The Carbon Footprint of Surgical Operations

A Systematic Review

Chantelle Rizan, MRCS (ENT),[*†‡§✉] *Ingeborg Steinbach, MA,*[§] *Rosamond Nicholson, MBChB,*[¶] *Rob Lillywhite, PhD,*[||] *Malcolm Reed, FRCS,*[†] *and Mahmood F. Bhutta, FRCS*[*†**]

Summary of background data and objectives: Operating theatres are typically the most resource-intensive area of a hospital, 3–6 times more energy-intensive than the rest of the hospital and a major contributor of waste. The primary objective of this systematic review was to evaluate existing literature calculating the carbon footprint of surgical operations, determining opportunities for improving the environmental impact of surgery.

Methods: A systematic review was conducted in accordance with PRISMA guidelines. The Cochrane Database, Embase, Ovid MEDLINE, and PubMed were searched and inclusion criteria applied. The study endpoints were extracted and compared, with the risk of bias determined.

Results: A total of 4604 records were identified, and 8 were eligible for inclusion. This review found that the carbon footprint of a single operation ranged 6–814 kg carbon dioxide equivalents. The studies found that major carbon hotspots within the examined operating theatres were electricity use, and procurement of consumables. It was possible to reduce the carbon footprint of surgery through improving energy-efficiency of theatres, using reusable or reprocessed surgical devices and streamlining processes. There were significant methodological limitations within included studies.

Conclusions: Future research should focus on optimizing the carbon footprint of operating theatres through streamlining operations, expanding assessments to other surgical contexts, and determining ways to reduce the footprint through targeting carbon hotspots.

Keywords: carbon footprint, environmental sustainability, surgical sustainability, surgical systems improvement, systematic review

(*Ann Surg* 2020;272:986–995)

Anthropogenic climate change poses one of the greatest current threats to public health in the 21st century, largely due to associated air pollution, rising temperatures, flooding and drought, and change in the spread of vector-borne diseases.[1] Whilst climate change may affect the health of current and future generations, the provision of healthcare itself produces greenhouse gases (GHGs) such as carbon dioxide (CO_2), which are responsible for the majority of healthcare-related climate change.[2,3] The US healthcare sector produces 655 million tonnes of CO_2 equivalents per year,[4] contributing 8%–10% of all national GHG emissions.[2,4] In the UK, the National Health Service (NHS) generates 22.8 million tonnes of CO_2 per year,[5] responsible for 6% of UK net CO_2 emissions,[6] and one quarter of all those produced by the public sector.[3] Operating rooms make a large contribution to the healthcare carbon footprint as they are typically the most resource-intensive area of a hospital.[7,8] Of UK NHS CO_2 emissions, 59% are associated with the supply chain, of which the largest hotspot is medical instruments and equipment (responsible for 15.5% of total emissions).[9] Operating rooms generate 21%–30% of hospital waste[8,10,11] and are 3 to 6 times more energy-intensive than the rest of the hospital which can be largely attributed to maintenance of the theatre environment (heating, ventilation, and air-conditioning).[12]

There are different approaches used to estimate the environmental impact of a process or product. Life cycle assessment (LCA) is a method used to account for a number of different environmental indicators (such as GHG emissions, eutrophication, and ecotoxicity). LCA is an inclusive measure but the endpoints are numerous and vary with the approaches and data sources used, reducing the extent to which direct comparisons can be made between studies. Only the carbon footprint component of LCA studies are considered in this review.

Carbon footprinting estimates the direct and indirect GHG emissions associated with a sector (such as healthcare sector), process (such as an operation), or product (such as a surgical instrument).[13] CO_2 is the dominant GHG emitted from healthcare and is responsible for 80%–85% of the global warming potential (GWP) of the healthcare sector in the US[2] and UK.[3] Healthcare also emits other GHGs such as methane, nitrous oxide, chlorofluorocarbons, and anesthetic gases, which together with CO_2, can be converted into carbon dioxide equivalents (CO_2e). The summation of all these different gases is a carbon footprint. Estimating the carbon footprint of surgical operations enables their GHG emissions to be quantified, and perhaps more importantly, allows the identification and targeting of carbon hotspots (largest GHG contributors) within surgery. Carbon footprinting can be used as a tool to model the relative impact of different measures aimed at reducing the GHG emissions of operative services, based upon existing variation in surgical care and hypothetical interventions. There are multiple guidelines on how to conduct carbon footprinting studies. The Greenhouse Gas Protocol[14] encompasses and builds on the other principal carbon footprint/LCA guidelines[15,16] and will be used as the standard in this review.

There are 2 main methodologies used to estimate a carbon footprint. The first is a ‘‘top-down’’ environmentally extended input-output (EEIO) model, which uses the monetary cost of a unit of interest to estimate the carbon footprint, on the premise that more expensive items involve greater resource use, with higher associated GHG emissions. An industry-specific conversion factor (emission factor) is applied to the monetary cost.[13,17] The EEIO approach incorporates all emission sources from upstream processes in the

From the *Brighton and Sussex University Hospitals NHS Trust, Brighton, United Kingdom; †Brighton and Sussex Medical School, Brighton, United Kingdom; ‡Royal College of Surgeons of England, London, United Kingdom; §Centre for Sustainable Healthcare, Oxford, United Kingdom; ¶University Hospitals of Leicester NHS Trust, Leicester, United Kingdom; ||University of Warwick, Coventry, United Kingdom; and **Medical Fair and Ethical Trade Group (International Department), BMA, London, United Kingdom.
✉chantelle.rizan@nhs.net.

This work was conducted as part of Chantelle Rizan's PhD, with research grants from the Health Education England and the Royal College of Surgeons of England.
The authors report no conflicts of interest.
Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.annalsofsurgery.com).

ISSN: 0003-4932/20/27206-0986
DOI: 10.1097/SLA.0000000000003951

supply chain (either direct or indirect, and including flow between sectors), taking into account ''hidden'' sectors such as marketing, and research and development (eg, behind the drugs administered during an operation).[18] It is relatively inexpensive and simple to perform,[17] but lacks specificity and detail, and should not be used for comparing the carbon footprint of products from within the same industrial sector.[19] The main value of estimating a carbon footprint via an EEIO method is for the rapid identification of hotspots, indicating where it may be useful to perform a more detailed carbon footprint.

