Environmental and patient safety outcomes of a health-system Green Anesthesia Initiative (GAIA): a retrospective observational cohort study

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Summary

Background Inhaled anaesthetics are greenhouse gases. However, changes in the delivery of inhaled anaesthetics can mitigate environmental impact. We hypothesised that system-wide changes to the delivery of anaesthesia care would reduce environmental harm without compromising patient outcomes.

Methods We launched the Green Anesthesia Initiative (GAIA) in March, 2022, with the aims of reducing the use of nitrous oxide, using less environmentally harmful inhaled fluorinated ethers, and increasing intravenous anaesthetic use. In this retrospective cohort study, we used electronic health record data from general anaesthetics performed on all patients older than 1 year between March 1, 2021, and Feb 28, 2023, at a single US academic medical centre across multiple sites, collecting data from before and after the introduction of GAIA. Patients with missing or invalid data recorded by the anaesthesia machine, patients given general anaesthetics for electroconvulsive therapy, and patients who met American Society of Anesthesiologists Physical Status Classification 6 were excluded. Using multivariable modelling, we compared estimated CO_2 equivalents and, secondarily, anaesthetic dose, postoperative nausea and vomiting, pain scores on a 0–10 scale, and reports of intraoperative awareness with explicit recall.

Findings We recorded 45 692 patients pre-intervention (23 193 [50·8%] female, 22 494 [49·2%] male, five [<0·1%] unknown) and 47 199 post-intervention (23 981 [50·8%] female, 23 209 [49·2%] male, nine [<0·1%] unknown). After the implementation of GAIA, CO_2 equivalents were reduced by 14·38 kg per patient (95% CI –14·68 to –14·07; p<0·0001). There was no clinically meaningful difference in median anaesthetic delivered (minimum alveolar concentration –0·02 [95% CI –0·02 to –0·01]; p<0·0001) nor pain scores (–0·34 [–0·39 to –0·29]; p<0·0001). Postoperative nausea and vomiting was unchanged (odds ratio 0·98 [95% CI 0·94–1·02]; p=0·26). A small number of definite intraoperative awareness events were reported in both periods (one pre-intervention and two post-intervention).

Interpretation A health-system wide intervention reduces greenhouse gas emissions attributable to anaesthesia care without detriment to patient outcomes.

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Introduction

Conservative estimates suggest that inhaled anaesthetic agents alone account for 3% of greenhouse gas emissions from the health system.[1] Tractable interventions to reduce direct greenhouse gas emissions include careful selection of inhaled anaesthetic agents, use of lower fresh gas flows, and use of intravenous agents for the maintenance of general anaesthesia.[2,3]

To illustrate the variability among anaesthetics, consider two modern, inhaled fluorinated-ether anaesthetic agents, sevoflurane and desflurane, which have minimal differences in clinical characteristics but almost 50-fold difference in environmental impact.[4–6] Modern anaesthetic delivery systems (ie, anaesthesia machines) use a closed rebreathing circuit with CO_2 absorption; the patient breathes and rebreathes from the circuit. Inhaled anaesthetic agents are added to this breathing circuit alongside controlled quantities of oxygen and air as fresh gas flow. Anaesthetic agent consumption is directly related to the fresh gas flow into the circuit. The volume of fresh gas flow can be substantially less than the volume inhaled in 1 min due to use of this rebreathing circuit. Reductions in fresh gas flow offer an additional pathway to reducing the climate impact without reducing therapeutic anaesthesia concentrations, but this approach has sometimes been misconstrued in popular media as a reduction in anaesthetic use and an increased risk for patient harm.[7] This crucial consideration of patient outcomes in the context of reducing adverse

Research in context

Evidence before this study

Inhaled anaesthetic agents are a source of environmental harm in modern health care. These agents include both fluorinated volatile agents and nitrous oxide. Relatively simple changes in the anaesthetic care process can considerably reduce the adverse environmental impact. However, these changes have sometimes been misconstrued as a reduction in therapeutic anaesthesia, which would risk patient harm. A PubMed review of literature was performed with the search terms "anesthetic greenhouse patient" and ("anesthesia" AND "environmental impact") for papers published from database inception until Dec 31, 2024. Although previous work has described the effect of the elimination of specific anaesthetic agents or the promotion of the use of less environmentally harmful anaesthetic agents, data on patient outcomes were not identified during the literature search.

Added value of this study

The substitution of inhaled anaesthetic agents can reduce the adverse environmental impact without meaningful reduction in equipotent anaesthetic use. We found no meaningful detrimental effect on patient reports of pain, nausea and vomiting, or intraoperative awareness. Our findings suggest that improvements in environmental sustainability of anaesthesia can occur without evidence of patient harm.

Implications of all the available evidence

Modifications to anaesthesia care practice can be performed to substantially reduce environmental impact without detriment to patient outcome. This study suggests that mitigating environmental impact and safe clinical care are not in conflict with each other and consequently creates further scope to reduce adverse environmental impact.

environmental impact has not been addressed in previously reported work.

In 2022, we introduced the Green Anesthesia Initiative (GAIA) to reduce the environmental impact of anaesthesia care across a large academic health system by a suite of measures, including the elimination or reduction in use of the most environmentally harmful inhaled anaesthetic agents. We hypothesised that this intervention would reduce the attributable environmental footprint, as expressed in CO_2 equivalents during the maintenance of anaesthesia, without affecting anaesthetic delivery, measured as minimum alveolar concentration (MAC) ratio (ie, a standard anaesthetic dosing metric), and patient outcomes.

