Modelling the 'carbon footprints' of inhalational and total intravenous anaesthesia in the paediatric population

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Short title:	Carbon footprint of paediatric TIVA
Keywords (MeSH):	Climate Change; Inhalation Anaesthesia; Intravenous Anaesthesia; Paediatrics

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Abstract

Background

Tackling the climate emergency is now a key target for the healthcare sector. Avoiding inhalational anaesthesia is often cited as an important element of reducing anaesthesia-related emissions. However, the evidence supporting this is based in adult practice. The aim of this study was to identify the difference in the 'carbon footprints' of inhalational and intravenous anaesthesia when used in children.

Methods

We used mathematical models to compare general anaesthetic techniques children weighing 5-50 kg, comprising: total intravenous anaesthesia, intravenous induction then inhalational maintenance, inhalational induction then intravenous maintenance, and inhalational induction and maintenance. We modelled inhalational induction with sevoflurane alone, and co-induction with sevoflurane and nitrous oxide. We modelled both remifentanil-propofol and propofol-only intravenous anaesthesia. For each technique, we drew on previously published life cycle data to calculate carbon dioxide equivalents for anaesthetic durations up to 480 minutes.

Results

Total intravenous anaesthesia with propofol and remifentanil creates a smaller carbon footprint over a typical anaesthetic duration of 60 minutes (1.26 kg CO_2e for a 20kg child) than intravenous induction then inhalational maintenance (2.58 kg CO_2e), and inhalational induction and maintenance (2.98 kg CO_2e). Inhalational induction then intravenous maintenance only yields carbon footprint benefits over inhalational induction and maintenance when used in longer procedures (>77 minutes for children 5-20 kg; >105 minutes for 30-50 kg).

Conclusion

Intravenous anaesthesia has climate benefits in paediatric practice. However, when used following inhalational induction, this is only achieved in longer procedures.

Introduction

Climate change is potentially the most profound long-term health threat of the 21st Century and has become a key priority for clinicians and healthcare leaders.[1,2] The healthcare sector is responsible for 4-5% of the UK's carbon footprint,[3] and the National Health Service (NHS) in England has pledged to reduce its carbon footprint (based on emissions of greenhouse gases controlled directly by the NHS) to 'net zero' by 2040.[1,2] To achieve this, the NHS will need to reduce the carbon footprint of the emissions that it directly controls by 80% by 2032 (compared to a 1990 baseline);[2] substantial changes must be made to meet these targets.

Anaesthetic practice makes a significant contribution to the greenhouse gas emissions of the healthcare sector. Most notably, inhalational anaesthetics including halogenated agents and nitrous oxide (N_2O) contribute around 5% of the carbon footprint of acute NHS trusts.[4] Efforts to reduce the carbon footprint of anaesthesia include the avoidance of desflurane and N_2O, using total intravenous anaesthesia (TIVA) and regional anaesthesia in preference to inhaled anaesthesia, and using low-flow anaesthesia when inhalational agents are used.[5]

Approximately 550,000 paediatric surgical procedures are thought to be undertaken annually in England.[6,7] The use of TIVA is less common in paediatric (8%) than adult (12.5%) anaesthetic practice.[8] Although this represents a substantial increase from a decade previously,[9] it remains at a low level when considered in the context of the increased awareness of the environmental issues related to inhaled agents.

Though several analyses indicate that TIVA has a lower carbon footprint than inhalational anaesthesia in adult practice,[10-12] there are potential reasons why these findings may not translate to the paediatric setting. These include the regular use of inhalational induction because of challenges in obtaining vascular access, that paediatric procedures are often relatively short in duration, and that many of the resources used in TIVA (e.g., giving sets, syringes, ampoules of drugs) are of a fixed mass or volume, so 'carbon footprint' benefits may not scale to (smaller, lighter) children.

To better understand the influence of these factors and provide a much-needed basis for more sustainable paediatric anaesthesia, we used mathematical modelling based on pharmacokinetic models, drug doses, data from existing life cycle inventories of anaesthetic drugs, and emissions factors for waste processes, to compare the differences in the 'carbon footprint' of inhalational anaesthesia and TIVA when used in children.

