BJA

British Journal of Anaesthesia, 125 (5): 680–692 (2020)

doi: 10.1016/j.bja.2020.06.055
Advance Access Publication Date: 12 August 2020
Review Article

CLINICAL PRACTICE

Environmental sustainability in anaesthesia and critical care

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Summary

The detrimental health effects of climate change continue to increase. Although health systems respond to this disease burden, healthcare itself pollutes the atmosphere, land, and waterways. We surveyed the ‘state of the art’ environmental sustainability research in anaesthesia and critical care, addressing why it matters, what is known, and ideas for future work. Focus is placed upon the atmospheric chemistry of the anaesthetic gases, recent work clarifying their relative global warming potentials, and progress in waste anaesthetic gas treatment. Life cycle assessment (LCA; i.e. ‘cradle to grave’ analysis) is introduced as the definitive method used to compare and contrast ecological footprints of products, processes, and systems. The number of LCAs within medicine has gone from rare to an established body of knowledge in the past decade that can inform doctors of the relative ecological merits of different techniques. LCAs with practical outcomes are explored, such as the carbon footprint of reusable *vs* single-use anaesthetic devices (e.g. drug trays, laryngoscope blades, and handles), and the carbon footprint of treating an ICU patient with septic shock. Avoid, reduce, reuse, recycle, and reprocess are then explored. Moving beyond routine clinical care, the vital influences that the source of energy (renewables *vs* fossil fuels) and energy efficiency have in healthcare’s ecological footprint are highlighted. Discussion of the integral roles of research translation, education, and advocacy in driving the perioperative and critical care environmental sustainability agenda completes this review.

Keywords: anaesthesia; anaesthetic gases; climate change; environment; intensive care; life cycle assessment; sustainability

Editor’s key points

- The scientific foundation for environmental sustainability in anaesthesia and critical care has progressed rapidly during the past decade, particularly with the incorporation of environmental life cycle assessments (LCAs).
- As a result of these new studies, anaesthetists and critical care physicians can make informed choices to reduce their environmental footprint.
- Translational research on recent environmental footprinting studies into routine anaesthetic/ICU practice is particularly required.

The climate crisis is the largest and most prolonged threat to global health ever described.[1] Owing to anthropogenic greenhouse gas (GHG) emissions, the temperature of the planet has been rapidly increasing since the Industrial Revolution.[2,3] The health implications associated with climate change are increasingly widespread.[1,4] The Intergovernmental Panel on Climate Change (IPCC) Special Report concluded we have less than 10 yr to *dramatically* reduce our GHG emissions to limit

Received: 16 March 2020; **Accepted:** 13 June 2020

global warming to an increase of 1.5°C and limit climate change-related public health disasters.[2] This call for flattening of the GHG curve is analogous to global efforts to slow the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) transmission to allow for a more manageable response.[5]

The Hippocratic oath to *First do no harm* guides physician practice, yet healthcare itself pollutes and harms public health.[6] If global healthcare were a country, it would be the fifth largest carbon emitter on the planet.[7] Sustainability is a guiding principle that 'meets the needs of the present generation without compromising the ability of future generations to meet their own needs,[8] and may reconcile this discrepancy. Sustainable healthcare requires balancing patient outcomes with economic, environmental, and social costs.[9] Practising more sustainability and protecting the environment is important to the overwhelming majority of UK healthcare staff.[10]

Much of the environmental emissions generated by healthcare are indirect, or embodied in upstream manufacturing of products and energy that support healthcare facilities.[7,11] In the infancy of the sustainability movement, efforts tended to focus on highly visible endeavours such as solid waste recycling efforts, and carbon emissions reductions. A broader view encompasses emissions to air, water, and soil, enables holistic environmentally preferable choices, and addresses efficient use of natural resources towards a circular economy.[1] Anaesthetists and critical care physicians are in positions of authority and responsibility to make valuable contributions in the transition to sustainable healthcare.

Climate change, chemistry, and anaesthesia

Although climate change was initially postulated by Fourier in the 1820s,[12] it was not until the 1970s that real concerns emerged of the dire consequences of increasing GHG emissions, with the majority of increases occurring after 1980.[13] Since the 1960s the effects of other increasing GHGs (mainly CH_4, N_2O, O_3, and halogenated compounds) have contributed as much to global warming as increasing CO_2 itself,[14] with halogenated compounds (including volatile anaesthetic agents) accounting for approximately 11%.[15] Nitrous oxide is responsible for the majority of ongoing ozone depletion,[16] and approximately 6% of anthropogenic global warming.[15] The term CO_2 equivalent (CO_2e) is used to indicate the global warming potency of GHGs relative to the reference unit of CO_2.