Methods

Study design

In this retrospective observational study, we assessed information derived from the perioperative records of all patients undergoing general anaesthesia across our institution (University of Michigan, MI, USA) between March 1, 2021, and Feb 28, 2023. Approval was received from the University of Michigan Institutional Review Board of the Medical School (IRBMED; references HUM00217676 and HUM00232871). The study was deemed exempt from requiring patient consent and Health Insurance Portability and Accountability Act authorisation was obtained from the Privacy Board of the University of Michigan IRBMED. Our system-wide intervention was formally introduced to the department via email from the Chair and subsequent presentations in March, 2022, but was developed and discussed between November, 2021, and February, 2022, before being formally initiated. We defined the 1-year period before March 1, 2022, as pre-intervention and the 1-year period after as post-intervention. An a priori statistical analysis plan was finalised before the construction of statistical models. Our report follows the RECORD extension of the STROBE reporting statement.[8]

GAIA

GAIA is a health-system-wide programme designed to decrease the environmental impact of anaesthesia care. Our health system includes over 110 anaesthetising locations across three distinct inpatient hospitals and three freestanding ambulatory surgery sites, with approximately 183 attending faculty anaesthesiologists, 129 residents and fellows, and 218 nurse anaesthetists (as of Feb 29, 2024).

Agent substitution in this multisite effort was accomplished by encouraging alternatives to the use of the inhaled agent nitrous oxide and the careful selection of inhaled volatile agent. This substitution was encouraged by providing equipment to allow the use of sevoflurane (the least environmentally harmful volatile agent) instead of isoflurane (previously the most commonly used volatile agent at our institution), the removal of desflurane (the most environmentally harmful volatile agent) from the institutional formulary, and the encouragement of the use of intravenous anaesthetic drugs for anaesthetic maintenance. The dissemination and implementation of this plan was accomplished by townhall meetings; focused communication, both in email and in person, to each clinical subspeciality group from a lead clinician; and the provision of sevoflurane vaporisers (an anaesthesia machine module to allow the use of this agent) with the simultaneous progressive removal of isoflurane and desflurane vaporisers from clinical use. Progress was monitored by department leadership via a custom-developed progress dashboard examining changes by clinical site. We did not develop clinician-level audit and feedback tools specifically for this intervention; however, we drew attention to an existing multicentre quality improvement dashboard and email

that described progress in mean fresh gas flow target and patient-estimated CO_2 equivalents during maintenance.

Department education included reminders on the importance of rapidly setting a reduced fresh gas flow after the airway has been secured. Decreasing fresh gas flow during anaesthesia reduces the amount of fresh oxygen and new inhaled anaesthetic agent added to the circuit each minute. Oxygen or inhaled anaesthetic agent that is above the capacity of the circuit and is not used for metabolism is released into the atmosphere. Therefore, fresh gas flows and oxygen supply exceeding metabolic demands lead to the excess use of inhaled anaesthetic agent that does not benefit the patient, but has environmental consequences. Crucially, reducing fresh gas flow does not decrease the concentration of inhaled anaesthetic agent delivered to the patient, which is key to therapeutic effect.

Patients and procedures

We included data from all general anaesthetics performed at our institution, documented by the anaesthesia clinician using an electronic medical record as part of routine clinical care in real time (paper records were only used during electronic health record downtime). In our analysis, patients were excluded if the monitoring of minute-to-minute end-tidal agent or information regarding the fresh gas flow recorded by the anaesthesia machine (required to estimate environmental impact) were missing or invalid. We also excluded patients on whom general anaesthetics were performed in a location dedicated to electroconvulsive therapy. General anaesthetics performed for electroconvulsive therapy (ie, typically 3–5-min anaesthetics accomplished by a single bolus of intravenous sedative–hypnotic agent and muscle relaxant) were excluded. We excluded patients younger than 1 year to allow us to calculate anaesthetic exposure using the age-adjusted MAC ratio; there was no upper age limit for inclusion.[9] Finally, we excluded patients who met the American Society of Anesthesiologists Physical Status Classification 6 (ie, "A declared brain-dead patient whose organs are being removed for donor purposes").[10]

Presented information, including sex, was derived from electronic health records to create an operational dataset used for management of GAIA. This dataset reports the use of each anaesthetic agent and key outcomes in the study on a patient-by-patient basis. Standardised data-handling methods developed by the Multicenter Perioperative Outcomes Group (MPOG), a research and quality improvement consortium of more than 60 hospitals and health systems across the USA, were used to describe study variables.[11] One author (DAC) specified the data to be included in this analysis from the available primary dataset.

Outcomes

The primary outcome was the estimated CO_2 equivalents during the maintenance of anaesthesia. We calculated CO_2 equivalents using methods developed by MPOG for subsequent use in a quality measure.[12] This measurement period covers the placement of the airway to the removal of the airway, with hierarchical alternatives defined if either of these documentation elements were not present (eg, the patient arrived with the airway in place or the airway was not removed and the patient was transferred to the intensive care unit). Full details of this calculation are provided in the methods section of the appendix (p 2). In brief, this estimate is based on the cumulative minute-to-minute calculation of the volume of anaesthetic agent used, derived from the measured inspired agent concentration multiplied by the recorded fresh gas flow. This calculation is based on the anaesthesia agent delivered to the patient and estimated on a per-patient basis instead of a calculation derived from pharmacy purchasing records. The required information for estimation is based on anaesthetic agents delivered to the patient and is automatically collected in each electronically documented anaesthesia record.

