The Carbon Footprint of Hospital Services and Care Pathways

A State-of-the-Science Review

Kouwenberg, L.H.J.A.; Cohen, E.S.; Hehenkamp, W.J.K.; Snijder, L.E.; Kampman, J.M.; Küçükkeles, B.; Kourula, A.; Meijers, M.H.C.; Smit, E.S.; Sperna Weiland, N.H.; Kringos, D.S.

DOI
10.1289/EHP14754

Publication date
2024

Document Version
Final published version

Published in
Environmental Health Perspectives

License
CC BY-NC-ND

A Section 508–conformant HTML version of this article is available at https://doi.org/10.1289/EHP14754.

The Carbon Footprint of Hospital Services and Care Pathways: A State-of-the-Science Review

Lisanne H.J.A. Kouwenberg,[1,2,3] *Eva S. Cohen,*[1,2,3,4] *Wouter J.K. Hehenkamp,*[2,4] *Lynn E. Snijder,*[1,2] *Jasper M. Kampman,*[2,7] *Burcu Küçükkeles,*[5] *Arno Kourula,*[5] *Marijn H.C. Meijers,*[6] *Eline S. Smit,*[6] *Nicolaas H. Sperna Weiland,*[2,7]* *and Dionne S. Kringos*[1,2,3]*

[1]Public and Occupational Health, Amsterdam UMC location University of Amsterdam, Amsterdam, the Netherlands
[2]Centre for Sustainable Healthcare, Amsterdam UMC, University of Amsterdam, Amsterdam, the Netherlands
[3]Amsterdam Public Health, Quality of Care, Global Health, Amsterdam UMC, University of Amsterdam, the Netherlands
[4]Department of Obstetrics and Gynecology, Amsterdam UMC location Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
[5]Section of Strategy and International Business, Amsterdam Business School, Faculty of Economics and Business, University of Amsterdam, the Netherlands
[6]Department of Communication Science, Amsterdam School of Communication Research, University of Amsterdam, the Netherlands
[7]Department of Anesthesiology, Amsterdam UMC location University of Amsterdam, Amsterdam, the Netherlands

Background: Climate change is the 21st century's biggest global health threat, endangering health care systems worldwide. Health care systems, and hospital care in particular, are also major contributors to greenhouse gas emissions.

Objectives: This study used a systematic search and screening process to review the carbon footprint of hospital services and care pathways, exploring key contributing factors and outlining the rationale for chosen services and care pathways in the studies.

Methods: This state-of-the-science review searched the MEDLINE (Ovid), Embase (Ovid), CINAHL (EBSCOhost), GreenFILE (EBSCOhost), Web of Science, Scopus, and the HealthcareLCA databases for literature published between 1 January 2000 and 1 January 2024. Gray literature was considered up to 1 January 2024. Inclusion criteria comprised original research reporting on the carbon footprint of hospital services or care pathways. Quality of evidence was assessed according to the guidelines for critical review of product life cycle assessment (LCA). PROSPERO registration number: CRD42023398527.

Results: Of 5,415 records, 76 studies were included, encompassing 151 hospital services and care pathways across multiple medical specialties. Reported carbon footprints varied widely, from 0.01 kg carbon dioxide (CO_2) equivalents ($kgCO_2e$) for an hour of intravenously administered anesthesia to 10,200 $kgCO_2e$ for a year of hemodialysis treatment. Travel, facilities, and consumables were key contributors to carbon footprints, whereas waste disposal had a smaller contribution. Relative importance of carbon hotspots differed per service, pathway, medical specialty, and setting. Studies employed diverse methodologies, including different LCA techniques, functional units, and system boundaries. A quarter of the studies lacked sufficient quality.

Discussion: Hospital services and care pathways have a large climate impact. Quantifying the carbon footprint and identifying hotspots enables targeted and prioritized mitigation efforts. Even for similar services, the carbon footprint varies considerably between settings, underscoring the necessity of localized studies. The emerging field of health care sustainability research faces substantial methodological heterogeneity, compromising the validity and reproducibility of study results. This review informs future carbon footprint studies by highlighting understudied areas in hospital care and providing guidance for selecting specific services and pathways. https://doi.org/10.1289/EHP14754

Introduction

Climate change is threatening the health of billions of people alive today.[1] Climate change causes direct health impacts as a result of heatwaves and other extreme weather events and indirectly affects health through its impacts on the physical, natural, and social systems on which health depends.[2] Health care systems are responsible for an estimated 4.4% of global greenhouse gas (GHG) emissions, with national shares of up to 10% in high-income countries.[3–6] Net-zero or low-carbon targets for health care systems have been set in 84 countries and areas, covering low-income countries (e.g., Malawi), middle-income countries (e.g., Peru), and high-income countries (e.g., the UK).[7] To inform decision-making on carbon reduction strategies, it is crucial to improve the quantitative understanding of the environmental impact of health care delivery on multiple levels.[8]

Impactful publications on sustainability in health care have shown that health care's footprint at a macro level is attributable to hotspots such as energy use, mobility, chemical substances, and disposables.[4,9,10] In clinical practice, the use of components such as disposables, pharmaceuticals, or energy is interconnected in clinical activities, particularly within hospital services and care pathways. These can be defined as the care provided to patients by health care workers within the hospital. Examining the climate impact of individual hospital services and care pathways enables the identification of environmental hotspots and comparative advantages of clinical alternatives.[8] Evaluating health care's footprint on a more detailed level also puts quantification analysis in a perspective that enables all stakeholders (e.g., clinicians, industry, policymakers, patients) to be part of impact reduction.

Quantifying the environmental impact of hospital services and care pathways often relies on model estimations derived from life cycle assessment (LCA) studies. LCA is a well-established method used to estimate the environmental impact of products and processes throughout their life cycle, spanning resource extraction and production to packaging, transportation, use, and waste disposal.[11] LCA results are highly sensitive to methodological choices.[12] Despite various guidelines and protocols for conducting, accounting, and reporting these assessments, large methodological heterogeneity exists among LCAs in health care.[13–15] This gives rise to critical issues such as limited comparability between studies and

*These authors contributed equally to this work.

Address correspondence to Lisanne H.J.A. Kouwenberg, Department of Public and Occupational Health, Amsterdam UMC, Meibergdreef 9, 1105 AZ Amsterdam, The Netherlands. Email: l.h.j.a.kouwenberg@amsterdamumc.nl

Supplemental Material is available online (https://doi.org/10.1289/EHP14754).

The authors declare no competing interests.

Received 2 February 2024; Revised 15 November 2024; Accepted 25 November 2024; Published 27 December 2024.

other questions in the evolving field of health care environmental footprint research. First, there is a lack of clarity regarding the underlying rationale for the selection of specific hospital services and care pathways for environmental impact analysis. Second, the overall quality of many carbon footprint assessments has not been systematically and critically appraised.[13] This lack of systematic evaluation leaves room for debate about appropriate assessment and interpretation of the resulting findings and conclusions. Third, there is limited understanding of the similarities in carbon footprints and hotspots across different hospital services, care pathways, medical specialties, and settings.

In this state-of-the-science review, we therefore aimed to answer three research questions: *a*) Which hospital services and care pathways have had their carbon footprint studied, and what rationale guided their selection? *b*) What methods have been employed to quantify the carbon footprint of hospital services and care pathways? *c*) What are the key factors contributing to the carbon footprint of hospital services and care pathways? This study focuses on one important environmental impact in particular (i.e., climate change) because the majority of existing studies on the environmental impact of health care primarily address climate impact, making the carbon footprint a well-documented and significant area for investigation[13] while recognizing that the impact of health care on our environment is broader. Ultimately, we believe that answering these questions helps to discern potential commonalities and patterns among the carbon footprint and hotspots of hospital services, care pathways, medical specialties, and settings. We believe this will help enable the development of comprehensive strategies to reduce carbon emissions in hospital care delivery as we progress toward net-zero and low-carbon health care systems.

Methods

This review was conducted and reported according to Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines and the Standardized Technique for Assessing and Reporting Reviews of LCA (STARR-LCA) checklist (Table S1).[16,17] This checklist is largely based on the PRISMA guideline but adapted for LCA studies, which often have large variability in methodology and reporting. The review protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO; ID CRD42023398527).

Search Strategy

The following electronic databases were searched up to 1 January 2024: MEDLINE (Ovid), Embase (Ovid), Cumulative Index to Nursing and Allied Health Literature (CINAHL; EBSCOhost), GreenFILE (EBSCOhost), Web of Science, and Scopus. The search strategy was developed based on relevant keywords identified from five known relevant articles (see the section "Full search strategy" in the Supplemental Material).[18–22] The strategy was developed by one author (L.H.J.A.K.) and peer-reviewed by two authors (D.S.K., N.H.S.W.) and consisted of two parts: *a*) environmental sustainability/carbon footprint/life cycle assessment; and *b*) hospital care/clinical pathway/surgery or related terms, synonyms, and spelling variations. Furthermore, the HealthcareLCA database was searched for "services," "procedures," "medical interventions," and "investigations" until 1 January 2024 for any missing relevant studies.[23]

Reference lists of included studies were screened for potential additional studies. In addition, gray literature from relevant organizations, such as governmental institutions or health care providers, was sought on their websites (see the section "Full search strategy" in the Supplemental Material).