All heteronuclear gases (possessing more than one type of atom, e.g. CO_2, H_2O), and limited homonuclear molecules (e.g. ozone [O_3]) are infrared active, meaning they vibrate/rotate/stretch in the presence of infrared radiation.[17,18] Molecular absorption, and later emission, of infrared light leads to heat retention (reduction of heat radiation from earth to space), described by the term global warming potential (GWP). Carbon dioxide has, by definition, a GWP of 1, whereas N_2O for example has a GWP of 265.[13] The IPCC (the leading international scientific authority on climate change) uses the 100 yr time horizon GWP (GWP_{100}) as the standard comparison of long-lived GHG effects,[13] although shorter GWPs (e.g. 20 yr) can be suitable for the relatively ephemeral volatile anaesthetics.[19,20]

A gas's GWP depends upon two factors. Firstly, radiative efficiency, that is the change in solar energy irradiance (W m^{-2}) on the earth's atmosphere that occurs with a change in the concentration of a particular compound, is routinely given as parts per billion (i.e. W m^{-2} ppb^{-1}).[13] Radiative efficiency depends on the strength and position of the compound's infrared absorption bands. Secondly, GWP depends upon the gas' atmospheric lifetime, measured as the time constant, τ=time to 37% (1/*e*) initial concentration.[13] The halogenated anaesthetic ethers isoflurane, enflurane, and desflurane have similar radiative forcings, with sevoflurane about 25% less,[21,22] whereas the alkane halothane (lacking the intense infrared absorption of an ether group) has about half of sevoflurane's radiative forcing.[22]

The atmospheric lifetime of a molecule depends upon how rapidly it is broken down, particularly by the OH^- radical (the atmospheric 'detergent').[23] The bond strength of carbon–fluorine (C–F) is greater than that of C–H, C–Cl, and C–Br,[24] and so atmospheric OH^- radicals less easily displace F atoms. Thus, sevoflurane, isoflurane, and desflurane respectively have differing atmospheric lifetimes of 1, 3, and 14 yr.[25] Fluorinated desflurane has a longer lifetime than the closely related isoflurane (Cl^- substituted for F^-),[24] whereas the CF_2H moiety of desflurane and isoflurane is less reactive to OH^- radicals than sevoflurane's CH_2F.[21,26] OH^- radicals also react more readily with halocarbon molecules where the C atoms have themselves more C atoms attached to them; for example a tertiary C atom (bound to three other C atoms) is more reactive than secondary or primary C atoms.[26] Sevoflurane, $(CF_3)_2C^*HOCH_2F$, has a C atom (C*), attached directly to two C atoms and a third C atom via the ether group, making it more reactive to OH^- than desflurane or isoflurane.[26] These small differences between sevoflurane and desflurane explain why sevoflurane's lifetime is less than 10% than that of desflurane.[21]

The GWPs of halothane, isoflurane, enflurane, and sevoflurane were quantified by Brown and colleagues.[22] Langbein and colleagues[26] studied these gases and desflurane, with further work by Ryan and Nielsen.[20] Sulbaek Andersen and colleagues[21] provide the most recent and comprehensive examination of anaesthetic gases' GWPs (which we use here). Importantly, volatile anaesthetic GWP variability is primarily caused by differences in atmospheric *longevity* rather than radiative forcing. The GWP_{100} of desflurane is 2540[21] (1 g desflurane has the same GWP as 2540 g CO_2), sevoflurane 130,[21,25] isoflurane 510,[25] and N_2O approximately 265.[13] The potent analgesic methoxyflurane ($CH_3OCF_2CHCl_2$) has multiple C–H bonds and a resultant atmospheric lifetime of 54 days, with a GWP of only 4.[27] The GWP of nitrous oxide has been revised down from 300 to 265 in the 2013 IPCC report, because of improved quantification, particularly the effects of increasing CO_2 levels upon the CO_2–N_2O infrared absorption spectra.[13] Per mass, desflurane has a GWP approximately 20 times that of sevoflurane, five times that of isoflurane, and 10 times that of N_2O. Notably, desflurane also has about one-third of the potency of sevoflurane.

Measured atmospheric concentrations of volatile anaesthetics were first published in 2016 by Vollmer and colleagues,[28] demonstrating that desflurane pollution was increasing, sevoflurane's static, with halothane and isoflurane's decreasing. Desflurane contributed 80% of the estimated greenhouse effect from all measured volatile anaesthetic pollution (3×10^6 tonnes CO_2e emissions per annum [p.a.]).[28] Nitrous oxide was excluded, because anaesthetic/non-anaesthetic sources of atmospheric N_2O were indistinguishable.[28] These data were in approximate agreement with those of Sulbaek Andersen and colleagues,[19] who estimated 4.4×10^6 tonnes CO_2e emissions p.a. from volatile anaesthetics (not N_2O) via a 'bottom up' extrapolation from one US institution that did not use desflurane. A similar estimation of 5×10^6 tonnes of CO_2e emissions p.a. from global volatile anaesthetic gas use was made by White and Shelton[29] from online market sources (excluding N_2O).[30] As a proportion of total anthropogenic CO_2e emissions, volatile anaesthetics used in human healthcare may be responsible for 0.1% of global warming, equivalent to 1 million US cars on the road.[25,31]

Worldwide anaesthetic N_2O use is estimated to contribute between 1%[32] and 3%[33] of N_2O's global emissions.[15] The UK's NHS estimated that 5% of the *total* carbon footprint of an acute NHS organisation was attributable to anaesthetic gases, particularly N_2O.[34] A considerable, although unknown, amount of N_2O is used in healthcare activities outside the operating suite in undefined air ventilation conditions.[35]

The earth's ozone layer protects life from harmful UV rays. The 1987 Montreal Protocol[36] aimed to phase out anthropogenic ozone depleting substances such as chlorofluorocarbons (CFCs), and has been highly successful, in stark contrast to the 2016 Paris Agreement on climate change.[37] Atmospheric Cl, and particularly Br atoms, form ozone depleting radicals, so halothane has an ozone-depleting potential (ODP), although its use is declining globally. Fluorine does not destroy O_3; thus, sevoflurane and desflurane have no ODP.[38] Nitrous oxide is also ozone depleting.[16] Because the Montreal Protocol successfully limited release of CFCs, anthropogenic N_2O generation is at present responsible for most ongoing ozone depletion.[16] The global contribution of anaesthetic N_2O use should not be ignored.[39] Limiting N_2O emissions would be beneficial for both ozone protection and climate change mitigation.