See Online for appendix

The secondary outcomes were median age-adjusted MAC ratio (ie, a standard index of anaesthetic dosing, calculated from end-tidal agent concentration, and age adjusted by the Mapleson equation[13]); the first-recorded pain score for each patient, on a 0–10 scale, in the post-anaesthesia care unit (PACU); postoperative nausea and vomiting reported or treated in the PACU, as per the MPOG reporting definitions;[14] and intraoperative awareness with explicit recall (ie, description of a memory of specific events that occurred during a period of intended unconsciousness).

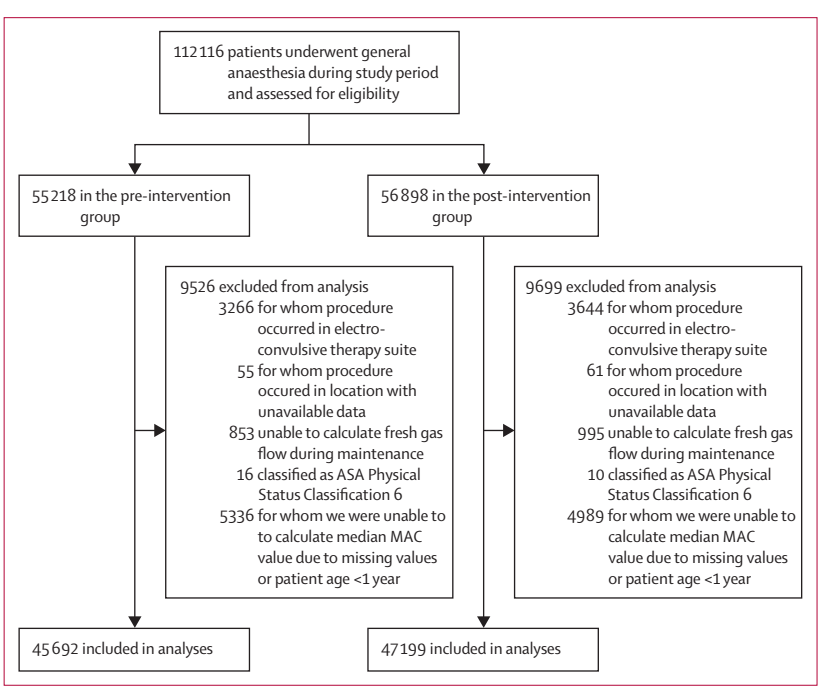

Figure 1: **Study profile**
ASA=American Society of Anesthesiologists. MAC=minimum alveolar concentration.

Intraoperative awareness with explicit recall was established based on a review of patient reports made to the quality improvement and safety programme. Reported events were reviewed by two unmasked investigators (DH and DAC) who assessed the reported event narratives, anaesthetic, and medical records for reported patients.