The alternative ''bottom-up'' process-based method involves collecting data on all the component processes underpinning the unit of interest.[13,17] Published emission factors can be applied, which provide average emissions for given attributable processes (eg, electricity consumption, transportation, and production of a given material). This enables detailed analysis with high specificity, allowing comparison between items from the same sector.[20] However, this method is resource-intensive and requires study boundaries to be carefully defined, resulting in ''truncation error'' due to the omission of certain processes, or where the so called ''hidden'' sectors are overlooked.[17] There is debate between the relative accuracy and value of top-down and bottom-up approaches.[21] Hybrid methods exist which attempt either to incorporate the detail of the process-based approach alongside inclusivity of EEIO models, or which use top-down approaches for attributable components for which process data cannot be obtained.[19,21] Despite limitations, a given carbon footprinting methodology can be used to identify hotspots and evaluate alternatives if it is consistently applied within a study.

There are a number of guidelines available for GHG accounting. These include the International Organization for Standardisation 14067:2018,[22] the Greenhouse Gas Protocol,[14] and the Publicly Available Specification 2050 guidelines.[15]

Previous reviews of the environmental sustainability of operating theatres have mostly focused on waste management strategies, encouraging reduction, reuse, and recycling (alongside ''rethinking'' and research).[23,24] Other investigators have recommended adding in reprocessing of single-use devices (processing to allow for additional use(s)), environmentally preferable procurement, and energy consumption management.[25] However, these reviews are predominantly based on low level evidence such as opinion reports, and included studies using a wide variety of methods to measure environmental sustainability (eg, weight of waste, volume of water, and cost).

The principle components making up the carbon footprint of an operating theatre are the hospital infrastructure, capital machinery, maintenance of the theatre environment (heating, ventilation, air-conditioning, lighting), electronic equipment energy, water, anesthetic gases, pharmaceuticals, and reusable and disposable items. The relative contributions of each of these components is disputed,[12,26,27] and hotspots will vary in different settings and with different operations. The aim of this systematic review was to evaluate existing literature which examined the carbon footprint of surgical operations, and to identify hotspots which can be targeted to reduce the GHG emissions associated with surgery.

METHODS

This review was conducted and reported in accordance with PRISMA guidelines[28] and registered with the International Prospective Register of Systematic Reviews (PROSPERO, ID 109928).

Study Selection

We included original peer-reviewed research evaluating the carbon footprint of individual surgical operations. We excluded case reports, opinion-based reports, congress abstracts, meta-analyses, and studies not written in English. Studies were further excluded if they focused exclusively on (a) pre- or post-operative care, (b) processes outside of the theatre itself (eg, sterilization), (c) anesthetic components of operations, (d) pharmaceuticals delivered intraoperatively, or (e) examined whole systems (such as healthcare sector with surgery as a subset, or whole operating suites).

The following databases were searched; Cochrane Database (-4/10/19), Embase (1947–2019 week 32), Ovid MEDLINE (1946-Week 32 2019) and PubMed (1966–4/10/19). Two search domains were used (Supplementary Table 1, http://links.lww.com/SLA/C166), with terms within each domain combined by ''OR'' and the 2 domains combined using ''AND.'' The search was conducted independently by 2 authors (CR, RN). Study titles and their citations were screened, and irrelevant articles and duplicates discarded. Full texts were obtained for remaining articles and inclusion and exclusion criteria applied. The references of included studies were screened for studies not identified through the original search. Data were extracted independently by 2 authors (CR, IS).

Evaluation of Study Characteristics

For each study we recorded descriptive data on the study setting (including country of origin), focus of study (including surgical specialty), and carbon footprinting approach (EEIO model, process-based approach, or hybrid approach, alongside the carbon footprinting guideline used).

Evaluation of Carbon Footprint

The Greenhouse Gas Protocol[14] was used as a framework for extracting endpoints in this paper. Where there was conflicting terminology between studies, the GHG Protocol was used as the standard.

For each study, we determined the ''scope of the product inventory'' which includes the functional unit and list of GHGs included. The functional unit is the process or product under examination (such as operation), for which the carbon footprint was estimated. The scope also identified the list of GHGs included (such as CO_2, nitrous oxide, and methane). The number of GHGs included was determined directly where explicitly stated, or otherwise deduced from the carbon footprinting guideline or databases used.

The inventory boundary was outlined for each included study, which describes the attributable processes that were included within the study. Where processes are omitted, this underestimates the carbon footprint of a given process. However, it is often difficult to obtain data on processes beyond the boundary of the hospital under investigation, and the inventory boundary could always be expanded, (eg, to include higher tier supporting industries such as research and development, or even the food eaten by theatre staff). It is; therefore, reasonable for inventory boundaries to be set, but these should be clearly stated.

The processes that are included within study inventory boundaries were classified according to GHG Protocol[17] definitions of GHG emission types (scope 1–3). Scope 1 emissions are those directly emitted from a given organization (eg, anesthetic gases), scope 2 emissions are indirect GHG emissions associated with electricity used by an organization (ie, purchased directly by the hospital), and scope 3 gases incorporate all other indirect emissions (including those embedded within the supply chain, travel, and waste disposal). A carbon footprinting study is most reflective of true emissions where all processes attributable to the functional unit (from all 3 scopes) are included.

The data collected for the carbon footprint estimations were further categorized according to the data type. These are classified as direct emissions data where directly emitted emissions are measured (eg, volume of anesthetic gas released). Data is categorized as process activity data where this relates to the inputs and outputs known to contribute GHG, but where direct measurement is not possible. This is known as primary process activity data, where original data is collected that is specific to a given functional unit under examination (eg, including the actual transportation used for theatre waste). Alternatively, secondary process activity data may be used, using average, or typical process data (eg, based on previously published studies or databases which are not specific to the functional unit). Finally, secondary financial activity data is used in EEIO models based upon the monetary cost of items. Where reported, we also extracted data on the number of observations made for a given process, the assumptions made in data collection, and on how data regarding shared processes were attributed to a particular process. The latter is called the allocation method which, for example, describes the way in which annual electricity consumption of an operating theatre is assigned to a single operation.

For each study, the source of the emissions factors and GWPs were also recorded. To estimate the carbon footprint, the activity data (unit) must be multiplied by an emission factor (kg GHG/unit) and also by the global warming potentials (GWPs). The GWP represents the extent to which a given GHG absorbs the Sun's infrared radiation and traps heat, relative to CO_2. Where the carbon footprint was conducted as part of a full LCA, the LCA database used was also extracted, which included information on embedded emission factors.

Where possible, numerical values for carbon footprinting results of overall operations and sub-processes were extracted, but descriptive data (eg, percentages or proportions) and graphic summaries were used where actual values were not recorded.

Evaluation of Quality and Applicability of Studies

There are 3 major sources of uncertainty within carbon footprint studies, and each of these were considered. Parameter uncertainty relates to the accuracy of direct emissions data, process activity data, emission factors, and GWPs. Scenario uncertainty describes variation in results due to methodological choices, such as allocation methods or assumptions made. Finally, model uncertainty describes the limitations associated with the chosen top-down or bottom-up carbon footprinting method. All stated uncertainties and limitations were extracted.