Methods

Based on modelling typical clinical scenarios, we calculated the differences in the drugs and equipment used in four anaesthetic techniques: TIVA; intravenous induction of general anaesthesia then inhalational maintenance; inhalational induction and maintenance of anaesthesia; and inhalational induction then intravenous maintenance of anaesthesia. For inhalational induction and maintenance of anaesthesia, we modelled inhalational induction with sevoflurane alone, co-induction with sevoflurane and N_2O, and the addition of remifentanil following induction of general anaesthesia. For TIVA and intravenous maintenance, we modelled anaesthesia with propofol and remifentanil, and with propofol alone. Otherwise, all inhalational anaesthesia was with sevoflurane, and intravenous induction was with propofol. Anaesthesia was modelled for children of 5, 10, 20, 30, 40 and 50 kg, to account for the variety of cases seen in paediatric practice. Ethical approval was not required as no human participants were involved in this study.

Cases involving TIVA and intravenous maintenance of anaesthesia were modelled using widely available software (TIVAtrainerX, accessed from www.tivatrainerx.com).[13] For each specified weight, the 50th centile of the Royal College of Paediatrics and Child Health growth charts was used to identify an average age and length or height;[14] these data were used when programming the algorithms (Table 1).

When modelling TIVA and intravenous maintenance of anaesthesia we included drug ampoules, blunt fill needles for drawing up drugs, 60 ml syringes (filled to 50ml) for drug administration, and a twin line infusion set. For TIVA and maintenance with propofol alone, we replaced the twin line infusion set for a standard single infusion line. Where inhalational anaesthesia was simulated, we included the use of 1/250th of a glass bottle per ml of sevoflurane. The mass of each of these materials, including their components, was measured by disassembling and weighing examples used in our practice (Table S1). In addition, we included the electricity used by two infusion pumps to deliver intravenous anaesthesia, with each pump assumed to run at 15 W.[15]

For TIVA and inhalational induction then intravenous maintenance of anaesthesia, we modelled the use of a propofol TCI using the Paedfusor model.[16] We modelled a weight-based remifentanil infusion as the Minto TCI model is not suitable for all of the weight categories used in our study,[17,18] and although pharmacokinetic models have been developed for remifentanil in younger children,[19,20] their use is not yet standard in UK practice.

For each model, the cumulative volumes of propofol and reconstituted remifentanil administered at regular time points were recorded. Propofol was assumed to be Propofol-Lipuro 1% (B. Braun, Melsungen, Germany) from a 50 ml vial, while remifentanil was assumed to be prepared from an ampoule containing 2 mg of remifentanil as powder, made up to a concentration of 20 mcg ml^{-1} and drawn up into two 60 ml syringes. The time at which additional syringes and drug vials would need to be opened was recorded, by assessing the time taken during the model to administer 50 ml propofol or 100 ml remifentanil (i.e., the amount initially drawn up). The quantity of drug usage for inhaled general anaesthesia was modelled using the Association of Anaesthetists' Anaesthetic Gas Calculator.[21-22]

In our propofol and remifentanil TIVA model, the propofol TCI was commenced at a target plasma concentration of 6 mcg ml^{-1}, and the remifentanil infusion was commenced at 0.5 mcg kg^{-1} min^{-1}.

After two minutes the propofol TCI was reduced to 3.5 mcg ml^{-1} and the remifentanil infusion reduced to 0.3 mcg kg^{-1} min^{-1}. These infusion rates were continued for the duration of the case. In our propofol-only TIVA model, we increased our induction target concentration by 20% to 7.2 mcg ml^{-1} and our maintenance target concentration by 50% to 5.25 mcg ml^{-1}, consistent with randomised control trial evidence on the propofol-sparing effect of remifentanil.[23]

For intravenous induction then inhalational maintenance of anaesthesia, we assumed the use of a 5 mg kg^{-1} propofol bolus (drawn up in a 20ml syringe from a 20ml ampoule of Propofol-Lipuro 1%). Sevoflurane was assumed to be commenced immediately at an inspired concentration of 4%. After five minutes, the inspired sevoflurane concentration was reduced to 3% for the remainder of the case. In children of 5 - 20 kg, a fresh gas flow rate of 6 l min^{-1} was used for the first five minutes, whereas in children of 30 - 50kg, a fresh gas flow rate of 10 l min^{-1} was used. In all cases, after five minutes, the fresh gas flow was reduced to 0.5 l min^{-1}.