Relevance to the individual anaesthetist

The CO_2e emissions from a single anaesthetist's daily routine use of inhalation agents can be large.[40–42] When expressing these CO_2e emissions as equivalent distance driven, it is unfortunately easy to 'drive more than 1000 km per day', even using low flow (1 L min^{-1}) desflurane and N_2O.[41,43] Such 'miles driven' has even prompted calls to 'abandon inhalation anaesthesia' in editorials.[29] One MAC-hour (2.2% sevoflurane, 1.2% isoflurane, 6.6% desflurane, at 1 L min^{-1} fresh gas flow [FGF]) with sevoflurane is equivalent to driving 4 mi (6.5 km),[40] isoflurane 8 mi (13 km),[40] and desflurane 190 mi (300 km).[40,43] Alternatively, combining 0.6 MAC N_2O for the hour results in an additional 60 mi (100 km)[44] beyond the 0.4 MAC 2 mi (3 km) of sevoflurane.[40] The GHG effect of N_2O and desflurane are similar per MAC-hour (60% FiN_2O=0.6 MAC).[43]

The most important, safe, and effective measures that anaesthetists can take individually to reduce their carbon are to: (1) avoid desflurane and N_2O, (2) practice low-flow anaesthesia, and (3) embrace techniques to minimise the requirement for inhalation agents, such as regional and total intravenous anaesthesia (TIVA). These techniques are encouraged by the ASA Task Force on the Environment, when clinically appropriate.[45] Free teaching tools for estimating one's personal anaesthetic 'carbon footprint' include Yale Gassing Greener[46] and the Association of Anaesthetists Anaesthetic Gases Calculator.[47]

Waste anaesthetic gas scavenging, destruction, and recycling

Waste anaesthetic gases (WAGs) are vented to the outdoor atmosphere, virtually unmetabolised, and unregulated. Minimum flow anaesthesia (<1 L min^{-1} FGF) is a safe, efficient, simple, and reliable means to reduce WAGs.[48–50] Concern about theoretical compound A-induced nephrotoxicity in humans from low flow sevoflurane has driven vast amounts of waste globally,[42,51] despite safety evidence 20 yr ago,[52] and newer non-compound A producing CO_2 absorbers.[51] Lower FGFs reduce CO_2 absorbents' lifetimes, although the overall financial cost of the anaesthetic is still reduced[53,54] and can be further minimised by changing absorbers only when indicated by the capnographic appearance of inspired CO_2.

Venting to the atmosphere can be mitigated via WAG capture and destruction technologies, some of which are commercially available already.[55–59] Recaptured volatile drugs may be adsorbed, and then either subsequently destroyed or desorbed, separated, and stored for potential reuse. N_2O is relatively inexpensive and difficult to capture; however, its destruction could dramatically reduce its harmful GWP and ODP effects, and is already routinely performed in Sweden.[60]

Activated charcoal contains a porous, favourable adsorption surface, and is used by veterinarians and dentists to capture volatile anaesthetics (not N_2O) in lieu of expensive scavenging systems, to reduce occupational exposure.[55] Activated charcoal can also be used to enable limited rebreathing of volatile anaesthetic gases.[56] Adsorbed volatiles (as the patient breathes out) are desorbed readily (as the patient breathes in), enabling the rebreathing of the volatile; however, efficiency is lost at higher flows. This system is primarily used in critical care where liquid volatile agents are delivered directly into the respiratory circuit; however, use is limited because of occupational exposure concerns. Volatile anaesthetics quickly desorb and emit to the atmosphere upon charcoal device disposal, and so this technology has short-term benefit only.[40]

Metal organic frameworks (MOFs) are solid crystalline compounds in which metal ions (e.g. Zn^{2+}) are linked by bridging organic molecules to create open networks that are able to accommodate guest molecules within pores.[57] MOFs are alternatives to charcoal for capturing volatile anaesthetics, with the advantage of precise control of pore size. Commercially available aluminosilicates (zeolite) can also adsorb volatile anaesthetics, including xenon.[58,59,61] Volatile aluminosilicates can be desorbed and condensed, and then either re-purified or destroyed.[58] Another adsorption/condensation system in development uses supercritical CO_2 before passing reclaimed drug through a purification process for potential reuse.[62]

Some WAG capture units have separate components that condense volatile anaesthetics[63] and destroy N_2O with a heated catalyst. Nitrous oxide from maternity wards of Sweden is routinely destroyed using rooftop installations.[60] It is possible to destroy both volatile gases and N_2O with a simple scavenging circuit UV lamp, although the efficiency of removing UV-resistant N_2O is much less (<10% N_2O destroyed).[64] Membrane technologies that filter through CO_2, O_2 and N_2 into the scavenging interface, whilst preventing the larger volatile anaesthetics from escaping into the scavenging stream, are also being actively examined.[65]

Anaesthesia scavenging interfaces continuously entrain large air volumes, diluting the WAGs and reducing suitability for effective volatile 'cold trap' condensation.[66] A commercially available dynamic scavenging interface has an on-demand, one-way valve that dramatically reduces air entrainment, and therefore WAG dilution, and may significantly reduce scavenging system energy requirements and costs.[67]

Notably, *only* scavenged WAG is treated. Furthermore, higher FGFs reduce WAG capture and treatment efficiency because of dilution.[66] Industry claims of WAG capture efficiency therefore require validation. Importantly, reclaimed drug is not yet approved for re-use, resulting in either a storage problem until such approval, or potential worsening of emissions depending on waste management procedure. Nevertheless, such technologies are promising, and could considerably reduce GHG emissions.