Finally, we evaluated the quality of each study making reference to relevant guidelines[14–16] and critical appraisal tools.[29,30] Studies were appraised independently by 2 researchers (CR, IS) using the system detailed in Supplementary Table 2, http://links.lww.com/SLA/C166, and discrepancies were discussed and resolved.

RESULTS

Study Selection

The search strategy identified 4604 records (Fig. 1). Screening of titles excluded 4381 of these and of the remaining 223, 83 were duplicates, leaving 140 articles for full text evaluation. After application of the inclusion and exclusion criteria, 8 studies were found to be eligible.[7,26,27,31–35] Of these, 4 were conducted exclusively in the US,[7,31,33,35] 2 in the UK,[27,32] 1 in Chile,[26] and 1 in India (Table 1).[34]

Variation in Methods for Carbon Footprinting (Table 1)

The carbon footprinting method and terminology varied between studies. Three studies exclusively used "bottom-up" process-based approaches, of which 1 simply described their method as a "carbon footprint,"[35] 1 described it as a "multi-component analysis/carbon footprint,"[26] and the other conducted a full LCA.[31] A "top-down" EEIO was used exclusively by 1 study[35] but was referred to as a "carbon footprint." Five studies used a hybrid approach, using both EEIO and process-based methodologies, of which 3 termed this an "economic-" or "environment input-output life cycle assessment"[7,33,34] and 1 a "component analysis study."[27]

Four studies[7,31,33,34] reported following International Organization for Standardisation guidelines,[16] one[35] following the GHG Protocol[14] and two[27,35] using Publicly Available Specification 2050 guidelines.[15] Two studies did not state the use of guidelines.[26,32]

Variation in Scope (Table 1)

The functional unit of all included studies were individual operations. Four studies examined operations in the field of Obstetrics and Gynecology,[7,31,33,35] 2 Ophthalmological operations,[27,34] 1 Gastrointestinal,[32] and 1 Plastic surgery.[26] With regards to the scope of GHGs included, 2 studies calculated CO_2 emissions only.[26,32] Other studies did not specify the number of GHGs included,[7,31,33–35] although this can be deduced (bracketed in Table 1) based on the guidelines or databases used.

Variation in Inventory Boundaries

Inventory boundaries are compared across studies in Table 2 and detailed in Supplementary Table 3, http://links.lww.com/SLA/C166. Stated exclusions of the inventory boundary are listed in Supplementary Table 4, http://links.lww.com/SLA/C166.

Across the 8 studies[7,26,27,31–35] the majority included electricity consumption (relating to electronic equipment, heating, ventilation, air conditioning, and lighting), which constitute scope 2 GHG emissions. The majority also included theatre waste (with variable inclusion of specified waste streams) and linen laundering (scope 3). There was variable inclusion of processes involved in the production of disposable and reusable items (raw material extraction, manufacturing, and transport), and linen manufacture (all scope 3). The majority of studies omitted pre- and postoperative processes, patient and staff travel, capital goods manufacture, water use, processing of reusable equipment (all scope 3), and pharmaceuticals (including scope 1 anesthetics gases).

Variation in Data Collected, Allocation Method, and Method for Calculating Inventory Results

No studies collected direct emissions data (scope 1). Three studies used primary process activity data only,[26,31,35] 1 used secondary financial activity data only[32] and all others used a mixture of data types (Supplementary Table 3, http://links.lww.com/SLA/C166).[7,27,33,34] Where studies used secondary financial activity data within an EEIO model, this incorporates all 3 scopes of GHG emissions where relevant. The assumptions made within data collection are listed in Supplementary Table 4, http://links.lww.com/SLA/C166. Allocation methods were explicitly stated by 4 studies.[7,31,33,34] A range of data sources were used for emission factors and GWPs.

Heterogeneity in functional units, methodology and reporting of results limits comparison across studies, and means meta-analysis is inappropriate. The study carbon footprint results extracted are presented in full in Supplementary Table 5, http://links.lww.com/SLA/C166.

Carbon Footprint of Operations

The carbon footprint of individual operations ranged from 6 to 814 kg CO_2e (Figs. 2–4).[7,26,27,31–35] This variation may be due to differences in methods and boundaries, but is also affected by the type of operation and the institution where it is performed. The carbon footprint of different operations will vary, and are likely to be dependent upon the invasiveness of the procedure, patient factors, and the surgical team, which will each impact on operative time and consumables used.