	Both groups (N=92 891)		Pre-intervention group (n=45 692)		Post-intervention group (n=47 199)		Standardised difference (pre-intervention *vs* post-intervention)
	Patients	Mean (SD)	Patients	Mean (SD)	Patients	Mean (SD)	
Patient characteristics							
Sex*	..	..	..	..	..	..	0·01
Male	45 703 (49·2%)	..	22 494 (49·2%)	..	23 209 (49·2%)	..	..
Female	47 174 (50·8%)	..	23 193 (50·8%)	..	23 981 (50·8%)	..	..
Age, years (continuous value)	..	44·1 (24·9)	..	44·5 (24·7)	..	43·8 (25·1)	–0·03
Age category	..	..	..	..	..	..	0·06
Toddler (12–23 months)	2316 (2·5%)	..	1003 (2·2%)	..	1313 (2·8%)	..	..
Child (early; 2–5 years)	6125 (6·6%)	..	2906 (6·4%)	..	3219 (6·8%)	..	..
Child (middle; 6–11 years)	6014 (6·5%)	..	2796 (6·1%)	..	3218 (6·8%)	..	..
Adolescent (early; 12–18 years)	6577 (7·1%)	..	3297 (7·2%)	..	3280 (7·0%)	..	..
Adolescent (late; 19–21 years)	2403 (2·6%)	..	1229 (2·7%)	..	1174 (2·5%)	..	..
22–34 years	9676 (10·4%)	..	4720 (10·3%)	..	4956 (10·5%)	..	..
35–44 years	9258 (10·0%)	..	4582 (10·0%)	..	4676 (9·9%)	..	..
45–64 years	25 882 (27·9%)	..	13 019 (28·5%)	..	12 863 (27·3%)	..	..
65–84 years	23 262 (25·0%)	..	11 453 (25·1%)	..	11 809 (25·0%)	..	..
≥85 years	1378 (1·5%)	..	687 (1·5%)	..	691 (1·5%)	..	..
ASA physical status classification†	..	..	..	..	..	..	0·03
Class 1	10 463 (11·3%)	..	4970 (10·9%)	..	5493 (11·7%)	..	..
Class 2	32 755 (35·3%)	..	16 313 (35·7%)	..	16 442 (34·9%)	..	..
Class 3	42 554 (45·8%)	..	20 805 (45·6%)	..	21 749 (46·1%)	..	..
Class 4	6694 (7·2%)	..	3378 (7·4%)	..	3316 (7·0%)	..	..
Class 5	356 (0·4%)	..	191 (0·4%)	..	165 (0·4%)	..	..
Airway management technique	..	..	..	..	..	..	0·04
Endotracheal tube	71 097 (76·5%)	..	35 216 (77·1%)	..	35 881 (76·0%)	..	..
Laryngeal mask airway	14 890 (16·0%)	..	7323 (16·0%)	..	7567 (16·0%)	..	..
Other	6904 (7·4%)	..	3153 (6·9%)	..	3751 (8·0%)	..	..
Surgical service	..	..	..	..	..	..	0·05
Cardiac	4259 (4·6%)	..	2120 (4·6%)	..	2139 (4·5%)	..	..
ENT, OMFS, and ophthalmology	19 632 (21·1%)	..	9435 (20·7%)	..	10 197 (21·6%)	..	..
General surgery and trauma	21 343 (23·0%)	..	10 481 (22·9%)	..	10 862 (23·0%)	..	..
Neurosurgery	4564 (4·9%)	..	2106 (4·6%)	..	2458 (5·2%)	..	..
Obstetrics and gynaecology	6272 (6·8%)	..	3124 (6·8%)	..	3148 (6·7%)	..	..
Offsite or other	7936 (8·5%)	..	3949 (8·6%)	..	3987 (8·5%)	..	..
Orthopaedics	9469 (10·2%)	..	4880 (10·7%)	..	4589 (9·7%)	..	..
Plastics	5130 (5·5%)	..	2516 (5·5%)	..	2614 (5·5%)	..	..
Thoracic	1991 (2·1%)	..	1035 (2·3%)	..	956 (2·0%)	..	..
Transplantation	1507 (1·6%)	..	712 (1·6%)	..	795 (1·7%)	..	..
Urology	9090 (9·8%)	..	4513 (9·9%)	..	4577 (9·7%)	..	..
Vascular	1698 (1·8%)	..	821 (1·8%)	..	877 (1·9%)	..	..
Site within health system	..	..	..	..	..	..	0·05
Cardiovascular centre	9469 (10·2%)	..	4727 (10·4%)	..	4742 (10·1%)	..	..
Labour and delivery	674 (0·7%)	..	356 (0·8%)	..	318 (0·7%)	..	..
Children's hospital	23 918 (25·8%)	..	11 223 (24·6%)	..	12 695 (26·9%)	..	..
Outpatient sites	16 540 (17·8%)	..	8266 (18·1%)	..	8274 (17·5%)	..	..
Main hospital	42 290 (45·5%)	..	21 120 (46·2%)	..	21 170 (44·9%)	..	..

(Table 1 continues on next page)

	Both groups (N=92 891)		Pre-intervention group (n=45 692)		Post-intervention group (n=47 199)		Standardised difference (pre-intervention *vs* post-intervention)
	Patients	Mean (SD)	Patients	Mean (SD)	Patients	Mean (SD)	
(Continued from previous page)							
Process of care							
Duration of anaesthesia care (min)	..	173·3 (128·3)	..	174·5 (128·3)	..	172·1 (128·3)	–0·02
Fresh gas flow between induction end and surgery end (L/min)	..	2·6 (1·5)	..	2·7 (1·5)	..	2·6 (1·5)	–0·06
Sevoflurane used	..	..	..	..	..	..	0·50
No	40 564 (43·7%)	..	25 553 (55·9%)	..	15 011 (31·8%)	..	..
Yes	52 327 (56·3%)	..	20 139 (44·1%)	..	32 188 (68·2%)	..	..
Total duration of sevoflurane use, when used (min)‡	..	97·0 (92·7)	..	84·1 (82·3)	..	105·0 (97·9)	0·23
Isoflurane used	..	..	..	..	..	..	–0·37
No	59 602 (64·2%)	..	25 276 (55·3%)	..	34 326 (72·7%)	..	..
Yes	33 289 (35·8%)	..	20 416 (44·7%)	..	12 873 (27·3%)	..	..
Total duration of isoflurane use, when used (min)‡	..	166·4 (131·4)	..	162·0 (130·4)	..	173·5 (132·7)	0·09
Desflurane used	..	..	..	..	..	..	–0·06
No	92 629 (99·7%)	..	45 484 (99·5%)	..	47 145 (99·9%)	..	..
Yes	262 (0·3%)	..	208 (0·5%)	..	54 (0·1%)	..	..
Total duration of desflurane use, when used (min)‡	..	66·6 (77·0)	..	72·8 (72·5)	..	42·7 (89·0)	–0·37
Nitrous oxide used	..	..	..	..	..	..	–0·62
No	52 625 (56·7%)	..	19 047 (41·7%)	..	33 578 (71·1%)	..	..
Yes	40 266 (43·4%)	..	26 645 (58·3%)	..	13 621 (28·9%)	..	..
Total duration of nitrous oxide use, when used (min)‡	..	45·5 (59·0)	..	53·1 (63·3)	..	30·5 (46·1)	–0·41
Total nitrous oxide use per patient, when used (litres)‡	..	57·2 (65·9)	..	66·6 (71·1)	..	39·2 (49·9)	–0·45
Propofol infusion used	..	..	..	..	..	..	0·04
No	54 112 (58·3%)	..	27 046 (59·2%)	..	27 066 (57·3%)	..	..
Yes	38 779 (41·8%)	..	18 646 (40·8%)	..	20 133 (42·7%)	..	..
Total duration of propofol infusion use, when used (min)‡	..	112·3 (106·1)	..	111·7 (106·0)	..	112·9 106·1	0·01