Inhalational induction and maintenance of anaesthesia were assumed to commence with a sevoflurane concentration of 8% for two minutes, reduced to 4% for a further three minutes, after which a further reduction was made to 3% for the remainder of the case. Again, 6 l min^{-1} fresh gas flow was used for the first five minutes in children of 5 - 20 kg, and 10 l min^{-1} was used in children of 30 - 50 kg, followed by a reduction to 0.5 l min^{-1} in both weight groups. Inhalational co-induction with sevoflurane and N_2O was modelled as described above for all groups, but with the addition of N_2O as a carrier gas for the first five minutes, at an inspired fractional concentration of 0.6. After five minutes the delivery of N_2O was stopped. Where remifentanil was added to inhalational maintenance, a remifentanil infusion was started at 0.3 mcg kg^{-1} min^{-1} after 5 minutes and continued for the remainder of the case. Due to lower sevoflurane MAC required with remifentanil, the dialled concentration was reduced to 2% at the onset of remifentanil infusion. [24]

Inhalational induction then intravenous maintenance was assumed to be equivalent to the above sevoflurane-based induction for the first five minutes, after which a propofol TCI was commenced at a target plasma concentration of 3.5 mcg ml^{-1}, and a remifentanil infusion was commenced at 0.3 mcg kg^{-1} min^{-1}. Inhalational anaesthesia was continued for one minute after commencing intravenous maintenance, with an inspired sevoflurane concentration of 3% and a fresh gas flow rate of 0.5 l min^{-1}. The addition of sevoflurane into the circuit was then stopped. For propofol-only maintenance of general anaesthesia, a higher target plasma concentration of 5.25 mcg ml^{-1} was used.

In all models, the 'carbon footprint' was reported by calculating carbon dioxide equivalents (CO_2e), a widely-used measure that relates an item or process to the release of CO_2. For example, a petrol engine releases the greenhouse gases methane and N_2O in addition to CO_2, but the combination of gases can be summarised for comparison in terms of CO_2e (e.g., driving 1 mile in an average UK petrol car equates to 281g CO_2e).[25] Where sevoflurane was used, its CO_2e was calculated using the Anaesthetic Gases Calculator, which calculates the mass of inhaled agent delivered (based on fresh gas flow and dialled concentration, and assuming metabolism for sevoflurane of 4%) and uses its 100-year global warming potential (GWP_{100}, a measure which expresses how much heat a gas released into the atmosphere will trap over 100 years compared to an equivalent mass of CO_2) to determine CO_2e.[21,22] For this calculation, we modified the Anaesthetic Gases Calculator to use the recent revisions of the GWP_{100} of sevoflurane proposed by Sulbaek Andersen et al. [21-22, 26] Where N_2O

or intravenous anaesthesia was used, its CO_2e was calculated using previously published life-cycle data.[12,27] The CO_2e of both the supply and incineration of consumable items were similarly calculated using previously published data.[25,28] Details of the data and the sources used are presented in online supplementary materials (Table S1). The CO_2e of the electricity used by the two infusion pumps to deliver TIVA was also calculated using published UK national data.[25] Drugs other than propofol, remifentanil and sevoflurane, and other disposables (e.g., tracheal tubes, venous cannulae) were assumed to be equivalent between anaesthetic techniques and were therefore not considered in our comparison.

Results

For each model, results are presented as graphs (Figs. 1-6) showing CO_2e against time. Carbon footprints at key time points are summarised in Table 2.

A comparison between the carbon footprint of TIVA with propofol and remifentanil and inhalational induction and maintenance of anaesthesia with sevoflurane is shown in Fig. 1. This demonstrates that TIVA generates less CO_2e in all weight categories and at all clinically relevant timepoints, with the difference increasing as the duration of anaesthesia increases.

The first hour of this comparison is shown in detail in Fig. 1b: because the drugs used in TIVA are prepared before induction of anaesthesia, the CO_2e at the start of TIVA is higher than that of inhalational induction and maintenance of anaesthesia. Following induction, the CO_2e of TIVA decreases very slowly over time as more propofol and remifentanil are administered to the patient, meaning that less mass of drug will require disposal by (energy intensive) incineration. As each new ampoule of drug is prepared, and therefore consumed, the CO_2e increases in a stepwise fashion. During inhalational anaesthesia, agents are constantly consumed at a rate proportional to fresh gas flow for a given vaporiser setting. As a result, its carbon footprint increases steadily. Within three minutes, the CO_2e of inhalational induction and maintenance of anaesthesia exceeds that of TIVA.