Inclusion criteria included articles that reported the carbon footprint of hospital services or hospital care pathways. Hospital services and hospital care pathways were defined as care that patients receive that is provided to them by health care workers in the hospital. The carbon footprint had to be reported on the level of an individual hospital service (e.g., for one surgery) or care pathway (e.g., a combination of multiple services or an explicit statement that it concerned a care pathway study). Studies were also included if they reported the carbon footprint for a group of patients receiving the same service or care pathway (e.g., a hemodialysis unit). Exclusion criteria were studies reporting the carbon footprint of entire hospitals or health care systems because these do not provide information at the level of care delivery. In addition, studies that only quantified the carbon footprint of an individual product used for a hospital service, such as surgical instruments or pharmaceutical ingredients, were excluded for the same reason. Studies that included only a single component of the carbon footprint, such as waste- or travel-related emissions, were excluded because these would not provide any information on the relative importance of different hotspots.

Only original empirical research was included; reviews, opinion-based reports, commentaries, and editorials were excluded. Articles in languages other than English or Dutch were excluded. Conference abstracts were excluded. Articles published before the year 2000 were excluded because the first international standards for LCA were only published between 1997 and 2000. Inclusion and exclusion criteria are presented in Table S2.

Duplicates were identified using EndNote's duplicate identification strategy and then manually removed. Titles and abstracts of all potentially eligible studies were screened by one reviewer (L.H.J.A.K.) using Rayyan software.[24] A random sample of all retrieved studies (30%) was independently screened by another reviewer. Multiple reviewers were involved in this process as indicated by the number of acronyms listed (E.S.C., B.K., D.S.K., W.J.K.H., N.H.S.W.). Any disagreements were resolved through a consensus meeting with all reviewers. Considering that there was a high level of agreement ($<2\%$ of all double-screened articles resulted in conflicting decisions), one author (L.H.J.A.K.) completed the title/abstract screening of the remaining articles. Articles that were subsequently included by one reviewer were checked by a second reviewer (N.H.S.W.). Next, all obtained full-text articles were reviewed by one reviewer (L.H.J.A.K.) and divided up among the review team for independent review by another author (E.S.C., B.K., D.S.K., W.J.K.H., N.H.S.W.). Any disagreements were resolved via consensus or through consultation with a third reviewer.

Data Extraction

A data extraction form was made and tested via the trial input of data from five articles known to be relevant.[18–22] The following information was extracted by one author (L.H.J.A.K.) and checked by another author (E.S.C., B.K., D.S.K., W.J.K.H., N.H.S.W., L.E.S.): author(s), year, type of study, journal, description of hospital service or care pathway, study or patient population, study location, goal of the study, intended use of results, target audience, reason(s) for the selected study focus, method(s) used to quantify the environmental impact(s), including the functional unit, protocol(s) followed, software and data types, as well as outcomes regarding the total carbon footprint in kilograms of CO_2 equivalents ($kgCO_2e$) and its contributing factors. Contributing factors were further grouped by one researcher (L.H.J.A.K.) into the following categories, which were adapted from the Care Pathways Guidance published by the Sustainable Healthcare Coalition[25]: travel (e.g., patient or staff travel), facilities (e.g., heating, lighting, water use, construction and maintenance of building), medical equipment (e.g., magnetic resonance imaging scanner, hemodialysis machine), medical consumables (e.g., disposable instruments, syringes, dressings, gloves, masks), pharmaceuticals (e.g., anesthetic gases, medical drugs, pharmaceutical packaging), waste disposal (e.g., waste incineration, landfill, recycling, wastewater treatment), and other (e.g., nonmedical consumables, food, office supplies; nonmedical equipment, computers).

When estimates were available on multiple levels (i.e., for both the whole hospital unit and the individual hospital service level), information was collected for the individual service or pathway level only. When estimates were not presented at the individual level in the respective study, they were divided by the number of patients studied to obtain an estimate per patient or treatment. Missing data was requested from study authors or extracted from graphs using imaging software (ImageJ; version 1.49v).[26]

Quality Assessment

A *pro forma* quality assessment tool by Drew et al. was used, based on Weidema's guidelines for critical review of LCAs.[15,27] The review team consisted of an LCA expert (L.E.S.) and medical experts (L.H.J.A.K., E.S.C., J.M.K.). Three pairs of reviewers independently assessed a total of 16 quality indicators on internal and external validity, including representativeness of data and the contextualization of results; consistency of methodological choices; reporting of results and conclusions; transparency about methodological choices, assumptions, and data sources; risk of bias; and completeness in terms of system boundaries. Any disagreements in quality scores were resolved via consensus. A maximum of 35 points could be allocated among the four phases of LCA, including the goal and scope definition (13 points), inventory analysis (7 points), impact assessment (6 points), and interpretation of results (9 points). An overall quality score was calculated as a percentage of the total points allocated. A description of how the assessment tool was operationalized by our research team can be found in Table 1.

Data Synthesis

The included studies were systematically categorized and presented in a descriptive manner, organized by medical specialty and hospital service or care pathway. Some studies could be categorized into multiple medical specialties, in which case the study was categorized to the medical specialty that the study authors emphasized. For each category of contributing factors, the relative contribution per service or pathway was calculated. In some studies, the relative contributions of contributing factors were not reported separately. If it was not possible to group a factor into one category, the total contribution of this factor was attributed to each applicable category (i.e., double counting).

Results

Search Results

A total of 9,799 records were identified from six databases (Figure 1). After removing duplicates, 5,415 records were screened, of which 5,317 were deemed irrelevant based on title and abstract. Ninety-eight articles were assessed for eligibility based on full-text review, after which 62 articles were included in the review. The search identified 14 additional relevant studies from the HealthcareLCA database, gray literature, and citation searching. In total, 76 studies were included, the majority of them published in the last 3 y ($n = 49$).

Hospital Services and Care Pathways Studied

Carbon footprints have been evaluated for a total of 151 different hospital services and care pathways and variants, as presented in Table 2. Study topics involved surgical care, including anesthesiology ($n = 25$); interventions from different medical specialties, such as obstetrics and gynecology ($n = 9$) and urology ($n = 5$); renal care ($n = 16$); diagnostic services ($n = 28$), among which a majority focused on medical imaging ($n = 10$) and blood and urine testing ($n = 11$); ophthalmological care, including cataract surgery ($n = 11$); cardiac care ($n = 6$); emergency care ($n = 8$); outpatient care ($n = 19$); and psychiatric treatments ($n = 3$). The majority of studies focused on distinct hospital services ($n = 59$), whereas 17 studies focused on entire hospital care pathways, such as the treatment of patients with acute decompensated heart failure or hemodialysis treatment during a whole year[18,19,22,32,34,46,51,60,63,67,69,74–77,80,98] (Table 2). Care pathway studies generally included multiple elements of care in the functional units of their analyses, such as diagnostics and follow-up care, and evaluated care during longer periods of time, such as the duration of a hospitalization or treatment during one or multiple years.[18,19,22,32,34,46,51,60,63,67,69,74–77,80,98]

Comparing the Carbon Footprint between Services, Medical Specialties, and Settings

The reported carbon footprints ranged between 0.01 kg carbon dioxide (CO_2) equivalents ($kgCO_2e$) for an hour of propofol anesthesia,[29] up to 10,200 $kgCO_2e$ for a year of hemodialysis treatment.[20] Given the differences in functional units and included elements of care, it was difficult to directly compare the magnitude of the carbon footprints between different studies. However, a number of studies ($n = 20$) compared similar services or modalities within their study, employing similar units of analyses, which made comparisons between services more informative.[21,28,29,32,37,41,43,44,53,60,62–65,67,69–71,85,89] Six studies evaluated the same service or pathway over time,[34,76,77,84,96,97] and 16 studies looked across different settings.[20,39,45,48,53,55,77,81,88,90–95,98] The majority of studies that compared care delivery at home vs. in hospital showed that home-based care delivery had a lower footprint (i.e., for hemodialysis[45,48] and outpatient consultations).[90–95] Regarding different facilities, one study showed that cataract surgery in a private hospital yielded a slightly larger footprint compared with such surgery in a public facility in the same region,[55] whereas another study demonstrated that the carbon footprint of skin cancer surgery was lower in a private facility.[88] One study showed that the carbon footprint of hemodialysis treatment varied substantially across 15 facilities in a single geographic region in the US.[20] Two studies conducted cross-country comparisons, showing that certain forms of surgical and intensive care unit care had the highest footprint in the US, compared with Canada, the UK, and Australia.[39,81]

Rationale for Selected Hospital Services and Care Pathways

Several reasons were mentioned for selecting hospital services and care pathways for carbon footprint quantification. The majority of studies ($n = 36$) rationalized the selected study topic by indicating the high volume of patients or services provided each year,[19,21,22,28,30,37,39,40,42–44,52–59,61,62,65–67,70,71,73,74,76,80,84,85,87–89] or an increasing (future) demand for care ($n = 11$).[45,48,59,61,70,85,87,91,93,97,98] Five studies mentioned high volumes of waste.[35,42,54,55,88] Others stated that the hospital service under study was particularly resource intensive in terms of, for example, energy use, water, or costs.[21,30,33,35,41,45,49,50,68,72,78,81,86,88] Some suggested that it would be interesting to evaluate environmental outcomes, especially when clinical alternatives for services and pathways were available and equally (cost-)effective.[18,21,28,41,45,62,74,92] Another frequently mentioned argument was the absence of carbon footprint assessments for the hospital service under study.[31,33,34,40,42,44,64–66,68,71,73,80,83,84,86,87] One study mentioned the

Table 1. Quality assessment tool, based on Drew et al.,[15] including its operationalization in this study.