Data are n (%) and mean (SD) unless otherwise specified. A total of 41 590 L of nitrous oxide were used, 27 358 L in the pre-intervention group and 14 232 L in the post-intervention group. ASA=American Society of Anesthesiologists. ENT=ear, nose, and throat. OMFS=oral and maxillofacial surgery. *Data missing from five (<0·1%) patients in the pre-intervention group and nine (<0·1%) in the post-intervention group. †Data missing from 35 (<0·1%) patients in the pre-intervention group and 34 (<0·1%) in the post-intervention group. ‡Refers to the use during the entire period of anaesthesia care (ie, including both induction and maintenance).

Table 1: **Population and process comparisons between the pre-intervention group and the post-intervention group**

They assembled relevant information about events into a narrative, presented in random order, with dates and patient identifiers removed to two masked reviewers (PP and TZD) with experience in assessing intraoperative awareness events. The masked reviewers classified events as definite, possible, or not intraoperative awareness with explicit recall.[15,16] If there was disagreement between reviewers, a third masked reviewer (GAM) with experience in assessing intraoperative awareness adjudicated.

Statistical analysis

The data are described with means with SDs and proportions with standardised differences when appropriate. We used SAS (version 9.4) for analyses. We compared variables before and after intervention using standardised differences, which describe the magnitude of the effect for any differences between the two populations.[17,18] We considered a standardised difference of greater than 0·2 or less than –0·2 to be indicative of clinically relevant effect size. A complete-case analysis was used.

To test our hypotheses, we used generalised estimating equations (GEEs) with identity link for continuous outcomes and logit for binary outcomes. We chose a GEE approach rather than an interrupted time series analysis because GEE does not require an assumption of linearity in the change over time and does not require an assumption of normal distribution of key variables. For

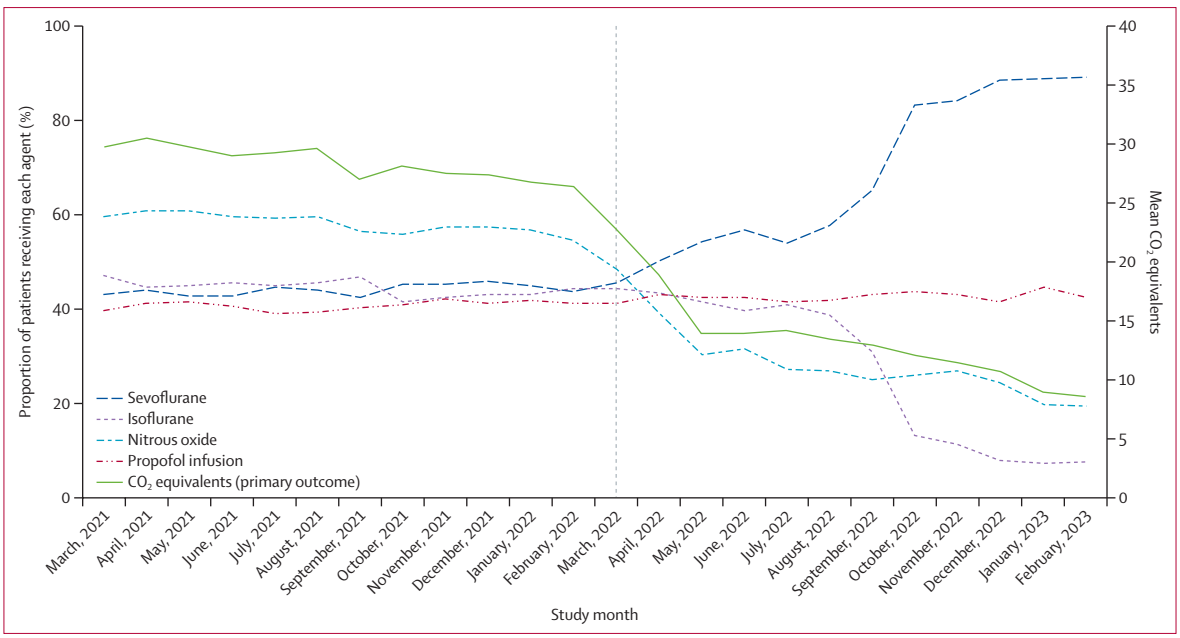

Figure 2: **Process and outcome over the study period**
The vertical grey line indicates the formal introduction of the Green Anesthesia Initiative intervention.

all outcomes, we used the exchangeable correlation matrix. We assessed multicollinearity using a variance inflation factor threshold of more than 10. The decision on the composition of the final model was primarily based on clinical characteristics of patient population to adjust for any change in the population composition that might have incidentally occurred over time.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

In total, 112 116 anaesthetic procedures were assessed for eligibility, resulting in 92 891 procedures included in the final analysis (45 692 in the pre-intervention group and 47 199 in the post-intervention group; figure 1). There were no major differences in distributions of baseline population characteristics between the pre-intervention and post-intervention groups (table 1).

