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# Atmospheric science, anaesthesia, and the environment

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## Key points

- The inhalational anaesthetic agents sevoflurane isoflurane and desflurane have global warming potentials 2-3 orders of magnitude higher than $CO_2$.
- Nitrous oxide contributes significantly to global warming and ozone depletion.
- 5% of the carbon footprint ($CO_2e$) of the NHS is attributable to exhaled anaesthetic agents.
- Most medical nitrous oxide liberation originates from Entonox use, including maternity use.
- Reducing the environmental impact of anaesthesia, can be achieved through behaviour change.

In this article, we describe the atmospheric science behind global warming including the specific role of anaesthetic agents and anaesthesia practice.

## Atmospheric structure

Earth's atmosphere is divided up into the troposphere, up to 10 000 m, the stratosphere, from 10 000 to 50 000 m, and the mesosphere, beyond 50 000 m. Eighty per cent of atmospheric ozone is in the ozone layer in the stratospheres between 20 000 and 30 000 m. It limits the earthward transmission of potentially harmful amounts of ultraviolet (280–315 nm). The troposphere comprises 80% of the mass of the atmosphere and contains nearly all the atmospheric water vapour. The boundary between the troposphere and the stratosphere is called the tropopause, the exact location of which varies from an altitude of 8000 m at the poles to 18 000 m at the equator. The height of the tropopause is defined by the change in temperature with altitude. Temperature decreases with ascent through the troposphere, but stabilizes and then increases with further ascent through the stratosphere (Fig. 1).

## Earth's energy budget and greenhouse gases

To be energy neutral, the Earth's incoming solar radiation of 342 W $m^{-2}$ (insolation) is balanced by 107 W $m^{-2}$ of reflected solar radiation and 235 W $m^{-2}$ outgoing long wave infrared (IR) radiation.[1] Figure 2 illustrates schematically the spectrum of solar insolation and outgoing IR radiation. The IR radiation spectrum varies depending upon Earth's temperature but at 290 K (17°C) the peak is at 10 µm. A relatively transparent 'atmospheric window' exists between the frequencies of 8 and 14 µm where little IR absorption by water vapour or GHG occurs. Outside these frequencies, the presence of atmospheric water vapour and GHG absorb outgoing IR and re-emit it, some of which will return to Earth and swings the energy balance to net energy gain.

## Terminology and definitions

Radiative forcing is a term devised by the Intergovernmental Panel on Climate Change (IPCC) to describe the change in irradiance (incoming solar–outgoing IR) at the tropopause (W $m^{-2}$). The accepted value for total radiative forcing was + W $m^{-2}$ in 2.88. The relative contributions of GHGs are presented in Table 1.

Radiative efficiency is the change in irradiance per ppb of a particular 2014 compound (W $m^{-2}$ $ppb^{-1}$) and depends on the strength and position of the compound's IR absorption bands.

The global warming potential (GWP) of a GHG is generally taken to be over the 100 yr time horizon ($GWP_{100}$) and is dependent on the radiative efficiency and the atmospheric lifetime. The $GWP_{100}$ for $CO_2$ is by convention 1.