Appraisal criteria	Indicator(s)	Operationalization by our research team
Phase 1: Goal and scope (13 points)		
Study goal is clearly stated, including the study's rationale (1), intended application (1), and intended audience (1)	Transparency	—
LCA method is clearly stated (1)	Transparency	If the term LCA was not explicitly used, this item scored zero points.
Functional unit is clearly defined and measurable (1), justified (1), and consistent with the study's intended application (1)	Consistency	No points were subtracted if the term "functional unit" was not explicitly used. Points were given based on a clear description of the unit of analysis. In case no intended application was mentioned (scoring item 1), consistency with the study's aim was assessed.
The system to be studied is adequately described with clearly stated system boundaries (1), life cycle stages (1), and appropriate justification of any omitted stages (1)	Transparency; bias	Points for appropriate justification of any omitted stages were not given if the study listed only excluded elements, without an explanation of why these were excluded.
The system covers production (1), use/reuse (1), and disposal (1) of materials and energy	Internal validity, completeness	The original assessment tool included: "half mark if only for energy and vice versa," which was unclear for our reviewers and left out of the assessment.
Phase 2: Inventory analysis (7 points)		
The data collection process is clearly explained, including the source(s) of foreground material weights and energy values (1); the source(s) of reference data (e.g., inventory database; 1); and what data are included (e.g., production and disposal of unit processes; 1)	Transparency, internal validity	—
Representativeness of the data is discussed (1), differences in electricity generating mix are accounted for (1), and the potential significance of exclusions or assumptions is addressed (1)	Internal validity; external validity	Point for electricity generating mix given if analyses were adjusted for local energy mix or if sensitivity to different energy mixes was assessed. Point for representativeness given only when explicitly mentioned with regard to either geographic, temporal, or technological representativeness, e.g., when prices were deflated. If geographical representativeness was only addressed in the context of the energy mix, only one point was given for "differences in electricity generating mix are accounted for." Point for addressing the potential significance of exclusions or assumptions given only if potential significance was explicitly stated, i.e., whether it potentially led to an under- or overestimation.
Allocation procedures, where necessary, are described and appropriately justified (1; mark given if no allocation was used)	Transparency; bias	This item was given a score of 1 if no substantial allocation was deemed necessary in the study.
Phase 3: Impact assessment (6 points)		
Impact categories (1), characterization method (1), and software used (1) are documented transparently	Transparency	Given that all articles mentioned the term "carbon footprint" (because this was included in the literature search), 1 point was always given for "impact categories."
Results are clearly reported in the context of the functional unit (1) (0.5 if graphically, 0 if only normalized results were reported)	Consistency; transparency	If no functional unit was described in phase 1, this item was judged based on the way results were presented in general.
A contribution analysis is performed and clearly reported (1), and hotspots are identified (1)	—	A point was given for contribution analysis if the results were summed up and presented as a total footprint.
Phase 4: Interpretation (9 points)		
Conclusions are consistent with the goal and scope (1) and supported by the impact assessment results (1)	Internal validity; consistency	If no goal and scope were described earlier, this item was judged based on the clearness of the provided conclusion(s) in general.
Results are contextualized through the use of sensitivity analysis (1) and uncertainty analysis (1)	Internal validity	If the study did not explicitly mention "sensitivity" or "uncertainty analysis," but presented ranges or standard deviations: 1 point was given for "uncertainty analysis."
Limitations are adequately discussed (1), and the potential impact of omissions or assumptions on the study's outcomes are described (1)	Bias	Only points given when the potential impact of the omission on the study's outcomes were explicitly mentioned, i.e., whether the omission likely led to an under- or overestimation.
The assessment has been critically appraised (i.e., peer review if journal article or independent, external critical review if report/thesis; 1)	Bias	No point was given in the case of a letter to the editor or a commentary because these are generally not peer-reviewed. However, if an included letter is peer-reviewed, 1 point will be given.
Source(s) of funding and any potential conflict(s) of interest are disclosed (1) and are unlikely to be a source of bias (1)	Bias	No point was given for the first item if only conflict(s) of interest were disclosed but no source(s) of funding were reported.

Note: —, not applicable; LCA, life cycle assessment.

duration of illness,[67] 2 mentioned the availability of data,[18,92] and 10 referred to previous research that either suggested a potentially large footprint of certain types of care[20,22,29,77,95–97] or a need for further research.[28,75,77,91,95–97] Finally, 13 studies did not clarify their reasons for selecting certain hospital services or care pathways.[32,36,38,46,47,51,60,63,69,79,82,90,94]

Applied Methods

Various methods were used for carbon footprint quantification, which were differently described by included studies. Table 3 lists the methods as described by the included articles. Most studies ($n = 32$) used an LCA technique, for which some used the

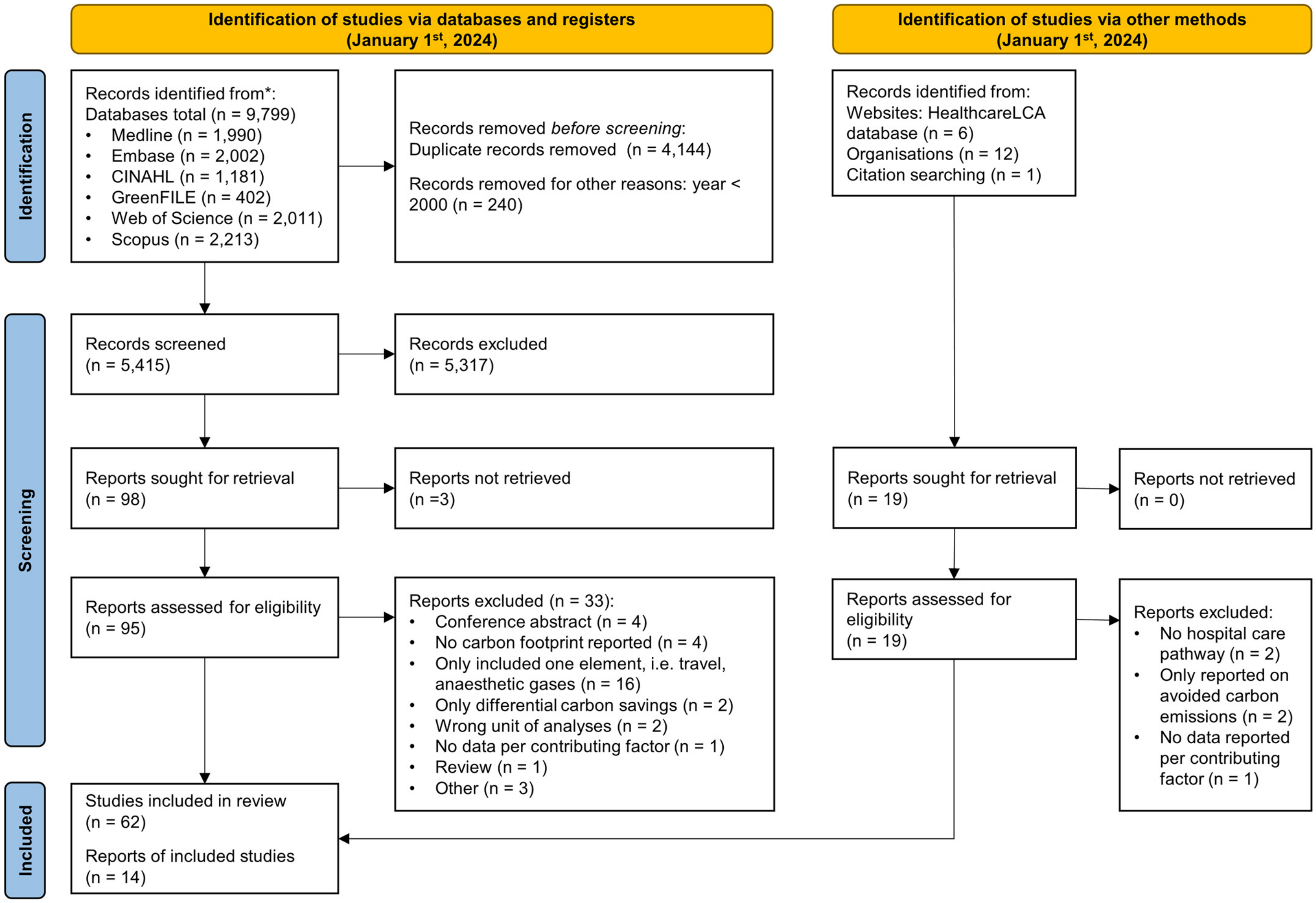

Figure 1. PRISMA Flow diagram. Note: CINAHL, Cumulative Index to Nursing and Allied Health Literature; PRISMA, Preferred Reporting Items for Systematic reviews and Meta-Analyses.

term life cycle analysis[54,59]; both abbreviated as "LCA." EIO-LCA was used as an abbreviation for both economic input-output LCA and environment input-output LCA,[52,87] and environmentally extended input-output (EEIO) was used for environmentally extended input-output LCA.[22,72] Several studies used (multi-) component analysis ($n=5$)[19,46,50,79,98] or Bilan Carbone methodology/software ($n=4$).[42,49,52,86] Although terminology varied between studies, methodological steps and approaches seemed quite similar, where most studies used process activity data ($n=40$) or combined process and financial activity data in a hybrid analysis ($n=26$). Only two studies used solely financial activity data, and they were both care pathway studies.[18,22]

Contributing Factors

Table 4 shows what type of factors were included per hospital service or care pathway and their relative contributions, presented by medical specialty. More detailed descriptions of included factors can be found in Tables S3–S21. Figure 2 graphically summarizes the results for six different medical specialties. These figures can be interpreted as the share of services and pathways, as currently studied within a medical specialty, that included certain contributing factors and how often they ranked in the top 2 of the largest contributions. A large variation between medical specialties existed in the type of factors that were included and the ones that prevailed as the first or second largest carbon hotspots for services studied within that specialty. In the next sections, results will be discussed per contributing factor.