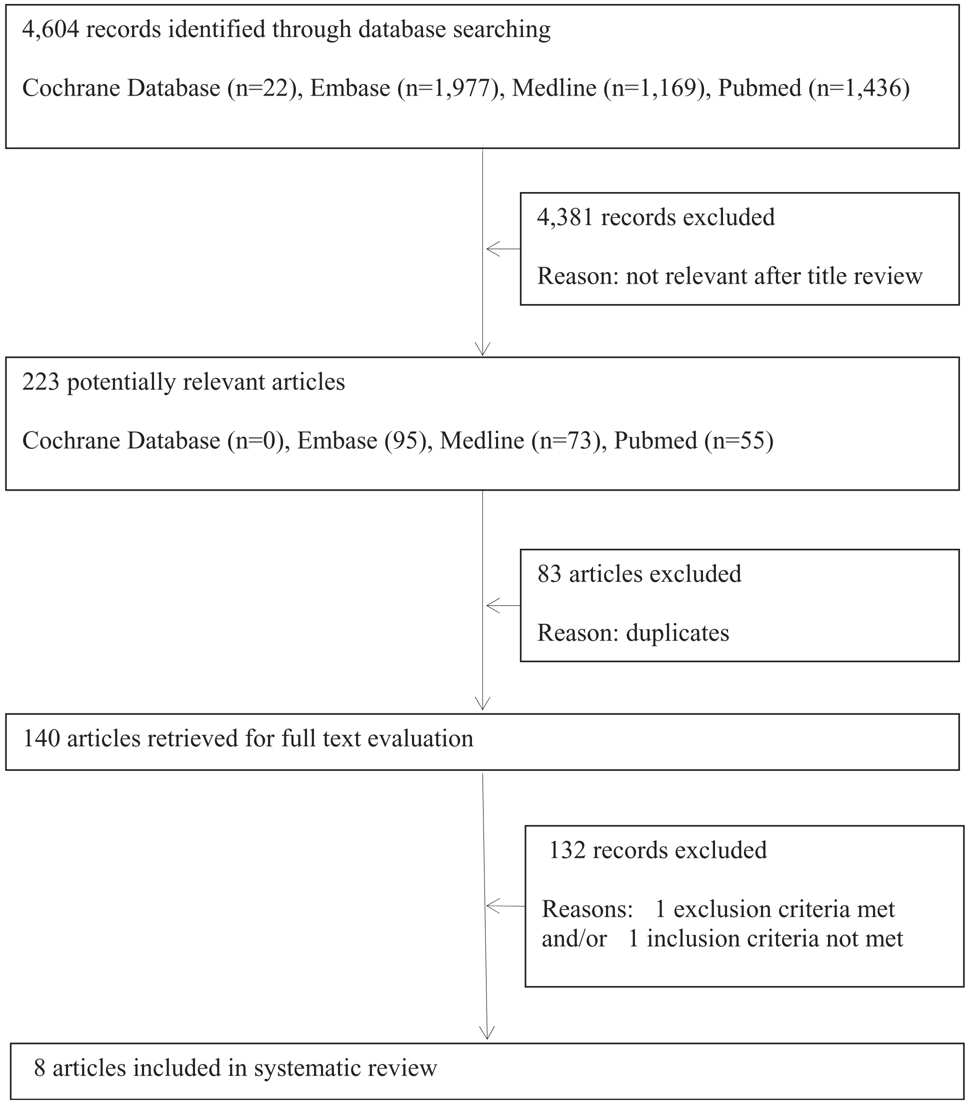


FIGURE 1. Flow chart of study selection.

Berner et al[26] found that an abdominoplasty had a greater carbon footprint than rhinoplasty, which in turn was greater than bilateral breast augmentation. Morris et al[27] calculated the carbon footprint of a cataract operation in the UK at 182 kg CO_2e, whilst Thiel et al estimated this to be 6 kg CO_2e in India.[34] Whilst the decision to manage a patient medically or surgically (and the surgical approach taken), is a decision made by the surgeon based upon clinical grounds and taking into account patient preference, a number of studies compared their carbon footprints. Thiel et al[7] and Woods et al[35] found that the most carbon-intensive approach to gynaecological surgery was robotic, followed by the laparoscopic approach, followed by laparotomy (followed by trans-vaginal approach within the former study). Two studies calculated the carbon footprint of an operation and compared it to non-surgical options. Campion et al[31] found that the carbon footprint of a cesarean section is twice that of a vaginal delivery. However none of these studies considered any processes beyond the theatre boundary, and did not take into account the impact different surgical approaches have on length of stay, infection rate and need for further intervention (all with associated CO_2 emissions). Gatenby[32] found that the carbon footprint of surgical approaches to gastro-oesophageal reflux disease treatment is higher than medical treatment up to 9 years after the operation, but becomes more carbon-efficient thereafter, following patients up until end of life.

Two studies extrapolated results of individual operations to estimate national carbon footprints, concluding that hysterectomies in the USA generate 212,000 tonnes CO_2e per year (~285–562 kg CO_2e per operation)[7] and cataract surgery in the UK generates 63,000 tonnes CO_2e per year (182 kg CO_2e per operation).[27]

Analysis of Contributions to Overall Carbon Footprints and Carbon Hotspots

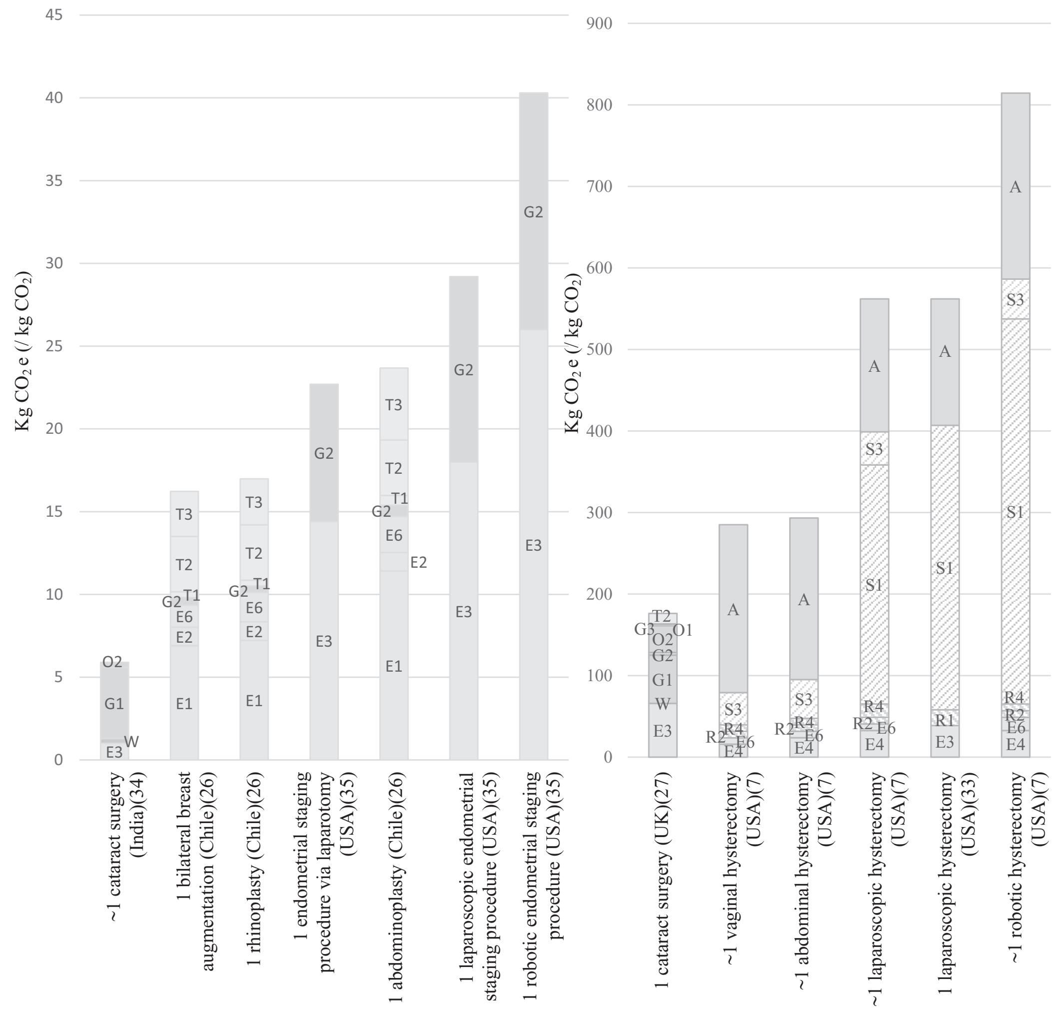
The relative contributions of individual processes to the overall carbon footprint of surgical operations is illustrated within Figs. 2–4. Three studies[26,31,35] found electricity to be the largest source of GHG emissions, accounting for 63%–78% of the carbon footprint of whole operations, and the amount of electricity consumed is likely to be closely linked with the operation duration. In 2 studies where electricity use was broken down, the highest consumption of electricity was for maintaining the theatre environment