Process-of-care measures showed differences after the GAIA intervention, with large reductions in the proportion of cases in which nitrous oxide (58·3% in the pre-intervention group *vs* 28·9% in the post-intervention group, standardised difference –0·62) and isoflurane (44·7% *vs* 27·3%, –0·37) were administered, and an increased use of the more environmentally favourable anaesthetic sevoflurane (44·1% *vs* 68·2%, 0·50; table 1). The inclusion of a propofol infusion in the anaesthetic technique did not change over the measurement periods (figure 2) nor between pre-intervention and post-intervention groups (40·8% *vs* 42·7%, 0·04; table 1). Mean fresh gas flows did not differ before and after intervention (2·7 L/min *vs* 2·6 L/min, –0·06; table 1). Unadjusted mean estimates of CO_2 equivalents during maintenance decreased from 28·5 kg per case (SD 33·7) to 13·5 kg per case (SD 19·5; standardised difference –0·54; appendix p 4).

In multivariable models, accounting for patient age, American Society of Anesthesiologists Physical Status Score, surgical service, airway management technique, and duration of anaesthesia care, the GAIA intervention was associated with a mean decrease of 14·38 kg per case (95% CI –14·68 to –14·07; p<0·0001) in CO_2 equivalents during the maintenance of anaesthesia (table 2; appendix p 4). We report per-patient values, rather than per hour, to improve the applicability of our results and comparisons to other literature.

By use of similar models, the median age-adjusted MAC ratio in cases in which the maintenance of anaesthesia only involved inhaled agent decreased by 0·02 units (95% CI –0·02 to –0·01; p<0·0001; table 2). This decrease is clinically insignificant based on prespecified criteria and because MAC ratio is typically reported on anaesthesia monitors only to one decimal place. Thus, a meaningful change in MAC ratio would be at least an order of magnitude greater than what was observed. In a sensitivity analysis, including cases for which maintenance of anaesthesia could include both inhaled agents and a propofol infusion, the median age-adjusted MAC ratio also decreased by a clinically insignificant 0·02 units (–0·02 to –0·01; p<0·0001). Full model parameters are provided in the appendix (pp 5–9).

First-recorded pain score decreased by a clinically insignificant –0·34 units (95% CI –0·39 to –0·29, p<0·0001) on a 1–10 scale. The incidence of postoperative nausea and vomiting in the PACU did not change (odds ratio 0·98, 95% CI 0·94 to 1·02; p=0·26; figure 3).

Seven candidate intraoperative awareness events were identified from clinical event reports. Of these events, three were classified as representing definite intraoperative awareness: one event was pre-intervention and two were post-intervention (appendix p 10). Due to the extremely low incidence of events, no statistical comparison is provided.

	Estimate of difference (95% CI)	Odds ratio (95% CI)	p value
Primary outcome: CO_2 equivalents (kg/patient)	–14·38 (–14·68 to –14·07)	..	<0·0001
Secondary outcomes			
Median MAC ratio from inhaled anaesthetics when general anaesthesia was exclusively with inhaled anaesthetic	–0·02 (–0·02 to –0·01)	..	<0·0001
Median MAC ratio from inhaled anaesthetics when general anaesthesia included an inhaled anaesthetic	–0·02 (–0·02 to –0·01)	..	<0·0001
First-recorded postoperative pain score (0–10 scale)	–0·34 (–0·39 to –0·29)	..	<0·0001
Postoperative nausea and vomiting	..	0·98 (0·94 to 1·02)	0·26

Outcome estimates emerge from models adjusting for health-system location, age category, American Society of Anesthesiologists Physical Status classification, airway management technique, surgical service, and duration of anaesthesia care. MAC=minimum alveolar concentration.

Table 2: **Adjusted study outcomes**

Discussion

In this report, we describe the halving of estimated CO_2 emissions attributable to the maintenance of anaesthesia in a health system-wide initiative over the period of 1 year. Importantly, this improvement was not associated with a clinically meaningful change in therapeutic anaesthetic delivery, pain scores, postoperative nausea and vomiting in the recovery room, or intraoperative awareness with explicit recall. The magnitude of the change we report should be placed in context. Across the 1-year intervention period at a single institution, we halved CO_2 emissions during anaesthesia maintenance, which equates to 2·7 million km (1·7 million miles) driven by a standard passenger car.[19] Although other investigators have reported changes of similar or greater magnitude, this study advances the field by showing effects across a large, organisationally diverse health system, and, crucially, showing no difference in relevant patient experience and safety outcomes, which other authors have identified as fundamental gaps requiring further work.[20–26]

The minimal change in fresh gas flows suggests that the observed difference was accomplished by the substitution of anaesthetic agents. The stable age-adjusted MAC ratios indicate that this change resulted in the use of equipotent anaesthetic doses, arguing against a misunderstanding that reducing environmental impact requires the use of less anaesthesia in a way that compromises patient outcome. The three patient-centred secondary outcomes reported represent patient priorities in the selection of anaesthesia technique.[27] We show that improving environmental impact and the patient's outcome and safety are not in conflict.

