5.7 kilowatt-hours and hot water from gas boiler 18 megajoules for a full load of 80 trays. Energy was kept separate for kilowatt-hour electricity and megajoule gas due to the differing carbon dioxide equivalent emissions per unit of energy. †Anesthetic circuits were washed weekly (single-use filters for all patients). Since approximately 25 operations per week were undertaken and six complete circuits could be washed in one load, the energy use per circuit per operation is approximately 10.7/(6 × 2 5) = 0.1 kilowatt-hours (*i.e.*, kilowatt-hour + megajoule, but shown as kilowatt-hour only as it was a minor contributor to carbon dioxide equivalent emissions). ‡Data for electricity (kilowatt-hour) for sterilization obtained from previous study by McGain *et al.*[44] Sterilization electricity use = 1.9 kilowatt-hours/kg items sterilized (including standby energy and so forth) For example, plastics washed and sterilized (reusable laryngeal mask, spinal tray, polypropylene surgical gown = 1.45 kg) will be equivalent to approximately 10 trays in the washer, and then add 1.9 kilowatt-hours/kg for sterilization. Sterilization was purely electric.

Appendix 3: Pharmaceutical Masses Used per Patient

	General Anesthesia		Spinal Anesthesia		Combined General Anesthesia + Spinal	
Pharmaceuticals	Average (mg/case)	Range (mg/case)	Average (mg/case)	Range (mg/case)	Average (mg/case)	Range (g/case)
Alfentanil	0.3	0–1	0	0	0	0
Atracurium	15	0–50	0	0	0	0
Atropine	0.12	0–1.2	0	0	0.12	0–1.2
Bupivacaine (heavy)	0	0	40	0–50	30	0–50
Bupivacaine (light)	0	0	20	0–100	45	0–100
Cefazolin*	1,800	0–2,000	2,000	0	2,000	0
Clindamycin	60	0–600	0	0	0	0
Dexamethasone	2.4	0–4	0	0	0.8	0–4
Droperidol	1	0–2.5	0.25	0–2.5	1	0–2.5
Ephedrine	25	0	2.5	0–25	11.0	0–50
Fentanyl	0.2	0–0.5	0.1	0–0.2	0.1	0–0.2
Glycopyrrolate	0.2	0.2–0.4	0	0	0.1	0–0.6
Hydralazine	2	0–20	0	0	0	0
Lignocaine	20	0–50	55	50	50	50
Metaraminol	1	0–10	3.5	0–10	5	0–10
Midazolam	1	0–5	3.5	0–5	2	0–5
Morphine	5.5	0–10	0	0	2.2	0–10
Neostigmine	1.3	0–2.5	0	0	0.3	0–2.5
Ondansetron	1.2	0–4	0	0	0.4	0–4
Paracetamol*	200	0–1,000	200	0–1,000	100	0–1,000
Parecoxib	20	0–40	0	0	20	0–20
Propofol*	300	200–1,000	610	200–1,100	600	200–1,400
Rocuronium	10	0–50	0	0	5	0–50
Ropivacaine	55	0–400	0	0	0	0
Tramadol	70	0–200	0	0	0	0
Tranexamic acid*	1,500	0	1,400	1,000–1,500	1,500	0
Vecuronium	2	0–10	0	0	1	0–10

Once a pharmaceutical was opened, it was assumed entirely used for that patient, even if some/most was discarded rather than actually given to the patient. Average masses were calculated over all the cases for each of the three groups, so if 1,000 mg of drug was given to two patients in a group (*e.g.*, paracetamol), the average mass across 10 patients would be 200 mg.