TABLE 1. Study Characteristics and Scope of Product Inventory

Study Characteristics				Scope	
Study (yr)	**Study Setting;** ***Country***	**Focus of Study;** ***Surgical Specialty***	**Carbon Footprinting Approach;** ***Guideline***	**Functional Unit;** ***Start point-endpoint***	**Included GHGs, () Where Deduced;** ***Guideline/ Database***
Berner et al (2017)[26]	1 airforce teaching hospital; *Chile*	(a) Abdominoplasty versus (b) bilateral breast augmentation versus (c) rhinoplasty; *Plastic surgery*	Process-based *Nil*	1 abdominoplasty/breast augmentation/ rhinoplasty*; patient/ staff commute to theatre-recovery*	CO_2 *Nil*
Campion et al (2012)[31]	1 university hospital; *USA*	Childbirth: (a) cesarean section versus (b) natural delivery; *O&G*	Process-based *ISO 14040 and 14044*	Birth 1 baby; (*a*) *patient enter theatre-leave* (*b*) *Stage 2 + 3 labour*	(91 GHGs) *TRACI 2*
Gatenby (2011)[32]	21 hospitals; *UK*	GORD: (a) surgical versus (b) medical management; *GI*	EEIO *Nil*	1 reflux patient; *Start of secondary care for reflux-end of life*	CO_2 *Nil*
Morris et al (2013) [27]	1 university hospital; *UK*	Cataract surgery; *Ophthalmology*	Hybrid *PAS2050*	Cataract surgery 1 eye; *Referral to secondary care- discharge*	6 GHGs *Kyoto protocol*
Thiel et al (2015)[7]	1 university hospital; *USA**	Hysterectomy: (a) abdominal versus (b) vaginal versus (c) laparoscopic versus (d) robotic; *O&G*	Hybrid *ISO 14040 and 14044*	1 hysterectomy; *Patient enter theatre-leave*	(91 GHGs) *TRACI 2.1*
Thiel et al (2017)[34]	2 tertiary care hospitals; *India*	Cataract surgery; *Ophthalmology*	Hybrid *ISO 14040*	Cataract surgery 1 eye; *Patient enter theatre-leave*	(91 GHGs) *TRACI 2.1*
Thiel et al (2018)[33]	1 university hospital; *USA**	Hysterectomy: model interventions (a) anesthesia (b) surgical materials and equipment (c) energy for HVAC; *O&G*	Hybrid *ISO 14040 and 14044*	1 hysterectomy *Patient enter theatre-leave*	(91 GHGs) *TRACI 2.1*
Woods et al (2014)[35]	Not specified; *USA*	Endometrial cancer staging: (a) laparoscopy versus (b) laparotomy versus (c) robotic; *O&G*	Process-based *PAS2050, GGP*	1 endometrial staging procedure; *Patient enter theatre-leave*	(6 GHGs) *GGP, PAS 2050*

*Inter-related studies.

CO_2, indicates carbon dioxide; EEIO, Environmentally extended input output; GGP, greenhouse gas protocol; GHG, greenhouse gas; GI, gastrointestinal; GORD, gastro-oesophageal reflux disease; HVAC, heating, ventilation, and air conditioning; ISO, international standards organisation; O&G, obstetrics and gynecology; PAS, publicly available specification; SUD, single-use device.



Legend for figures 2-4.

Bar colour	Category	Sub-category	
	Electricity	E1=Building energy (theatre) E3=Electricity use E5=Lighting E7=Operation time	E2=Building energy (recovery) E4=HVAC E6=Medical equipment energy
	Water	W=Water	
	Consumables (General)	G1= Consumables procurement G3= Laundry	G2 = Waste
	Consumables (Other)	O1=Other procurement O3= Pharmaceuticals (ongoing)	O2 =Pharmaceuticals
	Reusables	R1=Reusable instruments R3=Reusables production & sterilisation	R2=Reusables production R4=Reusables treatment & sterilisation
	Single-use items	S1=Single-use items production S3=Single-use materials (gowns, gloves etc)	S2=Single-use instruments production
	Travel	T1=Patient travel T3=Waste transport	T2=Staff travel
	Anaesthetics	A=Anaesthetics	
	Beyond operation	B1=Day case B3=Outpatient appointment	B2=Inpatient care B4=Outpatient tests

FIGURE 2. Carbon footprint results of single operations. ∼ = approximated from descriptive or graphical data, Thiel *et al.* (2015)[7] cross referenced in Thiel *et al.* (2018)[33].

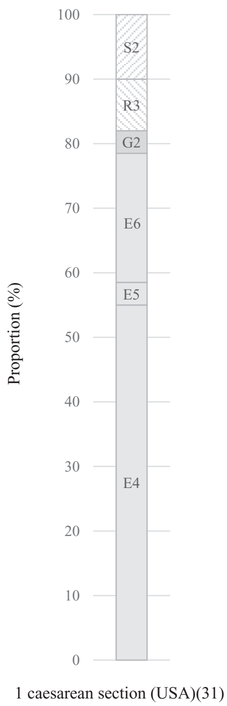


FIGURE 3. Carbon footprint results of 1 operation. (Only proportion data available).

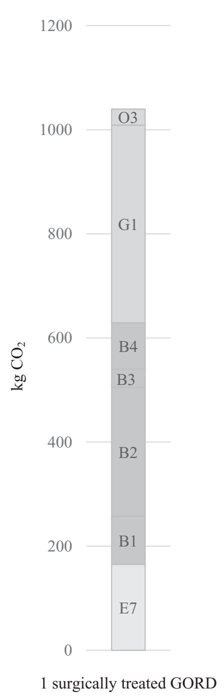


FIGURE 4. Carbon footprint results of surgically treated GORD patient over 20 yr. GORD indicates gastro-oesophageal reflux disease.

(heating, ventilation, and air-conditioning).[7,31] By contrast, 4 studies[7,27,33,34] found procurement to be the largest hotspot, with three[7,33,34] specifically identifying single-use items to be largest contributors, responsible for up to 78% of the carbon footprint (with 2 of these studies referring to the same dataset). In the 2 studies that accounted for patient and staff travel to hospital, this was responsible for 10%–37% of the footprint.[26,27]

Quality and Applicability of Studies

There were a number of points limiting the internal and external validity of studies, in addition to methodological points previously raised. No study stated a clear hypothesis, increasing risk of post-hoc analysis and selective reporting. Transparency was limited by failure to state either assumptions or exclusions within 2 studies,[26,33] and 1[7] did not state either. For a given process, the number of observations or data points collected was reported in 2 studies for all processes,[32,35] reported ambiguously or for a limited number of processes in 5 studies,[7,26,27,33,34] and not reported at all in 1.[31] Five studies broke down the carbon footprint in numerical data for all key sub-processes,[26,27,32,33,35] and 2[7,34] reported limited numerical data, with some sub-process results presented as descriptive or graphical data. One study reported only descriptive or graphical data.[31]

Parameter uncertainty (uncertainty relating to the data collection or emissions factors) was calculated by 2 studies.[7,35] Three studies performed scenario uncertainty tests to model the uncertainty due to methodological assumptions, 2[31,34] finding this affected results minimally, whilst another[36] found this varied results by 0.3%–19%.