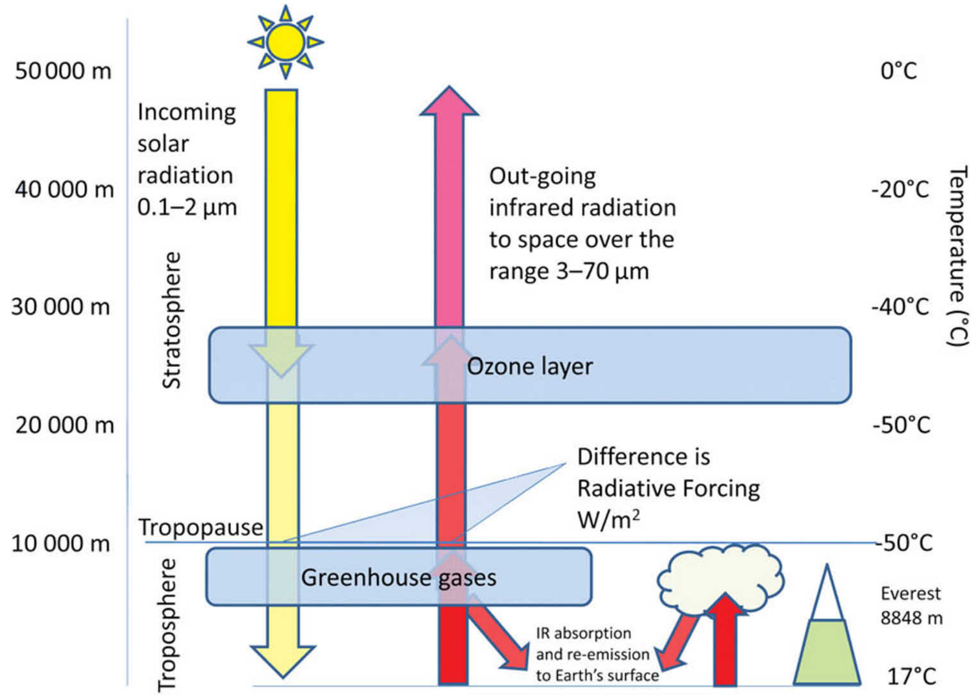


Fig 1 Simplified diagram of the Earth's energy balance. The difference between the incoming and outgoing radiation at the tropopause is called radiative forcing.

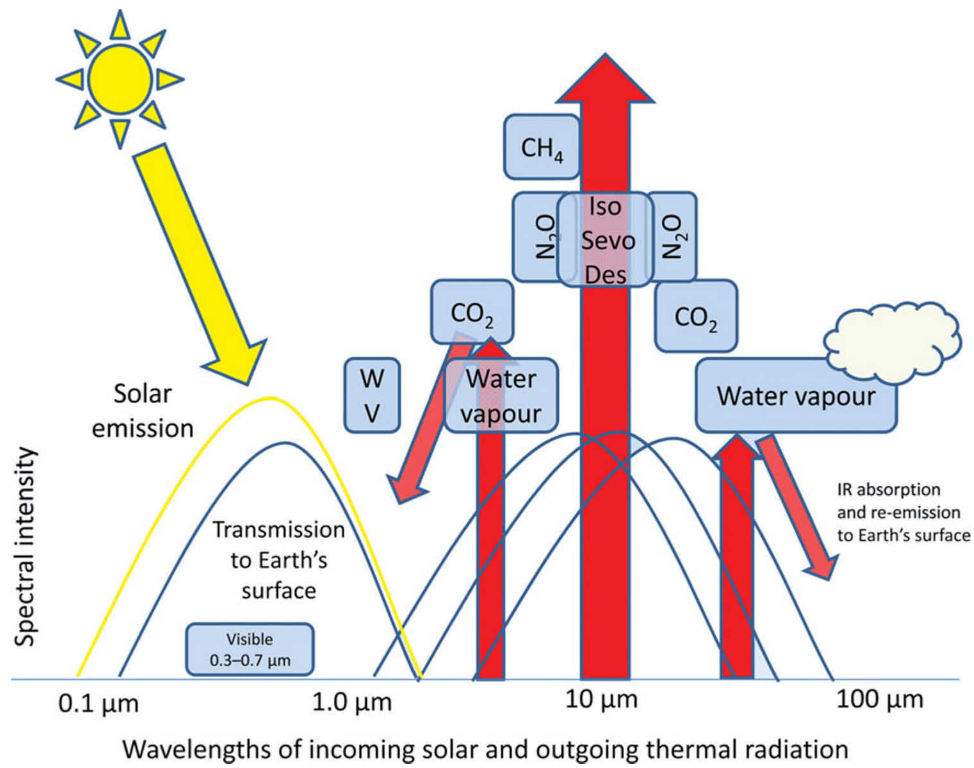


Fig 2 The spectra of incoming solar radiation and outgoing IR radiation. The boxes represent the approximate position of the peak absorption. Iso, isoflurane; Sevo, sevoflurane; Des, desflurane.