The mean fresh gas flow remains relatively high at our institution and will be an opportunity for future improvement in environmental performance. We did not pursue reductions in fresh gas flow (and consequently agent consumption) during the first phase of the initiative due to the increased complexity and cognitive burden of obtaining and maintaining target oxygen and anaesthetic agent concentrations, even in the presence of continuous end-tidal monitoring.[28–30] Technologies to support automated targeting of a set agent and oxygen concentration, which have been available in Europe for many years, are new to the US market, and our institution is undergoing a multiyear process to equip our anaesthesia machines to incorporate these features, after which we will work to decrease fresh gas flows. Preliminary work suggests that additional reductions of approximately 30% could be possible.[31]

Intraoperative awareness with explicit recall is a feared complication of anaesthesia care with substantial psychological sequelae.[32,33] In our dataset, we did not detect a change in the rate of definite intraoperative awareness; the absence of a meaningful change in MAC ratio—a surrogate marker of anaesthetic depth—suggests that surgical patients in this cohort were not more susceptible to insufficient inhaled anaesthesia.

However, we noted that two of the three intraoperative awareness events were associated with total intravenous anaesthesia, which excludes the use of potent volatile anaesthetic agents or nitrous oxide and instead provides anaesthetic medication by continuous infusion into a vein. This finding is relevant for several reasons. First, administering total intravenous anaesthesia eliminates the greenhouse gas effect of inhaled anaesthetics, although it might have other environmental impacts of unclear importance.[34] Second, total intravenous anaesthesia has been associated with a higher incidence of intraoperative awareness with explicit recall.[35] In the USA, target-controlled infusion pumps, in which the clinician sets the desired plasma concentration and the pump adjusts the medication infusion rate to achieve this plasma concentration, are not available outside of research settings. Instead, all changes to infusion rates have to be performed by the clinician,[36] which increases the risks of not reaching an adequate plasma concentration of anaesthetic agent and suboptimal down-titration of anaesthetic agent, resulting in delays to emergence. Several randomised trials have indicated that use of electroencephalographic monitoring can reduce

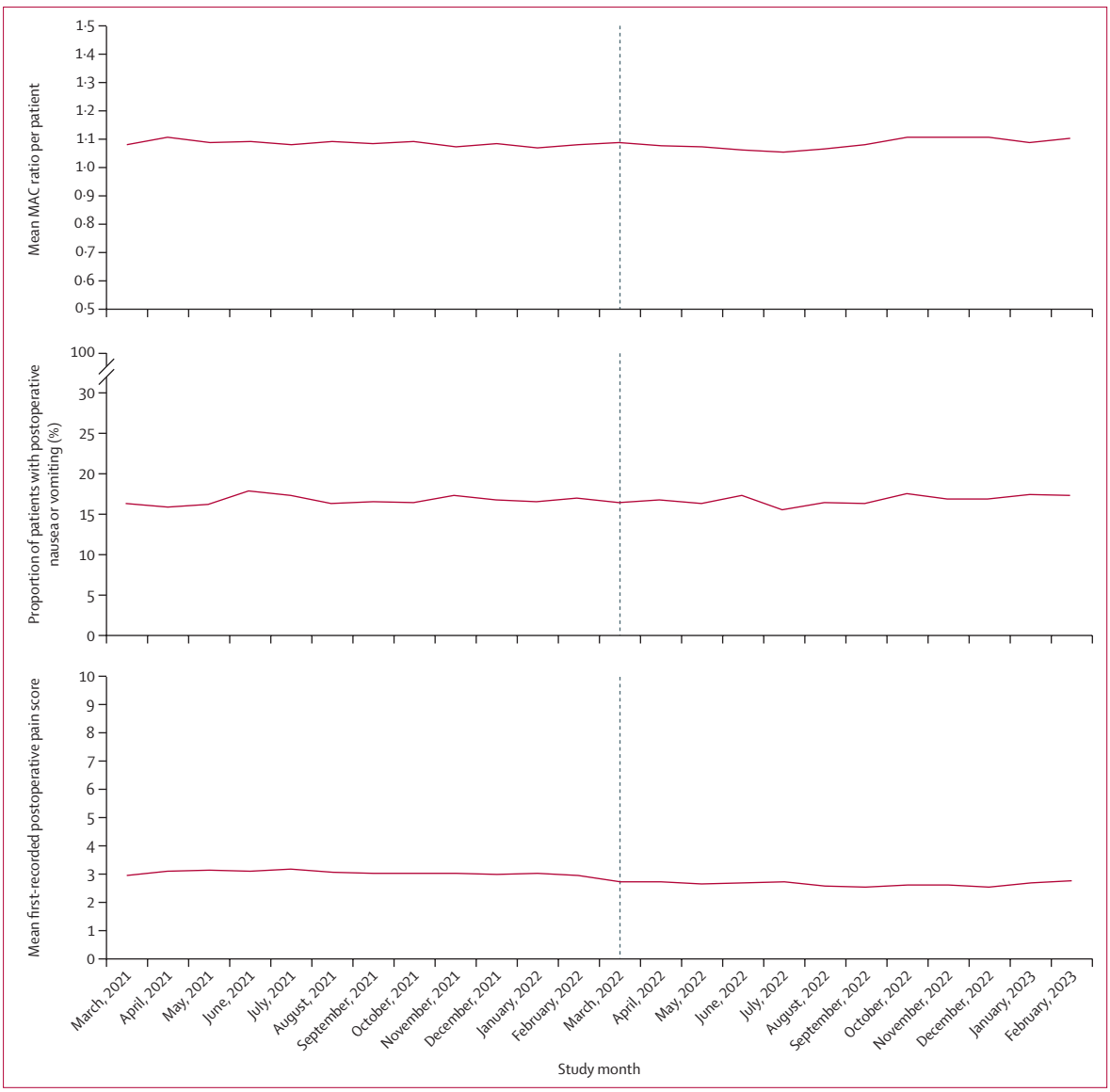

Figure 3: **Secondary outcomes over the study period**
The vertical grey line indicates the introduction of the Green Anesthesia Initiative intervention. MAC=minimum alveolar concentration.

the incidence of intraoperative awareness during total intravenous anaesthesia.[37,38] A shift in anaesthetic regimen to intravenous agents for environmental reasons might increase the risk of adverse patient outcomes, which should be mitigated by additional monitoring modalities. However, importantly, the two patients in this study with definite intraoperative awareness receiving only intravenous anaesthetics were distributed equally across the pre-intervention and post-intervention periods.