The extent to which carbon footprint study results may hold external validity to other operations of the same type is limited, for example, due to inventory boundaries, use of country-specific emission factors and differences in the operative processes between patients, surgeons, and institutions. Further limitations and assumptions (both stated within studies and identified by us) are summarised in Supplementary Table 4, http://links.lww.com/SLA/C166. There is a risk of publication bias across studies, although we found published studies without statistically significant effect sizes.

DISCUSSION

This review found that the carbon footprint of a single operation ranged from 6 (for cataract surgery in India)[34] to 814 kg CO_2e, (for a robotic hysterectomy in the US),[7] with the largest value being equivalent to driving up to 2273 miles in an average petrol car.[37] The carbon footprint estimates need to be considered with some caution, particularly in comparing results between studies due to significant differences in inventory boundaries, assumptions, and other methodological considerations. MacNeill et al calculated and compared the carbon footprint of whole operating suites across 1 year in 3 large hospitals in the UK, Canada, and US,[12] finding this ranged between 3219 and 5188 tonnes CO_2e. Whilst this study did not look at specific individual operations, results of average operations were in keeping with included studies, with emissions of 146 kg CO_2e per average case at the Canadian hospital, compared with 173 kg CO_2e in the UK, and 232 kg CO_2e in the US.

This review found that the major carbon hotspots within operating theatres are (a) energy use,[12,26,31,35] and (b) procurement of consumables,[27,34] both of which can be targeted for improvement. Anesthesia is another important consideration, but is beyond the scope of this systematic review and it is principally within the control of anesthetic departments, and their policy development is an important component of future strategies.[12,38]

TABLE 2. Comparison of Inventory Boundaries

Phase	Process/ Item		Berner et al[26]	Campion et al[31]	Gatenby[32]	Morris et al[27]	Thiel et al[7]	Thiel et al[34]	Thiel et al[33]	Woods et al[35]
Pre-op	Investigations				X					
	Outpatient appointments				X					
	Outpatient building energy use				?	X				
Operation	Patient/staff travel on day of surgery		X			X				
	Capital goods manufacture				?					
	Electronic equipment energy		X	X	?	?	X	X	X	X
	Heating			X	?	?	X		X	X
	Ventilation, air conditioning, lighting			X	?	?	X	X	X	X
	(Building energy use)		X			X			X	
	Water	Treatment before/after use			?	?		X		
		Heating			?	?				
		(Water)				X				
	Anaesthetic gases	Production			?	?	X		X	
		Direct emissions			?	?	X		X	
	Intravenous anaesthetics	Production			?	?	X	?	X	
		Direct emissions			?	?	X	?	X	
	Gas insufflation	Production			?					
		Direct emissions			?		X			
	(Operation time)				X					
	Linen	Manufacture			?		X		X	
		Washing & drying			?	X	X	X	X	
		Transport to linen facility	X		?	X				
	Consumables production	Raw material extraction		X	?	X	X	X	?	
		Manufacturing		X	?	X	X	X	?	
		Transport in procurement		X	?	X	X	?	?	
	Disposables EOL	Incineration		X	?	?	X	?		
		Landfill	?	X	?	?	X	?		X
		Autoclave/ sterilisation		X	?		X	?		
		Recycling			?		X	?	X	
	Reusables processing	Sterilisation		X	?		X	X	X	
		Repair			?					
	Reusables EOL	Landfill & incineration	?		?	?		?		
		Recycling			?			?		
	(Unspecified theatre waste)	Incineration			?	X		X	X	
		Landfill	X		?	X		X	X	
		Autoclave			?				X	
	Transport of (any measured) waste			X	?		X			
Peri/post-op	Recovery building energy & landfill waste		X		?					
	Postoperative inpatient care				X	X				
	Inpatient pharmaceuticals				X	X		X		
	IT, patient food & drink, stationary				?	X				
	Medical equipment				?	X				
	Outpatient follow up				X	X				
	Outpatient pharmaceuticals				X	X				

? indicates ambiguous; (), where likely includes other listed factors; EOL, end of life; IT, information technology; op, operative.

Optimizing Electricity Use in Theatres

Approaches to minimizing electricity use include developing and installing occupancy sensors,[31] low-energy lighting, energy-efficient air-conditioning systems, and water cooling systems.[25] Improving the energy efficiency of USA hospitals by 30% has been estimated to save $1 billion and a reduction in carbon emissions of 11 million tonnes.[39] Electricity should also be switched to renewable rather than fossil fuel based sources.

Optimizing Use of Consumable Items

Two studies identified that consumables are a major carbon hotspot within operations.[27,34] This is in line with estimates that attributable processes within the healthcare supply chain are responsible for 59% of the total NHS carbon footprint,[9] and 71% of healthcare's carbon footprint globally.[40] In light of this, attention should be given to reducing this footprint, for example through switching to reusable items and reducing resource use where clinically appropriate, and considering reprocessing of surgical instruments. Studies examining the carbon footprint of surgical scissors, laparotomy pads, and suction receptacles found that this can be reduced by 50%–97% through switching from single-use to reusable surgical devices.[36,41,42] This is consistent with reports that favor reusable rather than disposable perioperative textiles,[43] and anesthetic items (anesthetic drug trays,[44] laryngeal mask airways,[45] and laryngoscope handles and blades).[46]

Whereas use of reusable rather than disposable items is a good general principle, this preference is context specific and may not be universal. In Australia, Davis et al found that reusable ureteroscopes are marginally more carbon-intensive than single-use equivalents, a finding that is influenced by the predominant use of coal-based electricity in Australia.[47] Similar conclusions were drawn in 2 other

Australian studies examining anesthetic items,[48,49] but if the carbon emissions were instead modeled using energy source mixes typical of the UK/Europe (principally renewables) or USA (largely natural gas), reusable equipment once again had a lower carbon footprint.[49]

Reprocessing of single-use surgical instruments is another potential target, modeled to reduce the GHG emissions of an entire operation by 9%,[33] and costing half the price of single-use equivalents.[50] In 2010 around one quarter of US hospitals used 1 or more reprocessed single-use device,[50] and the proportion of hospitals is likely to have increased since then, but reprocessing is not widely used in other countries such as the UK or Australia. A LCA study examining 7 single-use medical devices (including endoscopic trocars, ligasure, arthroscopic shavers, and ultrasonic scalpels) found that reprocessed devices conferred lower global warming impacts alongside financial benefits.[51] The relative environmental impact of reprocessing specific single-use surgical instruments (compared with using new ones) is likely to be determined by the extent of reprocessing required (in turn depend upon the complexity of the instrument, extent of damage from use, and decontamination required), location of the reprocessing unit, and number of additional uses enabled.