A comparison between inhalational induction and maintenance of anaesthesia with sevoflurane and inhalational induction with sevoflurane then intravenous maintenance with propofol and remifentanil is shown in Fig. 2. In both cases, the inhalational inductions are performed identically, so the first four minutes generate the same CO_2e. In the fifth minute, the CO_2e of inhalational induction/intravenous maintenance is higher than the inhalational anaesthetic due to the large quantity of drugs and consumables used. However, the CO_2e rapidly levels off with the cessation of inhaled anaesthesia and at 77 minutes (5-20 kg) / 105 minutes (30-50 kg), the carbon footprint of inhalational anaesthesia exceeds that of inhalational induction and intravenous maintenance.

A comparison of inhalational induction followed by maintenance with sevoflurane and remifentanil against inhalational induction then maintenance with propofol and remifentanil is shown in Figure 3. The addition of a remifentanil infusion to sevoflurane leads to a step increase in CO_2e as maintenance anaesthesia is commenced, due to consumable items being opened as more remifentanil is used. However, due to the lower dialled sevoflurane concentration (2%), the ongoing rate of increase of CO_2e is reduced, which offsets the impact of the consumable items. The 'carbon footprint' of the sevoflurane-remifentanil technique exceeds that of propofol-remifentanil technique at 74 minutes (5-20kg) / 120 minutes (30kg) / 170 minutes (40-50kg).

A comparison of intravenous induction then inhalational maintenance with sevoflurane against TIVA with propofol and remifentanil is shown in Fig. 4. Intravenous induction then inhalational maintenance follows a similar pattern to that of inhalational induction and maintenance of anaesthesia, albeit at a lower level, as high initial concentrations of sevoflurane are not used. As a result, the carbon footprint of intravenous induction then inhalational maintenance exceeds that of TIVA within four minutes.

A comparison of intravenous induction then inhalational maintenance with sevoflurane against propofol-only TIVA is shown in Fig 5. The removal of remifentanil leads to a reduction in the CO_2e

such that the carbon footprint of inhalation maintenance exceeds that of propofol-only TIVA within 2 minutes.

A comparison of inhalational induction and maintenance of anaesthesia with sevoflurane against inhalational co-induction with sevoflurane and N_2O followed by maintenance with sevoflurane alone is shown in Fig. 6. Using N_2O increases the carbon footprint of the inhalational induction of anaesthesia nearly six-fold. After five minutes, using N_2O and sevoflurane together generates a CO_2e of 10.9 kg in children weighing 5 to 20 kg, compared to 2.0 kg for sevoflurane alone. After N_2O is discontinued, anaesthesia is delivered identically in the two models; the CO_2e generated in the maintenance phase therefore increases at the same rate for the remainder of the case.

Discussion

Our study compares the carbon footprint of TIVA with inhalational anaesthesia in children, and demonstrates that TIVA generates substantially less CO_2e than inhalational anaesthesia. This is consistent with data published in adult practice.[10-12] Over 30 minutes, approximately twice as much CO_2e is generated by using sevoflurane-based inhalational anaesthesia compared to TIVA with propofol and remifentanil (Fig. 1). If N_2O is used for induction, inhalational anaesthesia generates approximately nine-fold the CO_2e of TIVA in the first 30 minutes (Fig 6).

The difference between TIVA and inhalational anaesthesia is magnified in smaller patients, as drug infusions are delivered based on the patient's weight. The mass of intravenous agents delivered is targeted to the patient's individual requirements according to a pharmacokinetic model, whereas inhalational anaesthesia, which is based on dialled concentration and fresh gas flow rate, may lead to large quantities of inhalational agents being wasted in smaller children.

The magnitude of the difference, while significant, is smaller than in previously published work by Sherman and colleagues.[11] This is likely accounted for primarily by the licensing regulations in the USA (where that study was conducted), which specify the use of a minimum fresh gas flow rate for sevoflurane of 2 l min^{-1}. Similarly, the magnitude of difference in our study is smaller than that calculated by Allen and Baxter,[10] who modelled a seven-hour anaesthetic in a 75 kg adult. They calculated that TIVA would generate 3.2 kg CO_2e (similar to our own findings), whereas sevoflurane would generate 69.9 kg CO_2e. This is likely explained by their use of real audit data on volatile use, which exceeds our theoretical calculations by a large margin. This and other data indicate that whilst low flow anaesthesia is recommended, it is seldom consistently achieved in practice.[29] This emphasises the potentially important role of technological solutions such as automated end-tidal control and electronic injection, which can optimise volatile agent use by reducing the influence of human factors.[30] As this technology becomes more widely established in practice, future research should evaluate its impact.