Life cycle assessments

Life cycle assessment (LCA) is a scientific method for analysing the 'cradle to grave' environmental 'footprint' associated with natural resource extraction, manufacturing, packaging, transport, use/reuse, and recycling/waste disposal of products or processes.[68,69] There are four phases integral to proper LCA methodology as described by the International Organization for Standardization (ISO), ISO-14000 series of standards.[70] First, is describing the goal and scope of the LCA. A *functional unit* refers to the object/process of interest. For example if one opens an entire anaesthetic drug tray pack (with cotton gauze, paper, and a plastic tray) even if using only the plastic tray, the functional unit is the entire pack and thus all component materials are accounted for.[71] A *system boundary* is how one defines the scope of an LCA. So, for the boundary of laryngeal mask manufacture we include the energy required to make the laryngeal mask airways (LMAs), but not the manufacture of the machines making the LMAs.[72]

Second, life cycle inventories (LCIs) refer to cataloguing of materials and their associated environmental emissions. LCIs are used to understand how much those materials contribute to environmental emissions and where in the life cycle of a particular product or process those emissions occur. CO_2e emissions are the most commonly reported environmental impact category; however, other categories exist including energy use, air, water, and soil pollutants, and ozone depletion, amongst others.

Third, life cycle impact assessment comparisons between items or systems of interest may indicate relative advantages for one outcome (e.g. CO_2e emissions), and disadvantages elsewhere (e.g. water and terrestrial pollution). Fourth, interpreting results is essential for decision-makers. Importantly, there may be large geographic variations in the CO_2 intensity of electricity generation (g CO_2e/kW h generated). For example, electricity produced in Europe[73] and the USA (renewables, nuclear, some coal and gas) is significantly less than that produced in China and Australia (coal dominated).[74] Thus, LCAs may be region-specific. Furthermore, results can change over time as both assessment methods and production practices change over time.

There are several types of LCAs, of which two are particularly relevant to healthcare: *process-based LCAs* and Environmentally Extended *Economic Input–Output (EEIO) LCAs*. *Process-based LCAs* arrive at an environmental cost for an item or activity based upon directly measured material inputs and using LCI databases that report emissions associated with those materials. For example, recent process-based healthcare analyses of blood pressure cuffs,[75] and pathology tests[76] measured the weights, compositions, and actual use of such items in detail. Process-based LCAs tend to focus on a small, targeted, easily defined product or process and are excellent for making comparisons (e.g. reusable *vs* disposable equipment).

In contrast, EEIO LCAs are most appropriate when dealing with very large data sets, where it is not feasible to perform a process-based LCA (i.e. difficult to physically measure a system's material and energy inputs). EEIO LCAs rely upon nationally reported economic input–output tables (e.g. via the Bureau of Economic Analysis, in the USA) and pollution emissions tables (e.g. via the US Environmental Protection Agency).[77] EEIOs attribute life cycle environmental emissions embedded in monetary value based on flows between economic sectors – that is they rely on an environmental footprint assigned to a monetary value spent. For example, a country may report its annual gross domestic product and carbon emissions arising from different economic sectors. This allows approximation of the CO_2e emissions per monetary value spent (e.g. kg CO_2e per \$/£/€) for different economic sectors (e.g. pharmaceuticals). Approximations of entire healthcare systems' CO_2e emissions are thus possible.

Health sector life cycle assessments

Several EEIO LCAs have been performed to estimate national-level healthcare sector environmental emissions. The UK Sustainable Development Unit (SDU) found that healthcare accounts for approximately 6% of England's entire CO_2e emissions.[9] The US healthcare system contributes nearly 10% of the total US CO_2e emissions,[77] equivalent to the CO_2e emissions for the *entire UK*.[77] Australian healthcare's CO_2e emissions (7% national total),[78] and Canada's (4% total),[79] have also been quantified. In 2019, two studies calculated that approximately 4.4–4.6% of global anthropogenic CO_2e emissions were attributable to healthcare's activities,[7,11] excluding WAGs.