Finally, there is potential from streamlining surgical instrument trays through minimizing material use and selecting reusable surgical instruments.[33] Farrelly et al[52] found that optimizing pediatric surgical trays could eliminate an average of 60% of instruments, although the effects of this on carbon emissions was not evaluated in this study, and will depend upon how such trays are sterilized. Zygourakis et al[53] reported that 13% of disposable items opened for neurosurgical procedures are discarded without use, hence changing processes to only open equipment when needed could bring financial and carbon savings. On a broader scale, it has been estimated that streamlining and optimizing resource use in operating theatres holds the potential to save £7 million (~US$9 million) per NHS trust in the UK each year.[54]

Overall Potential

The optimum approach to reducing the carbon emissions of a given operation should include a holistic approach, including looking at electricity use, anesthetic gases, and use of equipment, especially where disposable. Thiel et al[33] modeled that the carbon footprint of a hysterectomy operation could be reduced by up to 83%, through optimizing the instrument tray via use of minimal materials and maximum reuse (49%), switching anesthesia to intravenous anesthesia with propofol or similar agents (28%), and using renewable energy (6%). It is also important to consider reducing the need for surgery through health promotion, disease prevention, and correct patient selection.[55]

CONCLUSIONS

All studies estimating the carbon footprint of operations were published from 2011 onwards, reflecting that this field is still in its infancy, but needs further exploration as a priority. Future research evaluating the carbon footprint of operations should extend assessments to other surgical contexts, and focus on determining and evaluating targets to reduce the footprint. This may include reducing resource use, streamlining operations, switching to reusable equivalents, and improving the energy efficiency of theatre design. Studies comparing different surgical approaches or alternative models of care should include postoperative care, subsequent interventions, and patient outcomes. Full LCAs should be performed where time, expertise, and resources permit this, taking into account other environmental impacts beyond GHG emissions. Improving the environmental impact of surgery often leads to financial benefits and these should be reported alongside surgical carbon footprints, highlighting where green surgery is lean surgery, and providing additional impetus for change.

REFERENCES

1. Costello A, Abbas M, Allen A, et al. Managing the health effects of climate change: Lancet and University College London Institute for Global Health Commission. *Lancet*. 2009;373:1693–1733.
2. Chung JW, Meltzer DO. Estimate of the carbon footprint of the US health care sector. *JAMA*. 2009;302:1970–1972.
3. NHS Sustainable Development Unit, Stockholm Environment Institute. NHS England carbon emissions carbon footprinting report. London: Sustainable Development Unit; 2008. Available at: https://www.sduhealth.org.uk/policy-strategy/reporting/nhs-carbon-footprint.aspx. Accessed April 30, 2020.
4. Eckelman MJ, Sherman J. Environmental impacts of the U.S. health care system and effects on public health. *PLoS One*. 2016;11:e0157014.
5. Sustainable Development Unit, Carbon Footprint update for NHS in England 2015. Cambridge: Sustainable Development Unit; 2016. Available at: https://www.sduhealth.org.uk/policy-strategy/reporting/nhs-carbon-footprint.aspx. Accessed April 30, 2020.
6. Department for Business, Energy and Industrial Strategy, National Statistics. 2018 UK Greenhouse Gas Emissions, Provisional Figures. London: UK Government; 2019. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/790626/2018-provisional-emissions-statistics-report.pdf. Accessed April 30, 2020.
7. Thiel CL, Eckelman M, Guido R, et al. Environmental impacts of surgical procedures: life cycle assessment of hysterectomy in the United States. *Environ Sci Technol*. 2015;49:1779–1786.
8. Lee BK, Ellenbecker MJ, Moure-Eraso R. Analyses of the recycling potential of medical plastic wastes. *Waste Manag*. 2002;22:461–470.
9. Sustainable Development Unit, Public Health England, NHS England. Reducing the use of natural resources in health and social care. Cambridge: Sustainable Development Unit; 2018. Available at: https://www.sduhealth.org.uk/policy-strategy/reporting/natural-resource-footprint-2018.aspx. Accessed April 30, 2020.
10. Goldberg ME, Vekeman D, Torjman MC, et al. Medical waste in the environment: do anesthesia personnel have a role to play? *J Clin Anesth*. 1996;8:475–510.
11. Penn E, Yasso SF, Wei JL. Reducing disposable equipment waste for tonsillectomy and adenotonsillectomy cases. *Otolaryngol Head Neck Surg*. 2012;147:615–618.
12. MacNeill A, Lillywhite R, Brown C. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. *Lancet Planet Health*. 2017;1:e381–e388.
13. Berners-Lee M. *How Bad are Bananas; the Carbon Footprint of Everything*. London: Profile Books; 2010.
14. World Resources Institute. Greenhouse gas protocol, product life cycle accounting and reporting standard. USA: World Resources Institute; 2011. Available at: https://www.wri.org/publication/greenhouse-gas-protocol-product-life-cycle-accounting-and-reporting-standard. Accessed April 30, 2020.
15. Department for Business Innovation and Skills. PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. UK: Department for Business Innovation and Skills; 2011. Available at: http://www.bsigroup.com/Standards-and-Publications/How-we-can-help-you/Professional-Standards-Service/PAS-2050. Accessed April 30, 2020.
16. International Organization for Standardization. ISO 14040:2006 Environmental management- life cycle assessment- principles and framework. Geneva, Switzerland: ISO; 2006. Available at: https://www.iso.org/standard/37456.html. Accessed April 30, 2020.
17. World Resources Institute. Technical guidance for calculating scope 3 emissions. USA: World Resources Institute; 2013. Available at: https://ghgprotocol.org/sites/default/files/standards/Scope3_Calculation_Guidance_0.pdf. Accessed April 30, 2020.
18. Minx J, Wiedmann T, Barrett J, et al. *Methods Review to Support the PAS for the Calculation of the Embodied Greenhouse Gas Emissions of Goods and Services*. London: Stockholm Environment Institute and University of Minnesota; 2008.
19. Berners-Lee M, Howard DC, Moss J, et al. Greenhouse gas footprinting for small businesses-the use of input-output data. *Sci Total Environ*. 2011;409:883–891.
20. Kennelly C, Berners-Lee M, Hewitt C. Hybrid life-cycle assessment for robust, best-practice carbon accounting. *J Clean Prod*. 2019;208:35–43.