Carbon footprint—the total greenhouse gas emissions caused directly and indirectly by a person, organization, event, or product.[2]

Carbon dioxide equivalency ($CO_2$e) is a quantity that describes, for a given mixture and amount of greenhouse gas, the amount of $CO_2$ that would have the same GWP when measured over a specified timescale (generally, 100 yr). $CO_2$e reflects the time-integrated radiative forcing of a quantity of emissions or rate of GHG emissions that flow into the atmosphere—rather than the instantaneous value of the radiative forcing of the

Table 1 Physical characteristics and atmospheric effects of gases limited under the Kyoto Protocol. Data from www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf (accessed 19 July 2013); *J Quant Spectrosc Radiat Transf 78 (2003) 41–53; IPCC, Intergovernmental Panel on Climate Change; ppm, part per million; ppb, part per billion; ppt, part per trillion; HFCs, hydrofluorocarbons; PFCs, perfluorocarbons (organo-fluorine compounds containing only carbon and fluorine)

| | $CO_2$ | $CH_4$ | $N_2O$ | $SF_6$* | HFCs | PFCs |
|---|---|---|---|---|---|---|
| IR absorption peaks (μm) | 4.5, 7.8, 14–16 | 7.1, 8.1 | 4.5, 7.8, 12.5–17 | 10.5 | Variable | Variable |
| Atmospheric lifetime (yr) | 74 | 7 | 110 | 3200 | 5–200 | 3000–50 000 |
| $GWP_{100}$ | 1 | 23 | 310 | 22 000 | 300–12 000 | 5000–12 000 |
| Change in atmospheric concentration since the industrial revolution | From 280 to 400 ppm | From 700 to 1700 ppb | From 270 to 320 ppb | Absent before 1953 7.5 ppt in 2014 | | |
| Rate of increase in concentration | 1.9 ppm $yr^{-1}$ | Currently stable | 0.26% $yr^{-1}$ | 0.24 ppt $yr^{-1}$ | | |
| Per cent of total $CO_2e$ | 84 | 9 | 5 | | ~1 | |
| Contribution to RF ($W\ m^{-2}$) IPCC 2014 | 1.88 | 0.49 | 0.17 | 0.034 | 0.01 | |

concentration of greenhouse gases (GHG) in the atmosphere. $CO_2e$ is the concentration of $CO_2$ that would cause the same level of radiative forcing as a given type and concentration of the GHG. $CO_2e$ for a gas=mass released×GWP of the gas.

Commuting 7.5 miles to work in a car producing 160 g $CO_2$ $km^{-1}$, 5 days a week for 46 weeks a year (3450 miles) produces 1 tonne $CO_2$.

## Ozone depletion and the Montreal Protocol

Stratospheric chlorine containing compounds (chlorofluorocarbons or CFCs) such as $CFCl_3$ (CFC-11) undergo photolysis with the liberation of chlorine atoms, each one of which is capable of catalysing the destruction of up to 100 000 molecules of ozone.[3] The use of CFCs was universally banned under the Montreal Protocol (1987). Hydrochlorofluorocarbons or HCFCs [e.g. $CHFCl_2$ (HCFC-21)] have proportionately less chlorine and so a smaller ozone depleting potential (ODP) and were introduced as replacements for CFCs. The consumption and production of HCFCs is set to freeze in 2013 and to reduce in 2015, after which HCFCs are to be replaced with hydrofluorocarbons (HFCs) such as $CHF_3$ (HFC-23) with no ODP. The ODP of a compound is expressed relative to that of CFC-11.

## Global warming and the Kyoto Protocol

The UN Framework Convention on Climate Change set binding obligations to reduce the emission of GHG as the Kyoto Protocol in 1997. Whilst it has not been universally accepted, the UK agreed a target for a 12.5% reduction in GHG emissions between 2008 and 2012, 20% reduction by 2020 and 80% reduction by 2050, all relative to the 1992 baseline, with the intention of limiting the atmospheric $CO_2$ to 450 ppm. The gas emissions limited under the protocol are $CO_2$, nitrous oxide, methane and sulphahexafluoride, HFCs, and perfluorocarbons (PFCs, only contain carbon and fluorine) (Table 1). Substitutes for CFCs have significant GWP. HFC 134a (1,1,1,2-tetrafluoroethane), for example, widely used in refrigeration, air conditioning and as a propellant in cooling sprays and salbutamol metered dose inhalers, has an atmospheric lifetime of 14.6 yr and a $GWP_{100}$ of 1430.

## Nitrous oxide

In addition to the global warming effect, the atmospheric lifetime is sufficiently long to ensure that it reaches the stratosphere where it is capable of ozone destruction (Fig. 3). Photolytically generated oxygen atoms react with ozone to produce two oxygen molecules. Medical emissions of $N_2O$ account for <4% of all emissions of $N_2O$, the majority originating from microbial action on nitrogenous fertilizers.