Travel. Travel was included in 75 services (covered in 45 studies) of which most services included patient travel ($n=66$) and staff travel ($n=44$). Four services also included visitor travel.[36,46] Within each identified study that included travel, travel in general, and patient travel in particular, had relatively large contributions to the carbon footprint of hospital services and care pathways. Patient travel ranked as the first or second largest contributor in 67% of the services that included this factor (patient travel: $n=44$ of 66 services, contribution range: 0.5%–100%; staff travel: $n=19$ of 44 services, contribution range: 0.1%–75%). Results differed by medical specialty. For example, within nephrology, patient travel was included for nearly every studied hospital service and pathway (Figure 2A), but in only a part of these, it ranked as the first or second largest hotspot. In contrast, for services within pathology and radiology, patient travel was never included (Figure 2C,D).

Facilities. Facilities that are needed for delivering hospital care were included in 84 services (48 studies), ranking as the first or second largest contributor in 61% of the services that included this factor ($n=51$ of 84 services, contribution range: 0.4%–100%). Most studies included only energy use of the building, such as electricity used for lighting or heating, ventilation, and air-conditioning. Some studies included the carbon footprint of water use or wastewater treatment,[19,20,22,36–38,46,48–51,57,67,82,88,90,98] which almost always had low contributions (<4%) to the carbon footprint. Only a few studies included other facility-related factors such as construction, sanitation, or sewerage treatment.[46,50,51,98] For certain medical specialties, including nephrology and surgical care, the facilities-related footprint was especially large (Figure 2A,E).

Table 2. Hospital services and care pathways studied, by medical specialty.

Medical specialty	Hospital service or care pathway	Care pathway[a]	Diagnostics[b]	Treatment[b]	Inpatient care[b]	Outpatient visits[b]	Specifics under study[c]	Studies (n)	Carbon footprint ($kgCO_2e$)	Reference(s)
Anesthesiology	Anesthesia for total knee replacement	—	—	Y	—	—	General; General + spinal; Spinal	1	14.9–18.5	McGain et al.[28]
	Maintenance anesthesia for 1 h	—	—	Y	—	—	Desflurane; Isoflurane; Propofol; Sevoflurane	1	0.01–56.5	Sherman et al.[29]
Cardiology and cardiac surgery	Atrial fibrillation catheter ablation procedure	—	—	Y	—	—		1	76.9	Ditac et al.[30]
	Cardiac surgery	—	—	Y	—	—		1	124.3	Grinberg et al.[31]
	Cardioversion care pathway	Y	Y	Y	Y	Y	DOAC; Warfarin	1	58.2–85.5	Orton and Pierce[32]
	Care pathway for acute decompensated heart failure	Y	Y	Y	Y	—	—	1	263	Zhang et al.[22]
	Elective CABG with cardiac bypass	—	—	Y	—	—	—	1	505.1	Hubert et al.[33]
Dermatology	Melanoma follow-up pathway	Y	Y	—	—	Y	Various melanoma stages (1a–3d), following 2015 vs. 2022 guidelines	1	157.9–1,657.7	Grover et al.[34]
Emergency medicine	Bed day	—	—	Y	Y	—	High-intensity ward; low-intensity ward; in ICU; in acute care unit	3	12–161.6	Hunfeld et al.[35]; Penny et al.[36]; Prasad et al.[37]
	Emergency department visit	—	?[d]	Y	—	—	—	1	13.8	Penny et al.[38]
	Treatment of septic shock in ICU	—	Y	Y	Y	—	American hospital; Australian hospital	1	88–178	McGain et al.[39]
Gastroenterology	Colonoscopy	—	Y	—	—	—	—	1	5.4	Elli et al.[40]
	Esophagogastroduodenoscopy/upper endoscopy	—	Y	—	—	—	With vs. without EndoFaster to reduce rate of biopsy	2	0.5–6.7	Elli et al.[40]; Zullo et al.[41]
	Gastrointestinal endoscopy	—	Y	—	—	—	Average of different types of endoscopy, including gastroscopy and colonoscopy	1	28.4	Lacroute et al.[42]
	Medical treatment of gastroesophageal reflux	Y	—	Y	Y	Y	—	1	247	Gatenby[18]
Gynecology and obstetrics	Cesarean section	—	—	Y	—	—	—	1	37	Campion et al.[43]
	Endometrial cancer staging	—	—	Y	—	—	Laparoscopy; laparotomy; robot-assisted	1	22.7–40.3	Woods et al.[44]
	Hysterectomy	—	—	Y	—	—	Abdominal; laparoscopic; robotic; vaginal	1	285–814	Thiel et al.[21]
	Vaginal birth	—	—	Y	—	—	—	1	17	Campion et al.[43]
Nephrology	Ambulatory PD	—	—	Y	?	?	Continuous, at home; continuous, in PD center; daytime, at home; daytime, in PD center	1	363.5–409.5	Chen et al.[45]
	Bed day nephrology ward	—	Y	Y	Y	—	—	1	161	Connor et al.[46]
	Continuous renal replacement therapy (per 72 h)	—	—	Y	—	—	With Prismaflex system	1	113	Aspin[47]
	Hemodialysis (per treatment)	—	—	Y	—	—	—	1	58.9	Sehgal et al.[20]
	Hemodialysis (per year)	—	—	Y	—	—	Unit-based; home-based	1	207–1,404	James[48]
	Hemodialysis (per year)	—	—	Y	—	Y	At home; in center	1	5,110	Mtioui et al.[49]
	Hemodialysis (per year)	—	Y	Y	—	—	—	1	10,200	Lim et al.[50]
	Hemodialysis care pathway (per year)	Y	—	Y	—	Y	—	1	1,844	Connor et al.[46]

Table 2. (*Continued.*)

Medical specialty	Hospital service or care pathway	Care pathway[a]	Diagnostics[b]	Treatment[b]	Inpatient care[b]	Outpatient visits[b]	Specifics under study[c]	Studies (n)	Carbon footprint ($kgCO_2e$)	Reference(s)
	Hemodialysis care pathway (per year)	Y	Y	Y	—	—	—	1	3,382	Newcastle upon Tyne Hospital[51]
	Hemodialysis and PD (per year)	Y	Y	Y	—	—	—	1	7,094	Connor et al.[46]
	Outpatient appointment	—	?	?	—	Y	—	1	22	Connor et al.[46]
Ophthalmology	Cataract surgery	—	—	Y	—	—	Manual small incision cataract surgery; phacoemulsification; phacoemulsification at public hospital; phacoemulsification in private hospital; unspecified	7	5.9–158.6	Ferrero et al.[52]; Goel et al.[53]; Hong et al.[54]; Latta et al.[55]; Pascual-Prieto et al.[56]; Thiel et al.[57]
	Cataract pathway	Y	—	Y	—	Y	—	1	181.8	Morris et al.[19]
	Intravitreal injection	—	—	Y	—	—	—	2	13.7–14.1	Chandra et al.[58]; Power et al.[59]
Orthopedics	Total knee replacement care pathway	Y	Y	Y	Y	Y	With Care4Today program; without Care4Today program	1	336–421	Johnson & Johnson[60]
	Total knee replacement surgery	—	—	Y	—	—	Posterior-stabilized cemented, with tibial extension stem, performed by a medial parapatellar approach	1	190.5	Delaie et al.[61]
Otolaryngology	Tonsillectomy	—	—	Y	—	—	Monopolar electrocautery; cold excision without cautery; coblation	1	157.6–204.7	Meiklejohn et al.[62]
Pediatric medicine	Pediatric asthma care pathway (per year)	Y	?	Y	Y	?	With Smartinhaler; without Smartinhaler	1	39–89	Budgen[63]
Pathology	Blood testing	—	Y	—	—	—	ABG; CRP; coagulation profile; full blood examination; urea + electrolytes; chemistry; coagulation factors; CBC + differential; total protein; phlebotomy	2	0.04–0.7	McAlister et al.[64]; Spoyalo et al.[65]
	Urine testing	—	Y	—	—	—	Urinalysis	—	—	—
	COVID-19 testing	—	Y	—	—	—	—	1	0.6	Ji et al.[66]
Psychiatry	Schizophrenia pathway with antipsychotic injections	Y	—	Y	Y	Y	One-monthly; three-monthly; treatment interruption	1	364.9–766.5	Debaveye et al.[67]
Pulmonary medicine	Bronchoscopy	—	Y	—	—	—	—	1	1.1	Patrucco et al.[68]
	Monoclonal antibody therapy of severe eosinophilic asthma	Y	?	Y	Y	?	With benralizumab; without benralizumab	1	91–192	Budgen[69]
Radiology	CT scan	—	Y	—	—	—	—	2	6.7–9.2	Martin et al.[70]; McAlister et al.[71]
	Chest X-ray	—	Y	—	—	—	Nonmobile; mobile	1	0.5–0.8	McAlister et al.[71]
	Interventional radiology procedure	—	Y	Y	—	—	—	1	243	Chua et al.[72]

Table 2. (*Continued.*)