Our study also demonstrates how the 'carbon footprint' of intravenous anaesthesia changes in a stepwise way over the duration of the anaesthetic, in contrast to inhalational anaesthesia, in which the CO_2e increases linearly. The stepwise increase in the 'carbon footprint' of intravenous anaesthesia occurs because all consumable items that are opened, including unused drugs, will inevitably be disposed of. Accordingly, the CO_2e for both production and disposal of the item should be 'counted' at the point of its opening. As more propofol and remifentanil are delivered, the volume of drugs disposed of by incineration will reduce, until the next vial is opened. As a result, following each step increase, the CO_2e generated by intravenous anaesthesia reduces over time. This generates some findings that may seem paradoxical. For example, although a 30kg child requires more propofol in a case of 60 mins duration than a 20 kg child, a smaller volume of propofol and remifentanil would be disposed of by incineration with a 30kg child, so the CO_2e for that anaesthetic would be lower (Fig. 1). This finding underlines the importance of considering the likely drug requirements for a case, and avoiding drug wastage.

In paediatric anaesthesia, the difficulty of reliably obtaining venous access is a barrier to the use of TIVA. In this instance, an inhalational induction may be performed. Once venous access is secured, the inhalational agent may be continued or TIVA may be started to maintain anaesthesia (Fig. 2). Our analysis indicates that for shorter cases, inhalational induction followed by intravenous maintenance

results in a higher CO_2e than continuing sevoflurane at a low fresh gas flow, due to the large quantity of infusions (much of which will not be administered to the patient) and consumables used. However, the consideration of the duration of anaesthesia when deciding between inhalational or intravenous maintenance following inhalational induction is only useful when an inhalational induction is planned. When TIVA is the planned technique, but inhalational induction is performed due to unsuccessful intravenous access, using the already-prepared intravenous drugs for maintenance would be the lower-carbon option, as these drugs would otherwise be wasted. Though it can be difficult to predict which patients may require inhalational induction, with appropriate strategies success rates of 90% can be achieved for venous access in the paediatric setting,[31] making TIVA a realistic option for induction in most cases.

In paediatric practice, N_2O is commonly used as a carrier gas for the inhalational induction of anaesthesia. However, although speed of onset is an often-stated justification for its use, when combined with sevoflurane (itself a fast-acting agent), the available evidence suggests that a reduction in induction time is rarely observed.[32-34] In contrast, evidence from our study and others clearly indicates the negative environmental impacts of N_2O.[4,5,11,12,35] Our comparisons show that even if N_2O is only used during induction of anaesthesia, the resulting effect on the carbon footprint of the anaesthetic is substantial. Furthermore, the risks to healthcare workers of occupational N_2O exposure will be increased during inhalational induction of anaesthesia.[36] Avoiding its use altogether should remain an important approach to reducing the environmental impact of paediatric anaesthetic practice.

Our study has several limitations. We did not account for any emissions associated with the transport of drugs and equipment for different techniques, which may vary depending on local procurement policy and drug supplies. We also assumed that, apart from propofol, remifentanil, sevoflurane, N_2O and the associated packaging and disposables, all anaesthetic techniques are equivalent in terms of the resources used. Whilst this is feasible in practice, our study cannot reflect the wide variety of ways in which colleagues may choose to alter their techniques when using intravenous or inhalational anaesthesia, including the use of processed EEG monitoring,[37] differences in the fresh gas flow rates and plasma concentration targets at certain points of a case, the use of different airway devices,[38,39] the proportion by which propofol and sevoflurane requirements are altered by the use of remifentanil,[23,24] and switching off anaesthetic gas scavenging systems during TIVA.[5] Nevertheless, we modelled what we feel are typical, responsibly-delivered anaesthetic techniques, including the use low fresh gas flows for inhalational cases. However, this may not be representative of practice in all institutions, and the circumstances we modelled may not be consistently achievable. For example, high fresh gas flows may be required to rapidly change the depth of anaesthesia or compensate for leaks, and may sometimes be used because of simply forgetting to reduce the flows.[10,28] Conversely, our method does not account for the common practice of 'tapering' the anaesthetic dose towards the end of a case, which may mean that the carbon footprints of both intravenous and inhaled anaesthesia are greater in our models than if delivered in this fashion.[40]