## Halogenated anaesthetic agents

The commonly used inhalation anaesthetic agents, isoflurane, sevoflurane, and desflurane absorb IR within the range of 7–10 μm and within the atmospheric window. Accordingly, they all have a significant $GWP_{100}$ (Table 2, Fig. 2). Sevoflurane with the shortest life has the smallest $GWP_{100}$ and desflurane with the longest lifetime has the greatest the $GWP_{100}$. Vaporization of a bottle of desflurane has the same global warming effect as 886 kg $CO_2$. Degradation of anaesthetic agents occurs by reaction with atmospheric hydroxyl ions to species that have minimal GWP. Sevoflurane and desflurane do not contain chlorine and so do not have an ODP. Isoflurane has an ODP of 0.01 but as the tropospheric lifetime is short, the effect is minimal.

## The theatre environment

Within the operating theatre environment the Control of Substances Hazardous to Health regulations limit occupational exposure to anaesthetic vapours to an 8 h time-weighted average of 50 ppm for isoflurane and 100 ppm for nitrous oxide. Theatre contamination is minimized with anaesthetic gas scavenging systems (AGSS) as a legal requirement in theatre. Closed or circle systems create less theatre pollution than open or semi-closed systems combined with appropriate fresh gas flow rates. Other practical measures include ensuring good seals with airway devices, using cuffed tubes in paediatrics and minimizing disconnections between the anaesthetic circuit and machine, for example, by considering anaesthetising in theatre as opposed to in the anaesthetic room.

## Reducing environmental contamination by inhalation agents

As anaesthetic vapours are minimally metabolized they are exhaled predominantly unchanged. All vapour added to the circuit ultimately ends up in the environment and thus the strategies above may act to reduce theatre pollution but will

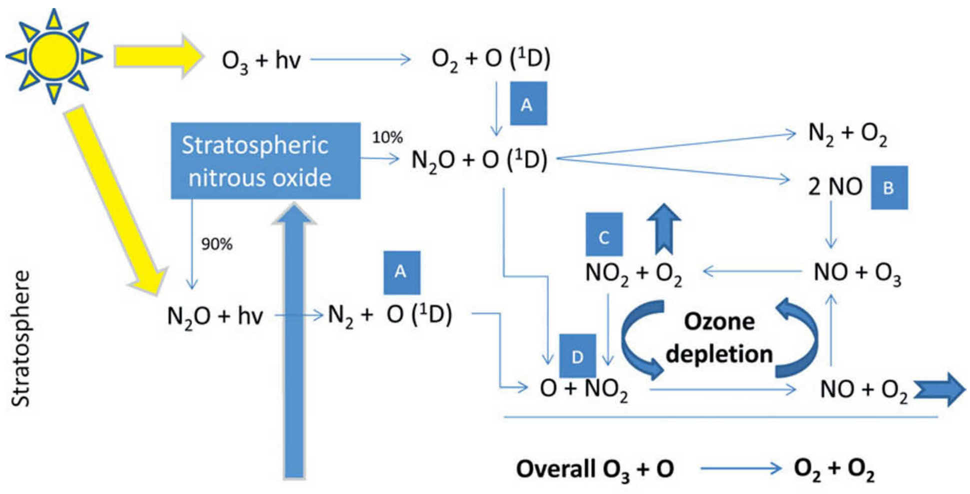


Fig 3 A simplified diagram of the fate of stratospheric nitrous oxide and the steps to destruction of ozone. Incident solar radiation (*hν*) causes photolysis of both ozone and nitrous oxide to produce excited oxygen atoms, O ($^1$D) (A) and NO (B). NO reacts with ozone ($O_3$) to produce nitrogen dioxide (C) which is converted to NO by reacting with oxygen atoms (D) and the cycle continues.

Table 2 The atmospheric characteristics of inhalation anaesthetic ethers. Data from references[4 5]

| | Isoflurane | Sevoflurane | Desflurane |
|---|---|---|---|
| Tropospheric lifetime (yr) | 3.2 | 1.1 | 14 |
| IR absorption peak (μm) | 8.5 | 8 | 8.1 |
| IR absorption range (μm) | 7.5–9.5 | 7–10 | 7.5–9.5 |
| Radiative efficiency ($W\ m^{-2}\ ppb^{-1}$) | 0.453 | 0.351 | 0.469 |
| $GWP_{100}$ | 510 | 130 | 2540 |
| $CO_2e$ of a vaporized bottle of the agent=mass×GWP | 190 kg per 250 ml | 49 kg per 250 ml | 886 kg per 240 ml |

have limited effect on the levels of overall environmental pollution.