Medical specialty	Hospital service or care pathway	Care pathway[a]	Diagnostics[b]	Treatment[b]	Inpatient care[b]	Outpatient visits[b]	Specifics under study[c]	Studies (n)	Carbon footprint ($kgCO_2e$)	Reference(s)
	MRI scan	—	Y	—	—	—	Prostate; not specified	3	17.5–22.4	Esmaeili et al.[73]; Leapman et al.[74]; Martin et al.[70]; McAlister et al.[71]
	Ultrasound	—	Y	—	—	—	—	2	0.5–1.1	Martin et al.[70]; McAlister et al.[71]
Radiotherapy	External beam radiation therapy	Y	—	Y	—	Y	Average treatment course (various disease sites); during pandemic; pre-pandemic (various treatment courses)	2	249–489	Ali and Piffoux[75]; Cheung et al.[76]
	External beam radiation therapy	Y	Y	Y	—	—	Prostate VMAT, pre-COVID; prostate VMAT, during COVID; breast IMRT, pre-COVID; breast IMRT, during COVID	1	75–227	Chuter et al.[77]
	Proton therapy	—	—	Y	—	—	Various disease sites treated, e.g., breast cancer, prostate cancer	1	1,361–1,409	Dvorak et al.[78]
Surgery	Abdominoplasty	—	—	Y	?	—	—	1	23.7	Berner et al.[79]
	Anastomotic leak care pathway	Y	Y	Y	Y	Y	Grades A, B, and C	1	1,302.97	Bischofberger et al.[80]
	Anti-reflux surgery	Y	Y	Y	Y	Y	—	1	1,038	Gatenby[18]
	Average surgery	—	—	Y	—	—	American hospital; Canadian hospital; UK hospital; hospital in low- or middle-income country	3	8.4–232	MacNeill et al.[81]; Penny et al.[82]; Umo et al.[83]
	Bilateral breast augmentation	—	—	Y	?	—	—	1	16.2	Berner et al.[79]
	Carpal tunnel release	—	—	Y	—	—	Standard vs. lean and green; endoscopic; open	2	6.6–106.5	Kodumuri et al.[84]; Zhang et al.[85]
	Elective endovascular aortic repair	—	—	Y	—	—	—	1	108	Sénémaud et al.[86]
	Minimally invasive surgery	—	—	Y	—	—	—	1	141	Power et al.[87]
	Rhinoplasty	—	—	Y	?	—	—	1	17	Berner et al.[79]
	Skin cancer surgery	—	—	Y	—	—	Clinic-based; hospital-based	1	28.5–80.8	Tan and Lim[88]
Urology	Prostate biopsy pathway (included 3 separate services: prebiopsy prostate MRI, TRUS biopsy, and pathology analysis)	Y	Y	—	—	—	—	1	36.2–80.7	Leapman et al.[74]
	Radical prostatectomy	—	—	Y	Y	—	Laparoscopic; robot-assisted	1	47.3–59.7	Fuschi et al.[89]

Table 2. (*Continued.*)

Medical specialty	Hospital service or care pathway	Care pathway[a]	Diagnostics[b]	Treatment[b]	Inpatient care[b]	Outpatient visits[b]	Specifics under study[c]	Studies (*n*)	Carbon footprint ($kgCO_2e$)	Reference(s)
Outpatient consultations in multiple medical specialties	Face-to-face consultation	—	—	?	—	Y	Geriatric medicine clinic; psychiatry clinic; rehabilitation clinic; speech therapy clinic; several different departments, i.e., urology	5	4.8–178.5	Bartlett and Keir[90]; Filfilan et al.[91]; Holmner et al.[92]; Penaskovic et al.[93]; Sillcox et al.[94]; Thiel et al.[95]
	Neuroemergent consultation	—	—	—	—	Y	With telehealth; without telehealth	1	131–437	Whetten et al.[96]
	Preoperative screening	—	Y	—	—	Y	After telehealth implementation; before telehealth implementation	1	76.4–84.5	Wang et al.[97]
	Virtual consultation	—	—	—	—	Y	By phone; by video; geriatric medicine clinic; psychiatry clinic; several different departments, i.e., urology	6	0–4.1	Bartlett and Keir[90]; Filfilan et al.[91]; Holmner et al.[92]; Penaskovic et al.[93]; Sillcox et al.[94]; Thiel et al.[95]

Note: Results should not be directly compared due to differing methodologies. —, Not applicable; ABG, arterial blood gas; CABG, coronary artery bypass graft; CBC, Complete blood count; COVID, Coronavirus disease; CRP, C-reactive protein; CT, Computerized Tomography; DOAC, direct oral anticoagulant; ICU, Intensive Care Unit; IMRT, Intensity-modulated radiotherapy; MRI, magnetic resonance imaging; PD, peritoneal dialysis; TRUS, transrectal ultrasound; VMAT, Volumetric modulated arc therapy.

[a]Studies that evaluated care pathways are indicated with "Y."

[b]"Y" indicates that this specified care type was included in the analysis.

[c]Several studies included specific details of the hospital service or care pathway under study, for example, about the setting in which the service was provided or which variants were compared. In case a study specified these, the details are listed in this column.

[d]"?" indicates that in some studies it was not entirely clear whether the analysis included an element of care in the functional units of their analyses.

Medical equipment. One hundred thirteen services (in 57 studies) included GHG emissions from various types of medical equipment, including reusable surgical instruments, anesthesia machines, imaging equipment, and patient air warmers. For most services, only the equipment's energy use was included, but some also included equipment production and sterilization of reusable equipment. Medical equipment ranked as the first or second largest contributor to the carbon footprint within certain medical specialties, such as radiology (Figure 2D). However, for most other specialties and hospital services, equipment did not contribute as much. Overall, medical equipment ranked first or second in 56% of the cases ($n = 64$ of 113 services, contribution range: 0.02%–100%).

Medical consumables. Medical consumables were included in 100 services (in 53 studies). A variety of medical consumables were included, such as drapes, gowns, gloves, syringes, packaging, medical injection packs, and other single-use medical supplies. Some studies found relatively large contributions for certain consumable items, such as packaging,[45] whereas others found that packaging had only a small impact on the carbon footprint.[98] For many hospital services, consumables ranked in the top two largest contributors (69% of the services/pathways that included consumables; $n = 69$ of 100 services, contribution range: 0.3%–89%). Interestingly, consumables were included in all services studied within ophthalmology and pathology, ranking first or second in all services except for one (Figure 2B,C). Within other specialties, including surgery, consumables are less often ranked first or second (Figure 2E).

Pharmaceuticals. Pharmaceuticals were included in 50 services (in 31 studies), ranking first or second place in 62% of the services that included pharmaceuticals ($n = 31$ of 50 services, range: 0.1%–100%). Some studies included specific pharmaceuticals such as anesthetics,[28,29,62,81] proton pump inhibitors,[18] antibiotics,[80] or antipsychotic injections.[67] Others tried including pharmaceuticals based on financial activity data, but the relative contributions were so high that they were eventually not included in the footprints.[39,58,59] In many specialties, pharmaceuticals were rarely or never included, including nephrology, urology, and outpatient consultations in different medical specialties. The studies that included pharmaceuticals found that their contributions were relatively large, especially for anesthetic gases.[21,62,81] On the contrary, a study that modeled the footprint of psychiatric medication injections found pharmaceuticals to be responsible for only a small part of the total footprint of the year-long pathway.[67]

Waste disposal. Waste disposal was included in 97 services (in 50 studies), with an average relative contribution lower than 5% (range –3% up to 77%), ranking first or second place in 38% of services that included disposal in the analyses ($n = 37$ of 97). Studies included different forms of waste, such as landfill waste, cytotoxic waste, municipal solid waste, sharps waste, and body tissue waste, as well as different forms of waste disposal, including incineration and recycling. Some studies also included transportation to the disposal site. A few studies found that disposal had a negative contribution to the carbon footprint.[45,50,57,88] This was explained as due to recycling or the capture of methane at landfills.[88]

Other. Finally, many studies included other factors such as laundry services, cleaning compounds, internet use, nonmedical equipment, such as computers, and nonmedical consumables, including food, paper, and office supplies. The relative contributions of these factors can be found in Tables S3–S21.

Quality Assessment

Methodological quality was heterogeneous, and scores varied between 20% and 97% of total possible points. In many studies, quality was found to be insufficient, with one-quarter of studies

Table 3. Methods used for carbon footprint quantification.