Although these data are derived from a single health system, the organisational diversity in both surgical population and practice style supports the generalisability of GAIA interventions to other settings. Each anaesthesia practice is at a different starting place, depending on their baseline anaesthetic agent selections. Our practice included nitrous oxide before the GAIA intervention, which disproportionately contributed to the reported CO_2 values and represented a clear pathway to marked reductions in environmental harm.

Nitrous oxide represents a major target of intervention because it is typically delivered as 50–70% of fresh gas flow compared with less than 3% for commonly used inhaled agents, such as sevoflurane and isoflurane. To further mitigate losses of nitrous oxide, any use should be from cylinders attached to the anaesthesia machine. Pipeline systems, in which a hospital distributes nitrous oxide from a central source, have extremely large percentage losses in distribution.[39–41] A considerable reduction in nitrous oxide use facilitates a transition to

cylinders. At our institution, we estimated similar apparent distributive losses, and GAIA has also allowed us to subsequently decommission the pipeline source.

A baseline differential use of nitrous oxide across surgical services, patient ages, and sites within the health system might have accounted for the substantial associations of these factors with changes in estimated CO_2 emissions. These changes might also be accounted for by the differential adoption of the GAIA programme across this organisationally diverse health system. Further progress to reduce environmental impact remains possible through decreases in fresh gas flow and an increased adoption of intravenous anaesthetics.

Another limitation is that exact conversion factors to calculate CO_2 equivalency can vary by source. The time horizons used, including the categorisation as near-term versus long-term climate forcers, and the role of production emissions and use of CO_2 equivalence, are subject to robust academic debate.[42–44] As such, estimates will vary based on these assumptions. However, nitrous oxide and desflurane elimination are major priorities given their lengthy atmospheric life and substantial impact.[44] Because this study is a secondary use of electronic health record data, the primary purpose of which is clinical documentation, the possibility of misclassification of some variables exists. This concern is mitigated by our use of an entirely automated collection and measurement of data (eg, anaesthesia agent and gas flows needed for primary outcome calculations are directly inputted from the anaesthesia machine to the electronic health record), the use of a validated and extensively used data source, and broad inclusion criteria, which reflect nearly all general anaesthetics provided at our institution. Our analysis emphasised the maintenance period of anaesthesia, consistent with the methodology used in the source data, but the short induction period in which inhaled anaesthetic agents might also be used represents an additional target for improvement. Unmeasured confounders might remain in our analysis. The measurement of intraoperative awareness with explicit recall is known to be captured at a lower rate with spontaneous patient reports in quality improvement systems than in prospective studies using a formal interview.[45] However, although formal post-operative interviews at multiple timepoints are used in prospective trials, this method is not standard of care. Therefore, although the overall incidence of intra-operative awareness might be higher than what was measured, there is no evidence to suggest that there would be higher discrepancies between spontaneous reports and formal interviews in our pre-intervention versus post-intervention periods.

In conclusion, this work shows the feasibility of making substantial improvement to the environmental impact of anaesthesia care at a systems level, with no appreciable adverse effect on patient-sensitive outcome measures.

Contributors

DAC did the conceptualisation, data curation, investigation, methodology, project administration, visualisation, and writing of the original draft. DH did the conceptualisation, methodology, project administration, supervision, and the review and editing of the manuscript. RR did the methodology, project administration, and the review and editing of the manuscript. YY did the data curation, formal analysis, validation, visualisation, and the review and editing of the manuscript. GBM did the formal analysis, methodology, supervision, validation, visualisation, and the review and editing of the manuscript. PK, TZD, and PP did the conceptualisation, methodology, supervision, and the review and editing of the manuscript. GAM did the conceptualisation, funding acquisition, methodology, and supervision, found resources, and did the review and editing of the manuscript. DAC, GBM, and YY directly accessed and verified the original data reported in this analysis. All authors reviewed and approved the final manuscript before submission and had final responsibility for the decision to submit for publication. All authors had full access to the data in this study. Artificial intelligence-based tools were not used in the development of this study or manuscript.

Declaration of interests

DAC declares past research support from Merck Sharp & Dohme and current research support from GE Healthcare and Chiesi USA, paid to the University of Michigan, unrelated to the presented work; and has received an honorarium from Medscape unrelated to the presented work. DH declares research support from GE Healthcare, paid to the University of Michigan, unrelated to the presented work, and is a consultant for GE Healthcare. All other authors declare no competing interests.

Data sharing

Aggregated de-identified data with an accompanying data dictionary and study protocol will be made available with publication upon reasonable request to the corresponding author via email (dougcolq@med.umich.edu) and execution of a data use agreement.

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