## Low flow anaesthesia

There is no standard definition, but low flow anaesthesia generally refers to a technique using fresh gas flows of < 1 litre $min^{-1}$. It has previously been covered in an article in this journal.[6] The equipment required for the technique is already standard in the UK. Feldman makes a number of recommendations for managing fresh gas flow in order to reduce environmental contamination.[7]

## Vapour capture condensation and destruction

Devices have been built that condense exhaled anaesthetic agents from the AGSS completely preventing atmospheric discharge.[8] Fractional distillation is required to separate the components theoretically allowing subsequent administration. USA FDA approval has not been granted for clinical use of salvage exhaled agent (personal communication). Technology using catalytic conversion of nitrous oxide to oxygen and nitrogen is widely used in industry and is available for small anaesthesia facilities as Excidio (Linde).

## How big an issue is the global warming effect of inhalation anaesthetics?

It has been estimated that the annual warming effect of all the inhalation agents is the equivalent to that of one coal fired power station, and 0.01% of that of the $CO_2$ released from current global fossil fuel combustion.[4] The Sustainable Development Unit of the NHS estimates that 5% of the $CO_2e$ from acute organisations is attributable to anaesthetic agents.[9] Our own calculations agree with this estimate and further, 90% is due to nitrous oxide and two-thirds of this is from Entonox use, most of which is used in the delivery suite.

# Total i.v. anaesthesia

Total i.v. anaesthesia (TIVA) avoids the use of volatile agent altogether, as can the use of regional anaesthetic techniques. When regional anaesthetic techniques are used as an adjunct to volatile anaesthesia they have a 'MAC sparing' effect, allowing use of less vapour. Whilst TIVA eliminates the greenhouse gas emissions associated with volatile agents, the drugs still exert an environmental impact as a result of their manufacture, transport and syringe driver delivery. In life-cycle assessments, of anaesthesia related GHG emissions from propofol TIVA are 4 orders of magnitude smaller than that from desflurane and nitrous oxide.[10]

## Environmental persistence, bioaccumulation, and toxicity (PBT)

Propofol metabolism ensures only trace amounts of an administered dose will reach the aquatic environment. Syringe residue discarded into the drains both persists and is toxic in the aquatic environment.[11] As complete destruction requires exposure to temperatures of 1000°C, residual propofol should be discarded into the sharps bin for incineration. Minimizing drug waste reduces the quantity that can potentially reach the environment unchanged and also reducing the mass of drug procured.[12] The

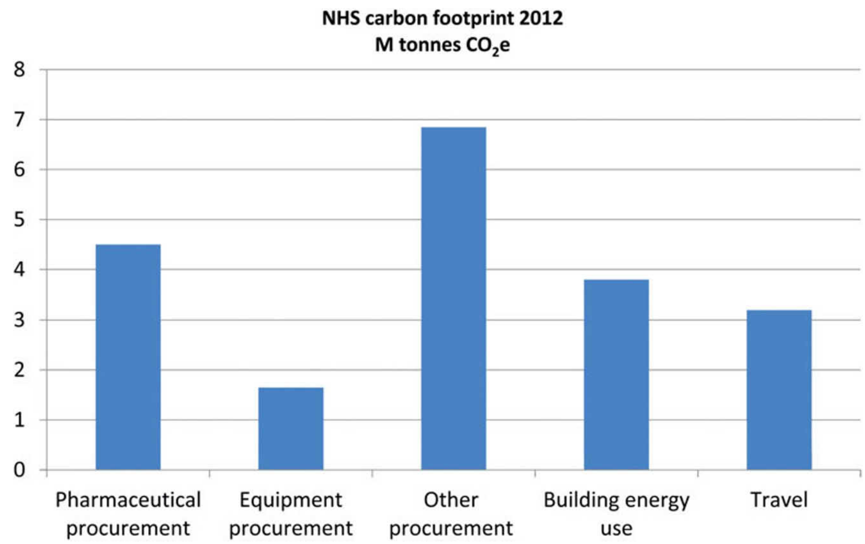


Fig 4 The NHS carbon footprint 2012.[13]

reader is invited to visit http://www.janusinfo.se/environment for an extensive list of PBT for anaesthetic drugs.