Method as described by study	Studies (*n*)	Medical specialty	Protocol(s)	Type(s) of activity data	Software	Characterization method(s)
Life cycle assessment or similar approaches						
Life cycle assessment	19	Anesthesiology; emergency medicine; nephrology; orthopedics; pathology; radiology; surgery; urology; outpatient consultations in multiple medical specialties	GHG protocol; ISO 04014; ISO 14040; ISO 14044; SCPG; not stated	Process; hybrid; Not stated	Ecodesign Studio software; JMP Pro 15; OpenLCA; Python; SimaPro; not stated	GWP100 work of Sulbaek Andersen et al.[115]; IMPACT World+; IPCC; International Reference Life Cycle Data System 2016; ReCiPe 2016; TRACI 2.0; TRACI 2.1; not stated
Hybrid (environmental) life cycle assessment (LCA)	4	Emergency medicine; gynecology and obstetrics; ophthalmology; otolaryngology	ISO 14040; ISO 14044; GHG protocol	Hybrid	TRACI 2.1; not stated	CML-IA baseline; cumulative energy demand; ReCiPe 2016; TRACI 2.1
Eyefficiency tool	4	Ophthalmology	ISO 14040; not stated	Hybrid	Eyefficiency; not stated	Not stated
Process life cycle assessment	1	Gynecology and obstetrics	ISO 14040; ISO 14044	Process	Not stated	TRACI 2.0
Process LCA and environmentally extended input-output LCA (EEIO LCA)	1	Radiology	Not stated	Hybrid	SimaPro	TRACI 2.1
Augmented process-based hybrid LCA	1	Emergency medicine	NHS' LCA-based guideline	Hybrid	SimaPro	IPCC
Hybrid life cycle analysis (LCA)	1	Ophthalmology	Not stated	Hybrid	Not stated	Not stated
Life cycle assessment (simplified)	1	Outpatient consultations in multiple medical specialties	Not stated	Process	Microsoft Excel	Not stated
Environmentally Extended Input-Output (EEIO) LCA	1	Cardiology	GHG protocol product standard	Financial	Not stated	IPCC
Economic input-output life cycle assessment (EIO-LCA)	1	Ophthalmology	Bilan Carbone protocol; GHG protocol; PAS 2050	Hybrid	Not stated	Not stated
Environment Input-Output life-cycle assessment (EIOLCA)	1	Surgery	GHG protocol	Hybrid	Not stated	Not stated
Life cycle assessment in combination with other modeling technique						
Life cycle assessment in combination with Markov model	1	Psychiatry	ISO 14040; ISO 14044	Process	SimaPro	ReCiPe 2016
Care Pathway Guidance methodology						
As described by Care Pathway Guidance document	1	Orthopedics	SCPG	Not stated	Not stated	IPCC
Sustainable Care Pathway Guidance tool/online calculator	2	Cardiology; Surgery	SCPG	Hybrid	SCPG	Not stated
Environmental impact assessment	1	Surgery	SCPG	Process	Not stated	Not stated
Carbon footprint method						
Bilan Carbone method	4	Gastroenterology; nephrology; ophthalmology; surgery	Bilan Carbone protocol; GHG protocol; ISO 14064-1; ISO 14067; ISO 14069; PAS 2050; not stated	Hybrid	Bilan Carbone tool	IPCC; not stated
Carbon audit	1	Gynecology and obstetrics	GHG protocol; PAS 2050	Process	Not stated	Not stated
Carbon footprint accounting/analysis/evaluation/CO_2 production evaluation	7	Dermatology; gastroenterology; radiotherapy; surgery	GHG protocol; IPCC; ISO 14064:2018; not stated	Process; hybrid	US EPA calculator; not stated	Not stated
Greenhouse gas inventory	7	Surgery	GHG protocol	Process	Not stated	GWP100 work of Sulbaek Andersen et al,[116]
Component analysis	4	Nephrology; ophthalmology	PAS 2050	Process; Hybrid	Not stated	Not stated

Table 3. (*Continued.*)

Method as described by study	Studies (n)	Medical specialty	Protocol(s)	Type(s) of activity data	Software	Characterization method(s)
Eco-audit method by Ashby[117]	2	Cardiology	Not stated	Process	Ansys Granta EduPack software	IPCC; Not stated
Environmental aspect analysis	1	Nephrology	Not stated	Process	Not stated	Not stated
Multicomponent analysis	1	Surgery	Not stated	Process	Not stated	Not stated
PAS2050 methodology	1	Pathology	PAS 2050	Process	Not stated	Not stated
Top-down model of carbon emissions	1	Gastroenterology; surgery	Not stated	Financial	Not stated	Not stated
Material flow analysis						
Material flow analysis (MFA)	1	Emergency medicine	Not stated	Process	Not stated	ReCiPe 2016
Not specified						
Not specified	13	Cardiology; nephrology; ophthalmology; pediatric medicine; pulmonary medicine; radiotherapy; outpatient consultations in multiple medical specialties	GHG protocol; ISO 14064-1; PAS 2050; SCPG; not stated	Process; hybrid-not stated	R; not stated	IPCC; Not stated

Note: CO_2, carbon dioxide; EEIO-LCA, environmentally extended input-output life cycle assessment; EIO-LCA, environment input-output life cycle assessment; EPA, Environmental Protection Agency; GHG, greenhouse gas; GWP100, Global Warming Potential 100; IPCC, Intergovernmental Panel on Climate Change; ISO, International Organization for Standardization standards 14040 and 14044; LCA, life cycle assessment; NHS, National Health Service; PAS, publicly available specification; SCPG, Sustainable Care Pathway Guidance; TRACI, Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts.

($n = 18$) scoring <50% (Table S22). In terms of transparency, more than half of the included studies did not clearly state the study goal and intended audience ($n = 49$), protocols followed ($n = 28$), or software used ($n = 48$). Although most studies scored high on completeness by covering multiple life cycle stages in their analyses ($n = 62$), it was not always transparently reported what elements of production were included. Many studies took emission factors for raw materials only and presented these as cradle-to-gate emissions. Regarding validity, studies rarely reported on the representativeness of the used data and the potential significance of exclusions or assumptions. Only two studies contextualized results in both sensitivity and uncertainty analyses. Limitations or the potential impact of omissions or assumptions on the study's outcomes were not adequately described by two-thirds of the studies ($n = 51$), creating a risk for bias. In half of the studies, the source(s) of funding and potential conflict(s) of interest were disclosed and unlikely to be a source of bias ($n = 38$). In terms of consistency, nearly two-thirds of the studies clearly defined and justified the functional unit consistently with the study's intended application ($n = 46$), and 82% of the studies drew conclusions consistent with both the goal and scope of the study and the impact assessment results ($n = 62$). Most studies performed contribution analyses ($n = 61$), identified hotspots ($n = 63$), clearly presented their results ($n = 65$), and had their assessments critically appraised as part of the peer-review process of the scientific journals in which the studies were published ($n = 64$).

Discussion

This review shows that the carbon footprint of an increasing number of hospital services and care pathways has been evaluated as currently reflected in the English and Dutch literature published between 2000 and January 2024. However, important medical specialties remain understudied, including internal medicine, otorhinolaryngology, and neurology. Reasons for selecting the studied topics were largely based upon volume or because no previous carbon footprint studies had been done. Methods used for carbon footprint quantification varied, and studies made different methodological choices regarding goal and scope, inventory analysis, and impact assessment. Terminology used to report on the methods was inconsistent. Factors that contributed most to the carbon footprint varied per service, pathway, medical specialty, and setting, but generally travel, facilities, and consumables were key contributors.

Implications and Suggestions for Future Research

Evaluating the climate impact of individual hospital services and care pathways provides granular information on carbon hotspots within health care and thereby enables different stakeholders, including policymakers and clinicians, to act and implement carbon reduction strategies. Although an increasing number of care topics are being studied, the task of conducting full resource-intensive LCAs for all yet unstudied and understudied services and care pathways is tremendous—especially given that results are highly context dependent. Given the urgency to rapidly move toward carbon-neutral health care systems, it is important to critically evaluate which hospital services and care pathways are most relevant for future footprint studies and how to prioritize them, for example, based on the feasibility of implementing changes to lower the carbon footprint. Presently, this prioritization is lacking, and further research should determine what types of care are deemed most relevant in this context. Furthermore, we need to consider the contexts in which the studies are performed. Currently, less than a quarter of all included studies compared similar services across different countries, hospitals, or

Table 4. Contributing factors and relative contributions ranked for each hospital service and care pathway (by row) from highest percentage (1) to lowest percentage (7), by medical specialty and hospital service or care pathway.