Importantly, the majority of healthcare's CO_2e emissions (the *carbon hotspots*) are attributable to the procurement supply chain (everything from the purchase and discard of a plastic syringe to a new MRI scanner).[9] Further disaggregation of a national healthcare's CO_2e emissions are most developed for the UK.[9] Medical equipment and pharmaceuticals are large CO_2e contributors at 13% and 12% of NHS England's total CO_2e emissions, respectively, whereas purchased electricity, gas, and direct energy use account for approximately 16%, patient (ambulance) and visitor travel 7%, and staff commuting 4%.[9]

Life cycle assessments in anaesthesia and critical care

Dettenkofer and colleagues[80] published the first LCAs relevant to surgery 20 yr ago, highlighting the intrinsic tension between infection prevention and environmental care.[81,82] Much of the LCA work in anaesthesia and critical care has since focused upon comparisons between reusable and single-use equipment[72,75,83,84] with a few studies detailing emissions produced via differing surgical approaches,[85] pharmaceuticals,[86,87] and perioperative services.[88]

CO_2e emissions associated with energy use vary considerably internationally based on the predominant energy source, for example Australia and China (coal), Europe (renewables and nuclear),[73] and the USA (mixed).[83] Whereas CO_2e emissions of disposables depend largely upon the electricity source of manufacturing large quantities of consumables, emissions from equivalent uses of reusables largely stem from undergoing repeated cleaning. The ecological footprint of reusable medical devices depends on: the number of reuses, type of cleaning (low level or high level disinfection), sterilisation (steam or ethylene oxide),[89] and waste disposal management.

Comparisons of reusable *vs* single-use critical care drug trays,[71] and central venous catheter insertion kits,[89] showed that reusable equipment had the same or higher carbon footprints (in Australia). In contrast, a US study found that the carbon footprint of reusable LMAs was two-thirds that of the single-use version,[72] and the reusable rigid laryngoscope handles and blades were approximately 20 and 7 times less, respectively.[84] Similarly, a 2020 study of reusable and disposable blood pressure cuffs found that reusable cuffs were environmentally preferable to disposables, in some clinical settings by a factor of 40.[75] A review of five studies from several countries comparing reusable *vs* single-use surgical linens concluded that using reusables produced 50% less carbon emissions than using single-use alternatives, even in Australia,[90] because of economies of scale (washing and sterilising using large machines).

Reusable items often save money when compared with single-use equipment.[72,75,84] An Australian LCA comparing reusable and single use anaesthesia devices such as face masks, rigid and videolaryngoscope handles and blades, and breathing circuits[91] found that reusable equipment saved approximately AUD$5000 per operating room (OR) p.a.; however, the carbon footprint was higher (about 100 kg CO_2e emissions per OR p.a.,[91] equivalent to 800 km yr^{-1} driven in an average UK car).[92] If the reusables had been washed and sterilised in Europe, the carbon footprint of reusable anaesthetic equipment would have been less by 800 kg CO_2e emissions per OR p.a.[91] (i.e. 6400 km yr^{-1} *less* driven)[92] because of different energy sources.[91] Anaesthesia breathing circuits can be used for variable periods of time in different countries, from individual patient use in the USA[93] to unclarified in Australia and New Zealand,[94] and weekly in Germany.[95] Two studies have indicated that it is as safe from a microbiological standpoint to reuse circuits, and to change and wash them weekly compared with daily.[96,97] Several studies in the USA, including laryngoscope handles and blades,[84] LMAs,[72] and blood pressure cuffs[75] found significant cost and environmental savings from reusable devices compared with disposables.

A 2015 LCA study compared abdominal, vaginal, laparoscopic, and robotic approaches to hysterectomy, including inhaled anaesthetics and propofol. The total carbon footprint of such hysterectomies varied from approximately <10−300 kg CO_2e emissions (i.e. equivalent to thousands of kilometres driven per operation), in large part attributable to whether the anaesthetic was inhaled *vs* intravenous.[92] Inhaled anaesthetic drug CO_2e emissions comprised approximately two-thirds of the total case CO_2e emissions for the open approaches (abdominal and vaginal-assisted) *vs* one-third for laparoscopic and robotic surgery.[85]

life cycle assessments of active pharmaceutical ingredients (APIs) are challenging, as they require either access to confidential manufacturing practices or reverse engineering from first principals using published patents, because commercial disclosure of pharmaceutical CO_2e emissions does not yet occur.[86,98] A first principles approach study by Sherman and colleagues[99] found that when accounting for the entire life cycle (natural resource extraction, manufacturing, transportation, usage, and disposal), the GWPs of inhaled anaesthetics are four orders-of-magnitude greater than a minimum alveolar concentration-equivalent quantity of propofol (even accounting for plastic syringes and tubing and drug pump electricity). From the climate change perspective, TIVA is preferable to inhaled anaesthetics (especially desflurane and N_2O).[99] Parvatker and colleagues[87] further estimated CO_2e emissions for the API of 20 common anaesthetic/critical care drugs, finding an average 340 g CO_2e/g API. McAlister and colleagues[86] directly observed industrial practices, estimating 2 g CO_2e emissions/mg morphine. Almost 90% of morphine's CO_2e emissions occurred from steam sterilisation and drug packaging, rather than the morphine API itself (0.2 g CO_2e/mg morphine). Although there are limitations to the scaling up approach,[23] at least for morphine's associated CO_2e emissions, there appears to be reasonable agreement with the direct study by McAlister and colleagues.[86]