The disposal of anaesthetic waste is a controversial topic, with many inconsistencies found between organisations, departments and individuals. In our analysis, we assumed that consumables would be destroyed by high temperature incineration, which is associated with the highest CO_2e of any waste disposal method, although this should not always be the case. This may have resulted in the 'carbon

footprint' of intravenous techniques being inflated compared to if they were delivered with meticulous waste segregation. For example, disposal of consumable items through landfill where appropriate would reduce the carbon emissions associated with waste by 58%.[25] Furthermore, although materials generate different amounts of greenhouse gas when incinerated, we used a standard figure for mixed medical waste in our study as individual calculations were not available.[28]

There is no single source for reliable emissions data for all items consumed during anaesthesia, and there is a lack of data from manufacturers about the processes used in drug and equipment production. Therefore, the data used in our study have been assembled from a range of published sources (Table S1), encompassing different locations and times. It is possible that differences between these studies may affect the precision of our results.

Though we were able to find life cycle data for most components in this study, data were not available to calculate the carbon footprint of all of the excipients of crystalline remifentanil for reconstitution, which contains substances such as glycine and hydrochloric acid. Our analysis of remifentanil is therefore not fully complete. In addition, data were not available to calculate the emissions associated with making sterile saline for reconstitution. A study investigating the carbon footprint of morphine production found production of the active pharmaceutical ingredient generated only 12% of the total CO_2e,[41] with the remainder accounted for by mixing into 100ml sterile saline bags, sterilisation, and packaging for distribution. The carbon footprint of remifentanil TCI in our scenarios may therefore be higher than described by our data. However, this is not likely to significantly increase the carbon footprint of the entire technique.

Our supplementary data demonstrate which aspects of intravenous anaesthesia make the most significant contribution to its CO_2e (Table S1), how many vials of drug are opened when intravenous maintenance is used (Table S2), and how many consumable items would be used in the first hour of anaesthesia (Table S3). As shown in Table S1, the largest single contributor to intravenous anaesthesia are the 50 ml aliquots of propofol 1%, which account for 0.28kg CO_2e (not including vial itself), whereas 2 mg of remifentanil reconstituted to 100 ml in normal saline contributes 0.09kg, due largely to the mass disposed of by incineration. The consumable item that generates the largest CO_2e is the twin line infusion set (0.28 kg CO_2e), however, this item is only used once. The 60 ml syringes, which generates 0.14 kg CO_2e, will contribute a greater proportion as multiple syringes will be used from the start.

To further demonstrate the sensitivity of changes to the anaesthetic technique on the carbon footprint, we modelled the effect of adding a remifentanil infusion to inhalation maintenance (Fig 3) and removing remifentanil from intravenous maintenance (Fig. 5). After an inhalational induction, adding a remifentanil infusion to inhalational maintenance initially increases its carbon footprint. However, as use of remifentanil allows a lower concentration of sevoflurane to be used for maintenance, the CO_2e will only increase above that of intravenous maintenance after 74 minutes (5-20kg) / 120 minutes (30kg) / 170 minutes (40-50kg). Thus, adding a remifentanil allows anaesthetists to reduce the carbon footprint of inhalational maintenance, making it a more sustainable option than intravenous maintenance in a greater number of cases. Similarly, removing remifentanil from TIVA results in a further reduction in CO_2e, even when accounting for the increased volumes of propofol used. For example, for a 20kg child undergoing a one-hour case, the CO_2e generated when using propofol-only TIVA is half (0.63kg) of that of propofol and remifentanil

TIVA (1.26kg). In situations where potent analgesia is not required, or when this is provided by other means (e.g., a regional anaesthesia), removing remifentanil from the TIVA technique could lead to significant reductions in carbon footprint.

Though it was not feasible for us to present every variation of general anaesthetic technique, our data (Table S1) can offer insights into how clinicians may fine-tune their anaesthetic techniques to optimise its carbon footprint. For example, a 20 kg child undergoing a 60-minute anaesthetic would require only 29.6 ml of propofol. To optimise the 'carbon footprint', this could be drawn up using two 20 ml ampoules of propofol rather than a single 50ml vial, which would reduce CO_2e by 0.16 kg. For inhalational anaesthesia, lower fresh gas flows could be used for both induction and maintenance of inhalational anaesthesia, thereby reducing its environmental impact.[42] Further possibilities include turning off the fresh gas flow (or vapouriser) during airway instrumentation, though this can create a latent error (forgetting to turn them back on) so is avoided by some.[43] Nevertheless, we aimed primarily to represent typical practice rather than modelling the 'best' or 'worst case' scenario for any technique, to maximise the applicability of our findings to current clinical practice.