Medical specialty	Hospital service or care pathway	Specifics under study	Patient travel (%)	(ranking)	Staff travel (%)	(ranking)	Facilities (%)	(ranking)	Medical equipment (%)	(ranking)	Medical consumables (%)	(ranking)	Pharmaceuticals (%)	(ranking)	Waste disposal (%)	(ranking)	Other (%)	(ranking)	Reference(s)
Anesthesiology	Anesthesia for total knee replacement	General	—	—	—	—	—	—	27	(3)	28	(2)[a]	48	(1)	28	(2)[a]	—	—	McGain et al.[28]
		General + spinal	—	—	—	—	—	—	46	(1)	27	(3)[a]	30	(2)	27	(3)[a]	—	—	
		Spinal	—	—	—	—	—	—	53	(1)	23	(3)[a]	26	(2)	23	(3)[a]	—	—	
	Anesthesia maintenance for 1 h	Desflurane	—	—	—	—	—	—	0.3	(2)[b]	0.3	(2)[b]	100	(1)	0	—	—	—	Sherman et al.[29]
		Isoflurane	—	—	—	—	—	—	0[b]	—	0[b]	—	99	(1)	1	(2)	—	—	
		Propofol	—	—	—	—	—	—	0[b]	—	0[b]	—	81	(1)	19	(2)	—	—	
		Sevoflurane	—	—	—	—	—	—	0[b]	—	0[b]	—	100	(1)	0	—	—	—	
Cardiology and cardiac surgery	Atrial fibrillation catheter ablation procedure		—	—	—	—	—	—	1	(3)	73	(1)	—	—	—	—	26	(2)	Ditac et al.[30]
	Cardiac surgery	—	—	—	—	—	3	(3)	—	—	87	(1)	11	(2)	—	—	—	—	Grinberg et al.[31]
	Cardioversion care pathway	DOAC	16	(3)	—	—	29	(2)	—	—	—	—	—	—	—	—	54	(1)	Orton and Pierce[32]
		Warfarin	15	(3)	—	—	20	(2)	—	—	—	—	—	—	—	—	65	(1)	
	Care pathway for acute decompensated heart failure		—	—	—	—	88	(1)	—	—	—	—	2	(3)	1	(4)	10	(2)	Zhang et al.[22]
	Elective CABG with cardiac bypass		—	—	—	—	—	—	5	(4)	80	(1)	6	(3)	8	(2)	—	—	Hubert et al.[33]
Dermatology	Melanoma follow-up pathway, various melanoma stages	Following 2015 guideline	4	(2)	—	—	—	—	—	—	—	—	—	—	—	—	96	(1)	Grover et al.[34]
		Following 2022 guideline	4–7	(2)	—	—	—	—	—	—	—	—	—	—	—	—	93–96	(1)	
Emergency medicine	Bed day	In ICU	—	—	—	—	—	—	—	—	86	(1)	9	(2)	—	—	5	(3)	Hunfeld et al.[35]
		High-intensity ward	—	—	6	(3)[c]	69	(1)	4	(4)	16	(2)[d]	4	(5)	2	(6)	—	—	Penny et al.[36]
		Low-intensity ward	—	—	10	(3)[c]	40	(1)	5	(4)	40	(2)[d]	5	(4)	1	(5)	—	—	
		In ICU	—	—	6–7	(4)	21–28	(3)	24–27	(2)	27–31	(1)	2	(6)	3	(5)	27–31	(1)	Prasad et al.[37]
		In acute care unit	—	—	7–8	(5)	34–42	(1)	9–10	(4)	16–19	(3)	3	(7)	5	(6)	19–22	(2)	
	Emergency department visit		—	—	6	(3)	70	(1)	2	(5)	6	(4)	15	(2)	0.3	(6)	—	—	Penny et al.[38]
	Treatment of septic shock in ICU	American hospital	—	—	—	—	87	(1)	2	(3)	11	(2)[a]	—	—	11	(2)[a]	—	—	McGain et al.[39e]
		Australian hospital	—	—	—	—	76	(1)	4	(3)	20	(2)[a]	—	—	20	(2)[a]	—	—	
Gastroenterology	Colonoscopy		—	—	—	—	29	(2)	13	(3)	52	(1)	—	—	—	—	6	(4)	Elli et al.[40]
	Esophagogastroduodenoscopy/upper endoscopy	—	—	—	—	—	18	(2)	11	(3)	65	(1)	—	—	—	—	7	(4)	Elli et al.[40]
		Without EndoFaster to reduce rate of biopsy	—	—	—	—	—	—	—	—	21	(2)	—	—	—	—	80	(1)	Zullo et al.[41]
		With EndoFaster to reduce rate of biopsy	—	—	—	—	—	—	3	(3)	26	(2)	—	—	0.1	(4)	72	(1)	
	Gastrointestinal endoscopy		45	(1)[f]	45	(1)[f]	12	(3)	32	(2)	3	(5)	1	(7)	3	(6)	4	(4)	Lacroute et al.[42]
	Medical treatment of gastroesophageal reflux		—	—	—	—	—	—	—	—	—	—	40	(2)	—	—	60	(1)	Gatenby[18]
Gynecology and obstetrics	Cesarean section		—	—	—	—	58	(1)	28	(2)	12	(3)	—	—	4	(4)	—	—	Campion et al.[43]
	Endometrial cancer staging	Laparoscopy	—	—	—	—	62	(1)[g]	62	(1)[g]	—	—	—	—	40	(2)	—	—	Woods et al.[44]
		Laparotomy	—	—	—	—	63	(1)[g]	63	(1)[g]	—	—	—	—	39	(2)	—	—	
		Robot-assisted	—	—	—	—	65	(1)[g]	65	(1)[g]	—	—	—	—	35	(2)	—	—	
	Hysterectomy	Abdominal	—	—	—	—	11	(3)	7	(4)	16	(2)	64	(1)	0		2	(5)	Thiel et al.[21]
		Laparoscopic	—	—	—	—	6	(3)	3	(5)	59	(1)	29	(2)	0		4	(4)	
		Robotic	—	—	—	—	4	(3)	3	(4)	64	(1)	28	(2)	0		1	(5)	
		Vaginal	—	—	—	—	10	(3)	6	(4)	14	(2)	69	(1)	0		2	(5)	
	Vaginal birth		—	—	—	—	58	(1)	31	(2)	5	(4)	—	—	6	(3)	—	—	Campion et al.[43]
Nephrology	Ambulatory peritoneal dialysis	Continuous, at home	3	(5)	—	—	7	(3)[g]	7	(3)[g]	79	(1)	—		8	(2)	4	(4)	Chen et al.[45]
		Continuous, in PD center	0		—	—	9	(2)[g]	9	(2)[g]	89	(1)	—		−2		4	(3)	
		Daytime, at home	2	(5)	—	—	7	(3)[g]	7	(3)[g]	79	(1)	—		8	(2)	4	(4)	
		Daytime, in PD center	0		—	—	9	(2)[g]	9	(2)[g]	89	(1)	—	—	−2		4	(3)	

Table 4. (*Continued.*)

Medical specialty	Hospital service or care pathway	Specifics under study	Patient travel (%)	(ranking)	Staff travel (%)	(ranking)	Facilities (%)	(ranking)	Medical equipment (%)	(ranking)	Medical consumables (%)	(ranking)	Pharmaceuticals (%)	(ranking)	Waste disposal (%)	(ranking)	Other (%)	(ranking)	Reference(s)
	Bed day nephrology ward		2	(5)	10	(2)	8	(3)	—	—	—	—	—	—	58	(4)	71	(1)	Connor et al.[46]
	Continuous renal replacement therapy (per 72 h)	With Prismaflex system	—	—	—		—	—	20	(2)	78	(1)	—	—	—		2	(3)	Aspin[47]
	Hemodialysis (per year)	At home	0–1	(6)	0–2	(5)	2–60	(2)[g]	2–60	(2)[g]	37–60	(1)	—	—	3–16	(3)	2–8	(4)	Connor et al.[98]
		In center	20	(3)	5	(5)	31	(2)[g]	31	(2)[g]	37	(1)	—	—	3	(6)	5	(4)	
		At home	—	—	—	—	100	(1)	—	—	—	—	—	—	—	—	—	—	James[48]
		In hospital	68	(1)	—	—	32	(2)	—	—	—	—	—	—	—	—	—	—	
			6	(4)	3	(6)	26	(2)	23	(3)[h]	23	(3)[h]	36	(1)	3	(5)	3	(7)	Lim et al.[50]
			13	(3)	9	(4)	45	(1)[g]	45	(1)[g]	—	—	—	—	6	(5)	27	(2)	Mtioui et al.[49]
		In center	27	(2)	5	(6)	32	(1)	2	(7)	10	(4)	18	(3)	6	(5)	—	—	Newcastle upon Tyne Hospital[51]
	Hemodialysis (per treatment)	—	31	(2)[f]	31	(2)[f]	43	(1)[g]	43	(1)[g]	9	(4)	—	—	17	(3)			Sehgal et al.[20]
	Hemodialysis and peritoneal dialysis		26	(2)[i]	26	(2)[i]	14	(3)	—	—	—	—	—	—	13	(4)	47	(1)	Connor et al.[46]
	Outpatient appointment		46	(1)	16	(3)	9	(4)	—	—	—	—	—	—	3	(5)	27	(2)	
Ophthalmology	Cataract surgery	Phacoemulsification	9	(3)	0.08	(7)	1	(6)	3	(4)	73	(1)	13	(2)	1	(5)	—	—	Ferrero et al.[52]
		Phacoemulsification	27–72	(1)[f]	27–72	(1)[f]	0–53	(3)	1–9	(4)	6–67	(2)	—	—	0–3	(5)	—	—	Goel et al.[53]
		Phacoemulsification	26	(2)[f]	26	(2)[f]	21	(3)	6	(4)	45	(1)	—	—	2	(5)	—	—	Hong et al.[54]
		Phacoemulsification at public hospital	8	(4)	12	(2)	1	(5)	68	(1)[h]	68	(1)[h]	10	(3)	0.1	(6)	—	—	Latta et al.[55]
		Phacoemulsification in private hospital	7	(2)	4	(4)	1	(5)	85	(1)[h]	85	(1)[h]	4	(3)	0.1	(6)	—	—	
		Phacoemulsification	11	(2)[f]	11	(2)[f]	4	(4)	—	—	78	(1)	7	(3)	0.4	(5)	—	—	Pascual-Prieto et al.[56]
		Phacoemulsification	—	—	—	—	22	(2)	63	(1)	15	(3)	4	(4)	−3		0		Thiel et al.[57]
		Manual small incision	27–71	(1)[f]	27–71	(1)[f]	1–54	(3)	1–9	(4)	3–65	(2)	—	—	0–4	(5)	—	—	Goel et al.[53]
	Cataract pathway	—	7	(4)	3	(5)	36	(1)	33	(2)[h]	33	(2)[h]	18	(3)	2	(6)	1	(7)	Morris et al.[19]
	Intravitreal injection	—	40	(2)[f]	40	(2)[f]	14	(3)	—	—	45	(1)[j]	45	(1)[j]	1	(4)	—	—	Chandra et al.[58e]
		—	77	(1)	—	—	4	(3)	—	—	19	(2)	—	—	0.04	(4)	—	—	Power et al.[59e]
Orthopedics	Total knee replacement care pathway	With Care4Today program	3	(2)	—	—	—	—	—	—	—	—	—	—	—	—	97	(1)	Johnson & Johnson[60]
		Without Care4Today program	3	(2)	—	—	—	—	—	—	—	—	—	—	—	—	97	(1)	
	Total knee replacement surgery	—	17	(3)	10	(5)	0.2	(6)	29	(1)	28	(2)	—	—	15	(4)			Delaie et al.[61]
Otolaryngology	Tonsillectomy	Coblation	—	—	—	—	1	(3)[g]	1	(3)[g]	31	(2)[a]	67	(1)	31	(2)[a]	1	(3)	Meiklejohn et al.[62]
		Cold excision without cautery	—	—	—	—	1	(3)[g]	1	(3)[g]	10	(2)[a]	88	(1)	10	(2)[a]	1	(3)	
		Monopolar electrocautery	—	—	—	—	1	(3)[g]	1	(3)[g]	10	(2)[a]	89	(1)	10	(2)[a]	1	(3)	
Pediatric medicine	Pediatric asthma care pathway (per year)	With Smartinhaler	7	(3)	—	—	—	—	—	—	—	—	72	(1)	—	—	20	(2)	Budgen[63]
		Without Smartinhaler	2	(3)	—	—	—	—	—	—	—	—	53	(1)	—	—	45	(2)	
Pathology	Blood testing	ABG	—	—	—	—	—	—	30	(2)	70	(1)[a]	—	—	70	(1)[a]	—	—	McAlister et al.[64]
		CRP	—	—	—	—	—	—	23	(2)	78	(1)[a]	—	—	78	(1)[a]	—	—	
		Coagulation profile	—	—	—	—	—	—	63	(1)	37	(2)[a]	—	—	37	(2)[a]	—	—	
		Full blood examination	—	—	—	—	—	—	22	(2)	78	(1)[a]	—	—	78	(1)[a]	—	—	
		Urea + electrolytes	—	—	—	—	—	—	58	(1)	41	(2)[a]	—	—	41	(2)[a]	—	—	
		Phlebotomy	—	—	—	—	—	—	23	(2)	76	(1)	—	—	2	(3)	—	—	Spoyalo et al.[65]
		Chemistry	—	—	—	—	—	—	79	(1)	20	(2)	—	—	1	(3)	—	—	
		Coagulation factors	—	—	—	—	—	—	3	(3)	92	(1)	—	—	4	(2)	—	—	
		Hematology	—	—	—	—	—	—	4	(3)	90	(1)	—	—	6	(2)	—	—	
		Total protein	—	—	—	—	—	—	53	(1)	45	(2)	—	—	2	(3)	—	—	
	Urine testing	Urinalysis	—	—	—	—	—	—	35	(2)	65	(1)[a]	—	—	65	(1)[a]	—	—	McAlister et al.[64]