A study comparing the ORs of one hospital each in Canada, USA, and UK found that anaesthesia could have greater CO_2e emissions than all surgical equipment and OR-associated energy including from heating, ventilation, and air conditioning (HVAC) combined, if desflurane were used; if not (UK hospital), then 84% CO_2e emissions arose from the HVAC, 12% from the surgical equipment, and only 4% from anaesthetic gases (sevoflurane).[88] None of these three hospitals used N_2O. This study by MacNeill and colleagues[88] complemented that of Sulbaek Andersen and colleagues,[25] which showed desflurane's high GWP,[21] and that of Sherman and colleagues,[99] which compared CO_2e from clinically relevant quantities of volatile anaesthetics with propofol TIVA. Ceasing desflurane and N_2O use would have the greatest effect in reducing the OR's carbon footprint, whilst energy efficiency efforts addressing the HVAC system and steam sterilisers would also be beneficial.[88]

Pollard and colleagues[100] performed an LCA in the critical care setting, finding that an English ICU's average electricity use for direct patient care and lighting was 15 kW h $patient^{-1}$ day^{-1}, similar to that of an average Australian four-person household. However, Pollard and colleagues[100] excluded energy for HVAC, consumables, drugs, and laboratory testing. A 2018 study examined the carbon footprint of treating ICU patients with septic shock in Australia and the USA, including HVAC, drugs, and testing using a hybrid LCA approach.[101] As the CO_2e emissions for tests and drugs were unavailable at the time (excluding morphine),[86] only financial (EEIO) LCA accounting was possible for these elements. The CO_2e emissions in both the USA (178 kg CO_2e $patient^{-1}$ day^{-1}=1425 km driven) and Australia (88 kg CO_2e $patient^{-1}$ day^{-1}=704 km driven), were dominated by energy use for HVAC (at least 75% of the total), with all plastics, nutrition, laundering, daily chest X-ray (CXR),[102] ventilators, and other ICU machines contributing only minor emissions. The USA's ICU had approximately double the CO_2e emissions of the Australian ICU, attributable primarily to differences in geographical climate, with more extreme temperature variations resulting in greater HVAC energy requirements. Interestingly, there was only minor variation in patient carbon footprints according to the intensity of care (respiratory ventilation, renal support, etc.). Changing the energy sources from coal and natural gas to renewables could have the greatest effect in mitigating the ICU's carbon footprint.[101]

Beyond carbon emissions

CO_2e is the most commonly reported emissions category in healthcare LCAs. As noted, there are other standard categories of pollution to air, land, and water, and including ecotoxicity, and carcinogenic and non-carcinogenic human health impacts. In the LCA finding that inhaled anaesthetic drugs were substantially less favourable than intravenous propofol from a GHG perspective,[99] the authors assumed that propofol waste was incinerated as recommended by manufacturers and health departments. Drug waste entering waterways and plastics entering landfill are also notable concerns. Approximately 50% of propofol in an operating suite can go unused.[103] Incorrect drug disposal can contribute to water contamination and toxicity.[103,104] Improper discarding of unused propofol to the environment may have other deleterious effects upon aquatic and terrestrial ecosystems as the drug has high persistence, bioaccumulation, and toxicity.[103,105] As multiple pollution categories exist, decision-makers must rank their import, and 'pick your poison'.[106] As climate change is an existential risk to civilisation, it is ranked as the highest LCA impact category of medium- and long-term concern.[107]

Waste prevention: avoid, reduce, reuse, recycle, reprocess

Operating suites produce a quarter of all hospital waste[108] (up to 25% of that from anaesthesia).[109] Critical care units are also resource intensive.[110] Waste generation seems like an inevitable outcome of treating patients. By following the waste hierarchy[111] (reduce, reuse, recycle) and adopting waste prevention programmes such as Choosing Wisely – an initiative that seeks to maintain/improve clinical care, whilst promoting rational resource use,[112] such as reducing unnecessary investigations and medications – can significantly reduce the environmental footprint of healthcare.[113] The same principles apply to avoiding medically ineffective operations and critical care admissions, or routinely opening consumables in case of an emergency. Several LCAs[77,78,98] have identified the substantial scale of pharmaceutical and medical device contributions to healthcare CO_2e emissions, and wasted unused supplies present opportunities for pollution prevention.[114] Stock volumes could be better managed to reduce wastage,[11] whereas unused supplies may be thoughtfully donated.[115] Anaesthetists and intensivists can participate in hospital product evaluation committees and introduce LCA considerations into the procurement process, encouraging manufacturers and suppliers to provide more environmentally friendly products.[6,116]

Simple measures to reduce waste by reusing are available. Reusable equipment (metalware instruments most obviously, but also basins, gowns and drapes) remain in many areas. A broader return to reusable surgical gowns, laundered hats, and dedicated theatre footwear (removing the need for single-use overshoes) will reduce the amount of single-use clothing whilst maintaining infection control standards. As noted previously, the net environmental effect of reusable *vs* single-use equipment is a complex calculation, and the carbon footprint importantly depends upon the local energy source (coal/natural gas/nuclear/renewables) and efficient equipment usage.[83] Switching to a less carbon intense energy source is also a favourable solution, with health co-benefits from reduced air pollution.