Importantly however, our study demonstrates how 'break-even points' – at which the 'carbon footprint' of one technique of anaesthesia exceeds another – are sensitive to fine-tuning of the anaesthetic technique. For example, our data indicates that inhalational induction then intravenous maintenance with propofol and remifentanil and inhalational induction then inhalational maintenance break-even at 105 minutes in 30kg children. In the intravenous maintenance technique, the first 50ml aliquot of propofol 1% runs out at 83 minutes. At this point, if the surgery was coming to an end, opening a 20ml ampoule of propofol 1% and drawing it up in a 20ml syringe would reduce the carbon footprint by 0.26kg, equivalent to 14 minutes of low-flow sevoflurane anaesthesia (0.018kg CO_2e per minute). So, the break-even point would occur at 91 minutes rather than 105.

It should be emphasised that whilst our study is focused on the climate impacts of general anaesthetic techniques, it does not account for the other ways in which anaesthetic agents may act as environmental toxins. For example, there are concerns that propofol and its metabolites may be toxic to aquatic life,[44] and the inhalation of volatile anaesthetic agents may impact the health of colleagues working in operating theatres and the post-anaesthetic recovery unit.[45]

Our study demonstrates a substantial reduction in the CO_2e generated by TIVA compared with inhalational anaesthesia in paediatric anaesthetic practice. However, for short cases after an inhalational induction, this reduction is not seen. We hope our models allow practitioners to adopt a more nuanced approach to estimating the lowest-carbon anaesthetic, according to patient factors (e.g., weight, likelihood of obtaining venous access) and predicted case duration. Although there are areas where further research is required, changes should urgently be made to routine practice in anaesthesia to meet carbon reduction targets. Using N_2O, even just for induction of anaesthesia, creates the largest increase in the carbon footprint of paediatric anaesthesia, whereas an increased use of TIVA could significantly reduce its climate impacts, particularly for longer procedures.

Details of authors' contributions

Study design: CS, CR, HN, TP

Data collection & analysis: HN

Writing of paper: HN, CR, CS, TP

Declaration of Interests

CS is a former trainee editor of *BJA Education*. JMTP is Environmental Advisor to the Royal College of Anaesthetists.

Funding

This work was conducted as part of a fellowship in sustainable healthcare supported by the North West School of Anaesthesia. The authors have no funding to declare.

Footnotes

* Graph showing CO_2e over time for TIVA and inhalational anaesthesia. Each line represents a different weight category. For inhalational anaesthesia, an initial steep increase occurs due to high fresh gas flows and high inhalational agent concentrations used during induction. The line continues to increase at a lower constant rate during low-flow inhalational maintenance. With TIVA, each line starts above zero, as the CO_2e of consumed items is 'counted' from when they are opened, rather than when they are used. As the case continues, a small decrease over time is seen, as less propofol will be disposed of in the sharps bin and therefore incinerated. As a new syringe and drug vial are opened, CO_2e increases in steps.

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Tables

Table 1 Patient characteristics used to programme pharmacokinetic models for TIVA models

Weight (kg)	Age (years, months)	Height (cm)
5	0y, 1.5m	56
10	1y 1m	77
20	5y, 8m	114
30	9y, 7m	136
40	12y, 5m	151
50	14y, 1m	163

Table 2 Carbon footprint of seven techniques of delivering anaesthesia to children at certain weights, expressed as total carbon dioxide equivalent generated, in kg, up to specific time points