21. Pomponi F, Lenzen M. Hybrid life cycle assessment (LCA) will likely yield more accurate results than process-based LCA. *J Clean Prod*. 2018;176:210–215.
22. International Organization for Standardization. ISO 14067:2018 Carbon footprint of products — Requirements and guidelines for quantification. Geneva, Switzerland: ISO; 2006. Available at: https://www.iso.org/standard/71206.html. Accessed April 30, 2020.
23. Kagoma Y, Stall N, Rubinstein E, et al. People, planet and profits: the case for greening operating rooms. *CMAJ*. 2012;184:1905–1911.
24. Guetter CR, Williams BJ, Slama E, *et al*. Greening the operating room. Am J Surg. 2018 July 19; [Epub]. Accessed on 30 April 2020 Available at: https://www.americanjournalofsurgery.com/article/S0002-9610(18)30087-4/fulltext
25. Kwakye G, Brat GA, Makary MA. Green surgical practices for health care. *Arch Surg*. 2011;146:131–136.
26. Berner JE, Gras MDP, Troisi L, et al. Measuring the carbon footprint of plastic surgery: a preliminary experience in a Chilean teaching hospital. *J Plast Reconstr Aesthet Surg*. 2017;70:1777–1779.
27. Morris DS, Wright T, Somner JE, et al. The carbon footprint of cataract surgery. *Eye*. 2013;27:495–501.
28. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *BMJ*. 2009;339:b2535.
29. Young JM, Solomon MJ. How to critically appraise an article. *Nat Clin Pract Gastroenterol Hepatol*. 2009;6:82–91.
30. Greenhalgh T. *How to Read a Paper - The Basics of Evidence-based Medicine*. 5th ed. West Sussex: Wiley Blackwell; 2014.
31. Campion N, Thiel CL, DeBlois J, et al. Life cycle assessment perspectives on delivering an infant in the US. *Sci Total Environ*. 2012;425:191–198.
32. Gatenby PA. Modelling the carbon footprint of reflux control. *Int J Surg*. 2011;9:72–74.
33. Thiel CL, Woods NC, Bilec MM. Strategies to reduce greenhouse gas emissions from laparoscopic surgery. *Am J Public Health*. 2018;108(S2): S158–S164.
34. Thiel CL, Schehlein E, Ravilla T, et al. Cataract surgery and environmental sustainability: waste and lifecycle assessment of phacoemulsification at a private healthcare facility. *J Cataract Refract Surg*. 2017;43:1391–1398.
35. Woods DL, McAndrew T, Nevadunsky N, et al. Carbon footprint of robotically-assisted laparoscopy, laparoscopy and laparotomy: a comparison. *Int J Med Robot*. 2015;11:406–412.
36. Ibbotson S, Dettmer T, Kara S, et al. Eco-efficiency of disposable and reusable surgical instruments - a scissors case. *Int J Life Cycle Assess*. 2013;18:1137–1148.
37. Department for Business, Energy and Industrial Strategy and the Department for Environment, Food and Rural Affairs. UK Government GHG Conversion Factors for Company Reporting. UK: UK Government; 2018. Available at: https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting. Accessed April 30, 2020.
38. Sherman J, Ryan S. Ecological responsibility in anesthesia practice. *Int Anesthesiol Clin*. 2010;48:139–151.
39. Cotton RT, Cohen AP. Eco-conservation and healthcare ethics: a call to action. *Laryngoscope*. 2010;120:4–8.
40. Healthcare without Harm. Health care's climate footprint climate-smart health care series green paper number one. Arlington, USA: Healthcare without Harm and ARUP; 2019. Available at: https://noharm-uscanada.org/content/global/health-care-climate-footprint-report. Accessed April 30, 2020.
41. Kummerer K, Dettenkofer M, Scherrer M. Comparison of reusable and disposable laparotomy pads. *Int J Life Cycle Assess*. 1996;1:67–73.
42. Ison E, Miller A. The use of LCA to introduce life-cycle thinking into decision-making for the purchase of medical devices in the NHS. *J Environ Assess Pol Manag*. 2000;2:453–476.
43. Overcash M. A comparison of reusable and disposable perioperative textiles: sustainability state-of-the-art 2012. *Anesth Analg*. 2012;114:1055–1066.
44. McGain F, McAlister S, McGavin A, et al. The financial and environmental costs of reusable and single-use plastic anaesthetic drug trays. *Anaesth Intensive Care*. 2010;38:538–544.
45. Eckelman M, Mosher M, Gonzalez A, et al. Comparative life cycle assessment of disposable and reusable laryngeal mask airways. *Anesth Analg*. 2012;114:1067–1072.
46. Sherman JD, Raibley LA, Eckelman MJ. Life cycle assessment and costing methods for device procurement: comparing reusable and single-use disposable laryngoscopes. *Anesth Analg*. 2018;127:434–443.
47. Davis NF, McGrath S, Quinlan M, et al. Carbon footprint in flexible ureteroscopy: a comparative study on the environmental impact of reusable and single-use ureteroscopes. *J Endourol*. 2018;32:214–217.
48. McGain F, McAlister S, McGavin A, et al. A life cycle assessment of reusable and single-use central venous catheter insertion kits. *Anesth Analg*. 2012;114:1073–1080.
49. McGain F, Story D, Lim T, et al. Financial and environmental costs of reusable and single-use anaesthetic equipment. *Br J Anaesth*. 2017;118:862–869.
50. Kwakye G, Pronovost PJ, Makary MA. Commentary: a call to go green in health care by reprocessing medical equipment. *Acad Med*. 2010;85:398–400.
51. Unger S, Landis A. Assessing the environmental, human health, and economic impacts of reprocessed medical devices in a Phoenix hospital's supply chain. *J Clean Prod*. 2016;112:1995–2003.
52. Farrelly JS, Clemons C, Witkins S, et al. Surgical tray optimization as a simple means to decrease perioperative costs. *J Surg Res*. 2017;220:320–326.
53. Zygourakis CC, Yoon S, Valencia V, et al. Operating room waste: disposable supply utilization in neurosurgical procedures. *J Neurosurg*. 2017;126:620–625.
54. NHS Institute for Innovation and Improvement. Improving quality and efficiency in the operating theatre. Coventry: NHS; 2009. Available at: http://harmfreecare.org/wp-content/files_mf/Improving-quality-and-efficiency-in-the-operating-theatre.pdf. Accessed April 30, 2020.
55. Mortimer F, Isherwood J, Wilkinson A, et al. Sustainability in quality improvement: redefining value. *Future Healthc J*. 2018;5:88–93.