If avoiding, reducing, and reusing are impossible, then recycling should be considered.[111] Approximately one-quarter of OR[117] and 15% of critical care[118] waste can be recycled. Recycling 11 tonnes of plastics, paper, etc. from a six-theatre operating suite produced approximately 15 tonnes less CO_2e emissions p.a.[117] (120 000 km driven)[92] than the manufacture of new plastics. Recycling 1 ton of mixed plastics is equivalent to saving 16.3 barrels of oil, 30 cubic yards of landfill and 5774 kW h of energy (enough to power an average US household for 6 months).[119] Recycling of cardboard/paper and several plastic streams is not novel, but recycling of medical polyvinyl chloride (PVC) (intravenous fluid bags and oxygen masks/tubing) is less common.[120] Metals are also increasingly recycled; in 2020 'les petits doudous' (cuddly toys) recycled 9376 kg of metals including copper (electro surgical wires), stainless steel (disposable laryngoscope blades and surgical tools), and aluminium (volatile anaesthetic cans and suture thread envelopes).[121]

Clinical recycling may reduce standard solid waste disposal costs by half.[117,122] Owing to differences in the composition of critical care to OR waste,[118] and changing international markets,[123] recycling can either cost or save money.

Medical device reprocessing, or 'remanufacturing', refers to cleaning and packaging of *single-use* equipment for reuse[124] and may save money and emissions.[125] Examples of reprocessed devices include surgical staplers, blood pressure and calf compressor cuffs, and cardiological catheters.[124] This is a multibillion dollar industry in the USA[124] and now occurs in many countries – 28% of hospitals in Canada,[126] 40% in Germany, 80% in Spain and 80–90% in Japan.[127] In other countries, for example Australia and France, reprocessing is not yet approved, although regulatory changes are under consideration in the UK.

Energy and infrastructure

Energy is the basis of much of our work's carbon footprint. Research on healthcare architecture and infrastructure is at a much more mature stage than how clinicians deliver healthcare.[128,129] Through sustainable healthcare architectural design, construction, and operations, environmental emissions can be reduced,[128] while patient well-being and staff satisfaction are improved. Quiet surroundings, natural lighting, and views or contact with nature improve patient recovery.[130] The costs of constructing a more ecologically friendly indoor healthcare environment may also be offset by happier, healthier staff.[128] Infrastructure planning should recognise the interdependence of economic, social, and environmental benefits.[128,130] Workplace efficiency reduces waste, energy, and costs; hence new and existing facilities could be designed or retrofitted to reduce wastage of natural resources.

Collaboration between hospital engineers and anaesthetists/intensivists could assist in improving OR/critical care engineering efficiencies and innovation.[131,132] Evidence to support why OR and critical care HVAC settings exchange room air 20 and 6 times per hour, respectively, is lacking. Unoccupied ORs need not undergo 20 air changes h^{-1};

Table 1 Research base for the environmental impact of anaesthesia and intensive care. GWP, global warming potential; HVAC, heating, ventilation, and air conditioning; LCA, life cycle assessment; LMA, laryngeal mask airway; TIVA, total intravenous anaesthesia.

Anaesthetic activity	Evidence and uncertainties
Gases Avoid, where possible, the use of anaesthetic gases with high GWP and minimise amount used of all anaesthetic gases.	*Known:* Avoid the use of desflurane and nitrous oxide.[99] The GWPs of anaesthetic gases are well researched. Encourage low flow and automated end tidal control anaesthesia.[49] *Uncertain:* What is the worldwide use of anaesthetic gases/TIVA and how is this evolving? Waste anaesthetic gas reclamation research is emerging, though currently rare clinically.[40] What are the environmental effects of medical use of O_2/air?
TIVA	*Known:* TIVA (propofol) itself has approximately 1% the GWP of even sevoflurane volatile anaesthesia.[87,99] *Uncertain:* TIVA's other environmental effects. Quantification of water contamination from anaesthetic pharmaceuticals. Balancing TIVA's plastic waste, etc. with the GWPs of volatiles.
Regional anaesthesia	*Uncertain:* What is the environmental footprint of regional anaesthesia? Are there trade-offs between the carbon footprint and other environmental effects?
Intensive care	*Known:* The carbon footprint of machines for treating[100] ICU patients and the overall ICU footprint.[101] ICU engineering HVAC formed the majority of the carbon footprint. Methods to reduce the use of excessive gowning for routine patient care whilst avoiding cross-contamination. *Uncertain:* How to safely reduce the carbon footprint of ICU engineering energy use.
Plastic syringes Avoid excessive use	Draw up the minimum practicable number of syringes. Leave emergency drugs/equipment unopened, but immediately available.[116]
Theatre attire Avoid disposables	Use washable, theatre-only hats and shoes.[165]
Energy consumption Turn off anaesthetic machine and scavenging use out of hours	Turn off the anaesthetic machine, scavenging and suction at the day's end. *Known:* Heating, ventilation and air conditioning make up a large proportion of OR carbon emissions so 'set back' out of hours[35,99]
Anaesthetic breathing circuits	*Known*: Evidence from two studies[96,97] that weekly circuit changes are as safe as daily changes. *Uncertain*: Unclear how widespread knowledge/translation of such knowledge is.
Surgical gowns	*Known:* Review of five LCAs comparing reusable to single-use showed reusable surgical gowns consistently have a lower environmental footprint (energy, water, waste).[90]
Anaesthetic drug trays	*Known:* One LCA of anaesthetic drug trays[71] showed reusable trays have lower financial and environmental footprints.
LMAs	*Known:* One LCA of reusable and single-use LMAs[72] showed reusables have a lower environmental footprint than single-use.
Face masks, circuits and laryngoscope blades.	*Known:* Using reusable anaesthetic equipment estimated to save AUD$5000/OR/annum[91]; however, in Australia, using reusable equipment can have a slightly higher carbon footprint than single-use. Conversely in Europe/UK/USA the carbon footprint is much lower for reusable equipment (more renewable electricity). Reusable laryngoscopes are less expensive and have a lower environmental footprint than single-use laryngoscopes.[84]
Reusable anaesthetic equipment can require greater use of water	*Known:* Washing reusable equipment uses more water than required for manufacturing single-use equipment.[91] Further research is available about methods to save water when sterilising.[137,138]
Donate equipment to less developed nations.	Donation of useful anaesthetic equipment can have social, financial and environmental benefits but these must be balanced against risks and problems such as access to appropriate training, consumables, and waste disposal management.[166]
Resources for further information	**Anaesthesia societies who have statements/guidelines on healthcare sustainability** UK and Ireland[147,167] France[148] European Society of Anaesthesiology[150] USA[146] Australia and New Zealand,[151] and Intensive Care[160] **Other Sustainable Healthcare Groups** The UK Sustainable Development Unit[168] The Centre for Sustainable Healthcare[169] Global Green and Healthy Hospitals[170] The Climate and Health Alliance (CAHA)[171] Doctors for the Environment Australia (DEA)[172]