Anaesthetic technique	Weight (kg)	CO_2e (kg)			
		Total at 30 minutes	Total at 60 minutes	Total at 120 minutes	Total at 480 minutes
Total intravenous anaesthesia with propofol and remifentanil	5	1.29	1.29	1.29	1.28
	10	1.29	1.28	1.27	1.81
	20	1.28	1.26	1.23	2.69
	30	1.26	1.24	1.79	3.58
	40	1.25	1.81	1.75	4.05
	50	1.24	1.79	2.31	5.53
Inhalational induction with sevoflurane, maintenance with sevoflurane	5-20	2.44	2.98	4.06	10.49
	30-50	3.78	4.31	5.39	11.82
Inhalational induction with sevoflurane, maintenance with propofol and remifentanil	5	3.31	3.31	3.31	3.30
	10	3.30	3.30	3.29	3.82
	20	3.30	3.28	3.25	4.71
	30	4.62	4.60	5.14	6.94
	40	4.61	5.17	5.11	7.42
	50	4.61	5.15	5.09	8.89
Total intravenous anaesthesia with propofol	5	0.67	0.66	0.66	1.08
	10	0.66	0.66	0.65	1.49
	20	0.65	0.63	1.06	2.31
	30	0.64	1.07	1.48	2.69
	40	1.07	1.05	1.46	3.53
	50	1.07	1.04	1.89	4.34
Inhalational induction with sevoflurane, maintenance with propofol	5	2.68	2.68	2.68	3.10
	10	2.68	2.67	2.66	3.51
	20	2.67	2.65	3.08	4.33
	30	3.99	4.42	4.39	6.05
	40	3.98	4.41	4.82	6.88
	50	3.98	4.40	4.80	7.70
Intravenous induction with propofol, maintenance with sevoflurane	5-20	2.05	2.58	3.65	10.09
	30-50	3.00	3.53	4.61	11.04
Inhalational induction with sevoflurane and nitrous oxide, maintenance	5-20	11.31	11.85	12.92	19.35
	30-50	18.55	19.09	20.16	26.60

with sevoflurane					
Inhalational induction with sevoflurane, maintenance with sevoflurane and remifentanil	5	2.79	3.14	3.86	8.14
	10	2.78	3.14	3.85	8.11
	20	2.78	3.13	3.83	8.46
	30	4.11	4.46	5.15	10.14
	40	4.11	4.45	5.13	10.07
	50	4.10	4.44	5.12	10.42

Captions for figures:

Figure 1: Carbon dioxide equivalent (CO_2e) plotted against time for inhalational induction and maintenance of anaesthesia (children weighing 5-20 kg – grey, children weighing 30-50 kg - black) and total intravenous anaesthesia, for children weighing 5 kg (red), 10 kg (green), 20 kg (purple), 30 kg (yellow), 40 kg (blue) and 50 kg (pink). (a): 0-480 minutes; (b) 0-60 minutes.*

Figure 2: Carbon dioxide equivalent (CO_2e) plotted against time for inhalational induction and maintenance of anaesthesia (children weighing 5-20 kg - grey, children weighing 30-50 kg - black) and inhalational induction then intravenous maintenance of anaesthesia with propofol and remifentanil, for children weighing 5 kg (red), 10 kg (green), 20 kg (purple), 30 kg (yellow), 40 kg (blue) and 50 kg (pink). (a): 0-480 minutes; (b) 0-120 minutes.

Figure 3: Carbon dioxide equivalent (CO_2e) plotted against time for inhalational induction then inhalational maintenance and remifentanil (dashed lines) and inhalational induction then intravenous maintenance with propofol and remifentanil (solid lines), for children weighing 5 kg (red), 10 kg (green), 20 kg (purple), 30 kg (yellow), 40 kg (blue) and 50 kg (pink). (a): 0-480 minutes; (b) 0-120 minutes.

Figure 4: Carbon dioxide equivalent (CO_2e) plotted against time for intravenous induction then inhalational maintenance of anaesthesia (children weighing 5-20 kg - grey, children weighing 30-50 kg - black), and for TIVA with propofol and remifentanil, for children weighing 5 kg (red), 10 kg (green), 20 kg (purple), 30 kg (yellow), 40 kg (blue) and 50 kg (pink). (a): 0-480 minutes; (b) 0-60 minutes

Figure 5: Carbon dioxide equivalent (CO_2e) plotted against time for intravenous induction then inhalational maintenance of anaesthesia (children weighing 5-20 kg - grey, children weighing 30-50 kg - black), and for propofol-only TIVA, for children weighing 5 kg (red), 10 kg (green), 20 kg (purple), 30 kg (yellow), 40 kg (blue) and 50 kg (pink). (a): 0-480 minutes; (b) 0-60 minutes.

Figure 6: Carbon dioxide equivalent (CO_2e) plotted against time for inhalational induction and maintenance of anaesthesia using sevoflurane (children weighing 5-20kg – solid grey, children weighing 30-50kg solid black) and inhalational induction and maintenance with nitrous oxide for induction alone (children weighing 5-20kg – dashed grey, children weighing 30-50kg – dashed black). (a): 0-480 minutes; (b) 0-60 minutes.