## NHS carbon footprint

In 2012 the carbon footprint of the NHS was 21M tonnes $CO_2$e, two-thirds of which is attributed to procurement (Fig. 4). Acute hospitals account for only 10% total $CO_2$e of pharmaceutical procurement but 70% of the $CO_2$e of procurement of instruments and equipment.[13] At every stage of the manufacture and distribution of any product used within the NHS, energy, largely from the combustion of fossil fuels, is required and carbon can be thought of as being 'embedded'. Anaesthesia's reliance on both drugs and disposables makes this all the more pertinent. Box 1 outlines the stages in procurement. Whilst for almost all drugs the upstream embedded carbon is greater than the downstream effect because of excretion, the same is not true for inhalation agents. The $CO_2$e of atmospheric sevoflurane, isoflurane, and desflurane is 8, 33, and 87 times greater, respectively, than the GHG emissions of procurement.[10]

## Disposable *vs* reusable

Life-cycle assessment is a process that involves analysis of the energy and emissions used in the production, use and ultimate disposal of an item. It takes into account raw materials used in manufacture, cleaning, and sterilizing during the product's lifetime and finally the cost of disposal to land fill or incineration. Global warming and ozone depletion is less with 40 reuse cycles of reusable laryngeal mask airways (LMAs) than with single use devices.[14] Steam for autoclaving is greater with reusable items and environmental procurement costs greater with single use items. LMAs intended for single use cannot be reprocessed as they contain large amounts of PVC including bis(2-ethylhexyl) phthalate (DEHP) which leeches out on exposure to heat and lipids. DEHP is considered a likely carcinogen and is an endocrine disruptor.[15] Similarly, life-cycle analyses of operating room gowns and drapes conclude that reusable textiles, use significantly less energy, water, carbon, organic chemicals, and solid waste for a similar cost and at the same level of protection and comfort than single use textiles.[16]

## Carbon intensity

For every pound spent on NHS procurement an average of 539 g $CO_2$e is produced.[17] Minimizing wastage of drugs and disposables saves money and reduces $CO_2$ emissions (Box 2).

## Anaesthesia related electrical energy consumption

One kWh of electricity from gas combustion produces about 450 g $CO_2$, though this may decrease to 365 g with modern generating technology. Modern anaesthesia equipment has low power consumption, an anaesthesia work station typically uses <100 W. Energy hungry equipment include warm air convective patient warming systems (~500 W), AGSS (~800 W), and radiant overhead heaters (~2000 W), such as may be found in anaesthetic rooms. The electricity required to for an hour's use can expect to produce 720 g $CO_2$.

## Anaesthesia and theatre waste

The mantra 'reduce, reuse, recycle' is chosen to emphasise that reducing use saves more carbon than reuse and recycling the least.

The NHS produces some 4% of the UK's solid waste, over 400 000 tonnes $yr^{-1}$, of which a third is clinical waste. Each theatre produces 2300 kg of waste per year and while only 10% of NHS waste is currently recycled it is estimated that 40% of anaesthetic waste could be recycled.[18] Domestic waste is ultimately disposed of via dwindling landfill capacity or via incineration.

Waste is expensive to dispose of, costing the NHS £90 million in 2011–12. Clinical waste is by far the costliest to dispose of, costing up to £450 per tonne for non-burn technology such as microwaving and up to £1000 per tonne for hazardous or pharmaceutical waste requiring high temperature incineration. By comparison household waste disposal costs around £100 per tonne. It is estimated that only 4% of waste in sharps bins is appropriate. Waste paper sent for recycling can earn up to £60 per tonne and plastic up to £200.