setbacks are readily feasible without leading to an increase in microbiological contamination.[133] Furthermore, hospitals can transition to more renewable energy sources, to considerably reduce CO_2e emissions and air pollution; however, such efforts require persistence and effort.

Water

Large amounts of water in hospitals are used for routine patient care (taps, baths, showers), air conditioning systems, or in specialised areas (e.g. dialysis).[134,135] Almost 20 L of water is used for each surgical handwash at manually operated sinks, whereas motion sensors could dramatically reduce this volume. Future ecological comparisons may consider water-based handwash with alcohol/chlorhexidine-based hand rub.[136] Similarly, almost 1000 L of water are used for each cycle of a large hospital steam steriliser,[137] with considerable savings possible through more efficient steriliser usage.[138] Recently, in times of drought, reducing direct water requirements to clean and sterilise reusable devices has often been ranked of greater short-term importance than reducing one's carbon footprint through avoidance of single-use devices.[139] Further, as freshwater itself becomes scarcer, there are increasing monetary value and CO_2e emissions attached to alternative sources such as through desalination.[138]

Travel

Considerable health benefits arise from less fossil-fuelled travel, both active and public transport.[140,141] Fewer 'carbon miles' reduces the public health burden of climate change and air pollution.[142] Greater active transport have health co-benefits through increasing physical activity, lowers rates of obesity, diabetes, and cardiovascular disease. Some preadmission appointments, for example could be performed remotely using telehealth methods. Anaesthetists and critical care physicians should be aware of the benefits of teleconferencing on the environment and health,[143] and also on academic and administrative meetings.[144,145]

Education and advocacy

Multiple anaesthesia organisations now have advocacy statements about environmentally sustainable practices (e.g. USA,[146] UK,[147] France,[148] Canada,[149] Europe,[150] and Australia/New Zealand.[43,151] Interest in environmental sustainability is also evident within anaesthesia editorials in *British Journal of Anaestheisa*,[35] *Anesthesia and Analgesia*,[152,153] *Anaesthesia*,[154,155] *Canadian Journal of Anesthesia*,[156] and *Anaesthesia Critical Care and Pain Medicine*.[157] Educational publications within anaesthesia journals, particularly describing climate change and the atmospheric effects of anaesthetic gases exist.[35,40,47] Such 'ecological interest' has also been demonstrated through anaesthetist professional surveys,[42,158] but is currently rare in intensive care medicine,[159] scientific meetings, and societies/colleges.[160]

Similarly, the link between the environmental and social pillars of sustainable development (Planet, Profit, and People) requires promulgation.[161] Often by improving workplace environmental (and financial) sustainability, social sustainability will also be improved in a 'virtuous cycle'.[162] For example through greater recycling of metalwork and plastics in French paediatric ORs, environmental and financial savings were achieved, staff felt positive about their actions, and toys were purchased for sick children with the recycling proceeds.[81] Importantly, behavioural change is possible, and 'social tipping points' will indeed be necessary to achieve rapid reductions in the transition to a low-carbon world.[163]

Conclusions

Healthcare itself pollutes.[6] Anaesthesia and critical care are the cause for a considerable contribution to such healthcare pollution. We recognise that there can be accord and conflict between individual patient health and public health commitments, particularly in the field of infection prevention,[164] although one can protect the patient *and* the planet.[81] Over the past decade considerable progress has been made in improving the research foundation of environmentally sustainable healthcare, a summary of evidence pertaining to anaesthesia and critical care can be found in Table 1. Such considerations do not usurp patient-centred nor fiscally prudent care, but rather complement such goals by protecting patients, our healthcare system, and the environment.[81]

Author's contributions

All authors contributed to the writing of this review article. FM conceived, wrote, revised, and edited the article. JM, CL, and JDS revised and edited the article.

Declarations of interest

FM received funding from the Australian and NZ College of Anaesthetists (ANZCA Grant 2018/011) examining methods to capture waste anaesthetic gases. JDS received support from the Yale School of Medicine Department of Anesthesiology and the Yale School of Public Health Department of Environmental Health Sciences. There are no other perceived or actual conflicts of interest for any other authors.

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Handling editor: Jonathan Hardman