*Cefazolin, paracetamol, propofol, and tranexamic acid formed the largest masses of pharmaceuticals given. This was important because the carbon dioxide equivalent emissions for drugs were weight-based. From the Parvatker *et al.*[31] study, the average gram carbon dioxide equivalent/gram drug across the 20 drugs was 340 g carbon dioxide equivalent/g drug. Since Parvatker *et al.*[31] had not studied cefazolin, paracetamol, and tranexamic acid, we used this average 340 g carbon dioxide equivalent/g drug to calculate the actual carbon dioxide equivalent emissions for each drug.

because the 95% CI is reflective of the mean only; it is not immediately relevant to the other directly obtained results such as the minimum/maximum (range).

Modeling and the Final Results

As noted in the Materials and Methods section, we used two life cycle inventories (Ecoinvent[46] and the Australian Life Cycle Inventory[47]) to obtain carbon dioxide equivalent emissions associated with devices and processes. For all processes involving local electricity consumption (kilowatt-hours), we have used the Australian inventory.[47] This is particularly relevant to electricity for patient warming, anesthetic scavenging, cleaning/sterilizing, liquid oxygen compression, and waste management. Importantly, Australian[47] carbon dioxide equivalent emissions per kilowatt-hour are considerably higher than the European average due to coal-fired electricity sources of electricity in Australia.[46] For all devices (*e.g.*, manufacture of plastic endotracheal tubes), we used the Ecoinvent[46] inventory to obtain the associated carbon dioxide equivalent emissions. Because most common products (*e.g.*, plastics, steel, cotton) are traded on the international market, their origin can be varied and multiple, and it can be difficult to trace the precise origins of their makeup. Ecoinvent thus uses a "rest of the world" approach, averaging the associated carbon dioxide equivalent emissions. For example, if we know the carbon dioxide equivalent emissions/kilogram plastic polypropylene manufacture for 30 countries, we use the average carbon dioxide equivalent emissions per kilogram for that process.

Data were modeled in SimaPro-9 LCA (life cycle assessment) software (PRé Consultants). We developed an inventory that quantified materials and energy used, and modeled this using the Ecoinvent[46] (version 3.5) and Australian Life Cycle Inventory[47] databases. We used the International Reference Life Cycle Data System 2016 (European Commission) impact assessment method to translate the inventory into environmental impact scores, along with Monte Carlo software algorithms (SimaPro) to obtain results and 95% CIs. We divided our data on environmental impacts by an average Australian person's total daily environmental effects in order to compare the environmental impacts with peoples' routine activities.[14] To ascertain a global perspective, we modeled our results (carbon dioxide equivalent emissions) with Ecoinvent electricity data[46] with those for identical anesthetics being provided in China, the European Union, and the United States. Note that the aforementioned rest of the world average approach across at least 30 countries means that the carbon dioxide equivalent emissions arising from other items such as plastics manufacture will not vary between countries. Only variations in the carbon intensity of electricity generation will lead to intercountry variability in carbon dioxide equivalent emissions.

It is routine to provide 95% CIs in life cycle assessment around the summated data, but atypical to do so for all further modeled data. For example, figure 4 gives the carbon dioxide equivalent emissions for different countries for general, spinal, and combination anesthesia. There are 12 bars in this figure, so any 95% CI analysis would be prolonged. There are reasons though why such effort would be quite superficial. By definition, the same items/processes are being used in Australia and China/Europe/the United States (*e.g.*, electricity for multiple processes, single-use plastics, pharmaceuticals). Only the carbon dioxide equivalent emissions per kilowatt-hour or kilogram plastic will vary. The uncertainty associated with the carbon dioxide equivalent emissions for each of these common items/processes is thus proportional. For example, if 1 kg of carbon dioxide equivalent emissions is produced by 1 kilowatt-hour of electricity in Australia, but only 0.5 kg of carbon dioxide equivalent emissions in the United States, the 95% CI is approximately (not precisely, but near enough) half that in the United States compared with Australia. If a process is highly uncertain in Australia, then it will be highly uncertain elsewhere, just relatively so (according to the associated carbon dioxide equivalent emissions). The same model is being used to determine the carbon dioxide equivalent emissions and the uncertainty.

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