The hierarchy of 'reduce, reuse, recycle' provides a framework to consider ways to reduce theatre waste. Reduction can be

**Box 1** The procurement related breakdown of GHG emissions for pharmaceuticals and equipment

*Pharmaceuticals*
R&D, clinical trials and marketing
Manufacture of active pharmaceutical ingredient
- Material and chemical inputs
- Material and chemical transport
- Energy/fuel generation and consumption
- Waste disposal
- Solvent manufacture, use and disposal
- Catalyst manufacture, use and disposal
- Solvent recovery and incineration
- Process emissions from synthesis
- Chemicals for cleaning
- Sterilisation
- Refrigerants

Preparation of the product form
- Tablet, injection
- Production and disposal of consumables

Manufacture of drug delivery system
- Syringe, syringe driver, vapourizer

Packaging
Distribution
Administration
Disposal/end of life
*Medical devices* (*anaesthesia related*)
- Production, processing, transport of raw materials
- Batteries and packaging
- Manufacture, sterilisation, packaging, storage, distribution
- Production and distribution of energy, water materials consumed during production
- Sterilisation process of the product
- Associated consumables
- Production line sterilisation and cleaning

**Box 2** Top tips for green anaesthesia modified from the Greenhouse Gas Protocol

Reduce direct liberation of GHGs into the atmosphere (Scope 1)
- Avoid car driving either commuting or on business
- Minimize the use of nitrous oxide
  - Wider use of epidural analgesia or PCA for labouring mothers
- Low flow anaesthesia where ever possible
- Minimize desflurane usage

Minimize (fossil fuel generated) electrical energy use (Scope 2)
- Switch to conductive warming devices from convective
- Turn off AGSS out of hours
- Turn off (or low power standby) equipment lighting and ventilation when not in use
- Purchase electrically powered devices in accordance with guidance on Green Public Procurement for Electrical and Electronic Equipment[23]

Minimize the indirect liberation of $CO_2$ into the atmosphere (Scope 3)
- Reduce the amount of drugs, disposables and gases used to deliver anaesthesia
- Purchase disposable devices made with less material
- Reuse as much material as possible
- Minimize waste, including drugs.
- Maximize recycling possibilities

Avoid contamination of the environment with drugs that persist, accumulate or are toxic

achieved by avoidance of unnecessary double packaging and use of paperless systems. Reuse may be of medical devices with low risk of cross-infection such as calf compression devices and blood pressure cuffs. Recycling involves segregation of recyclable materials from general or clinical waste before they become contaminated with patient debris or drugs. Hutchings and White suggest adding rethink and research to create the ‘5 R Approach’.[19]

## Anaesthetic room steel

The MHRA mandate that laryngoscope blades are used for a single patient and are then incinerated or otherwise disposed of. However, the regulations do not describe recycling and it has been suggested that blades and other anaesthetic room steel could be sterilised via the usual route and then recycled as scrap.[20] Recycled steel generates an income of only £100 per tonne but as it avoids the cost of incineration at £600 per tonne processing is cost neutral. The carbon footprint of producing 1 kg of steel from scrap is 1.97 kg $CO_2$, compared with 0.7 kg $CO_2$ if produced form iron ore. The potential for recycling of anaesthetic room steel should be discussed though must be undertaken within the MHRA regulations.[21]

### Single use airway devices

Disposable airway devices were introduced in the 1990s in response to the perceived risk of transmission of prions which are not removed by standard sterilization techniques. At the time, this was a pragmatic solution to a new and unexplored problem. Over a decade later all reported cases of prion transmission have been because of neurosurgical instrument use and there are yet to be any reported cases of prion transmission because of airway devices. The incidence of CJD is falling, but prevalence studies suggest that around 1 in 3000 adults in the UK may be infected with CJD prions and patient safety must remain the first priority. Timesco, manufacturers of single use steel laryngoscopes, offer a recycling process.

### Further reading

The Sustainable Development Unit (http://www.sduhealth.urg.uk) and the AAGBI (http://www.aagbi.ork/about-us/environment) both have valuable contemporary resources. ‘The science of anthropomorphic climate change: what every doctor should know’ provides a very readable contemporary overview of the science and potential global impacts of climate change, though not specifically directed to anaesthesia. The online version contains the corrections of the typographical errors in the original BMJ article.[22]

## Declaration of interest

We declare that this submission has not been published elsewhere, nor is under consideration for publication either in print

or in electronic media format. I accept that the Royal College of Anaesthetists will assume the intellectual property rights for this material. I will seek the permission of the Royal College of Anaesthetists, before making any attempt to publish this work elsewhere. We declare no conflict of interest.

## MCQs

The associated MCQs (to support CME/CPD activity) can be accessed at www.access.oxfordjournals.org by subscribers to *BJA Education*.

## Podcasts

This article has an associated podcast which can be accessed at http://www.oxfordjournals.org/podcasts/ceaccp_15.04.02.mp3.

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