Table 4. (*Continued.*)

Medical specialty	Hospital service or care pathway	Specifics under study	Patient travel (%)	(ranking)	Staff travel (%)	(ranking)	Facilities (%)	(ranking)	Medical equipment (%)	(ranking)	Medical consumables (%)	(ranking)	Pharmaceuticals (%)	(ranking)	Waste disposal (%)	(ranking)	Other (%)	(ranking)	Reference(s)
	COVID-19 testing		—	—	—	—	—	—	1	(3)	28	(2)	—	—	71	(1)	—	—	Ji et al.[66]
Psychiatry	Schizophrenia pathway with antipsychotic injections	One-monthly	53	(1)	0.4	(4)	44	(2)	—	—	—	—	2	(3)	0	—	—	—	Debaveye et al.[67]
		Three-monthly	67	(1)	0.3	(4)	29	(2)	—	—	—	—	3	(3)	0	—	—	—	
		Treatment interruption	31	(2)	0.6	(3)	69	(1)	—	—	—	—	—	—	—	—	—	—	
Pulmonary medicine	Bronchoscopy	—	—	—	—	—	—	—	23	(2)	—	—	—	—	77	(1)	—	—	Patrucco et al.[68]
	Monoclonal antibody therapy of severe eosinophilic asthma	With Benralizumab	4	(3)	—	—	—	—	—	—	—	—	50	(1)	—	—	35	(2)	Budgen[69]
		Without Benralizumab	4	(3)	—	—	—	—	—	—	—	—	62	(1)	—	—	33	(2)	
Radiology	CT scan	—	—	—	—	—	17	(2)	83	(1)	—	—	—	—	—	—	—	—	Martin et al.[70]
		—	—	—	—	—	—	—	88	(1)	9	(2)[a]	—	—	9	(2)[a]	4	(3)	McAlister et al.[71]
	Chest X-ray	Mobile	—	—	—	—	—	—	85	(1)	15	(2)[a]	—	—	15	(2)[a]	—	—	
		—	—	—	—	—	—	—	3	(3)	9	(2)[a]	—	—	9	(2)[a]	88	(1)	
	Interventional radiology procedure		—	—	2	(4)	50	(1)	4	(3)	41	(2)	0.08	(7)	2	(5)	1	(6)	Chua et al.[72]
	MRI scan	—	—	—	—	—	2	(3)	95	(1)	1	(4)	—	—	—	—	3	(2)	Esmaeili et al.[73]
		—	—	—	—	—	13	(2)	88	(1)	—	—	—	—	—	—	—	—	Martin et al.[70]
		—	—	—	—	—	—	—	94	(1)	2	(3)[a]	—	—	2	(3)[a]	5	(2)	McAlister et al.[71]
	Ultrasound	—	—	—	—	—	19	(2)	80	(1)	—	—	—	—	—	—	—	—	Martin et al.[70]
		—	—	—	—	—	—	—	88	(1)	12	(2)[a]	—	—	12	(2)[a]	—	—	McAlister et al.[71]
Radiotherapy	External beam radiation therapy	Average treatment course	43	(1)	5	(5)	14	(3)	24	(2)	3	(6)	0	—	2	(7)	10	(4)	Ali and Piffoux[75]
		During pandemic	99	(1)	—	—	—	—	0	—	1	(2)	—	—	—	—	—	—	Cheung et al.[76]
		Pre–pandemic	99	(1)	—	—	—	—	0.1	(3)	1	(2)	—	—	—	—	—	—	
		Prostate VMAT, pre-COVID	78	(1)	—	—	—	—	23	(2)	0	—	—	—	—	—	—	—	Chuter et al.[77]
		Prostate VMAT, during COVID	82	(1)	—	—	—	—	13	(2)	5	(3)	—	—	—	—	—	—	
		Breast IMRT, pre-COVID	76	(1)	—	—	—	—	25	(2)	0	—	—	—	—	—	—	—	
		Breast IMRT, during COVID	85	(1)	—	—	—	—	11	(2)	4	(3)	—	—	—	—	—	—	
	Proton therapy	—	—	—	—	—	16–17	(2)	83–84	(1)	—	—	—	—	—	—	—	—	Dvorak et al.[78]
Surgery	Abdominoplasty		14	(3)	18	(2)	53	(1)	9	(4)	—	—	—	—	3	(5)	3	(6)	Berner et al.[79]
	Anastomotic leak care pathway		0.5	(3)	—	—	—	—	—	—	0.3	(4)	3	(2)	—	—	96	(1)	Bischofberger et al.[80]
	Anti-reflux surgery		—	—	—	—	—	—	—	—	37	(2)	3	(3)	—	—	60	(1)	Gatenby[18]
	Average surgery	American hospital	—	—	—	—	36	(2)	1	(4)	12	(3)[a]	51	(1)	12	(3)[a]	1	(4)	MacNeill et al.[81]
		Canadian hospital	—	—	—	—	16	(3)	0	—	19	(2)[a]	64	(1)	19	(2)[a]	2	(4)	
		UK hospital	—	—	—	—	83	(1)	—	—	11	(2)[a]	4	(3)	11	(2)[a]	0	—	
		—	—	—	3	(5)	40	(1)	3	(4)	22	(3)	31	(2)	0.2	(6)	—	—	Penny et al.[82]
		In LMIC	—	—	—	—	21	(3)	—	—	—	—	44	(1)	35	(2)	—	—	Umo et al.[83]
	Bilateral breast augmentation		21	(2)	17	(3)	49	(1)	8	(4)	—	—	—	—	3	(5)	2	(6)	Berner et al.[79]
	Carpal tunnel release	Standard	—	—	—	—	—	—	65	(1)	35	(2)	—	—	—	—	—	—	Kodumuri et al.[84]
		Lean and green model	—	—	—	—	—	—	90	(1)	10	(2)	—	—	—	—	—	—	
		Endoscopic	—	—	—	—	100	(1)[g]	100	(1)[g]	—	—	—	—	1	(2)	—	—	Zhang et al.[85]
		Open	—	—	—	—	99	(1)[g]	99	(1)[g]	—	—	—	—	1	(2)	—	—	
	Elective endovascular aortic repair		9	(4)[f]	9	(4)[f]	0	—	25	(2)[b]	25	(2)[b]	—	—	49	(1)	16	(3)	Sénémaud et al.[86]
	Minimally invasive surgery		—	—	—	—	—	—	—	—	—	—	—	—	0.4	(2)	100	(1)	Power et al.[87]
	Rhinoplasty		20	(2)	16	(3)	49	(1)	11	(4)	—	—	—	—	2	(5)	2	(6)	Berner et al.[79]
	Skin cancer surgery	Clinic-based	75	(1)[i]	75	(1)[i]	17	(2)	7	(3)	3	(4)	—	—	–2	—	0	—	Tan and Lim[88]
		Hospital-based	28	(2)[i]	28	(2)[i]	65	(1)	0	—	7	(3)	—	—	0	—	0	—	
Urology	Prostate biopsy pathway	Prebiopsy prostate MRI	22	(2)[f]	22	(2)[f]	65	(1)[g]	65	(1)[g]	11	(3)	—	—	0	—	1	(4)	Leapman et al.[74]
		TRUS prostate biopsy	32	(2)[f]	32	(2)[f]	56	(1)[g]	56	(1)[g]	11	(3)	—	—	1	(4)	0	—	
		Pathology analysis biopsy	—	—	15	(3)	5	(4)[g]	5	(4)[g]	64	(1)	—	—	16	(2)	0	—	
	Radical prostatectomy	Laparoscopic	—	—	—	—	78	(1)[g]	78	(1)[g]	22	(2)[a]	—	—	22	(2)[a]	—	—	Fuschi et al., 2023[89]

Table 4. (*Continued.*)

Medical specialty	Hospital service or care pathway	Specifics under study	Patient travel (%)	(ranking)	Staff travel (%)	(ranking)	Facilities (%)	(ranking)	Medical equipment (%)	(ranking)	Medical consumables (%)	(ranking)	Pharmaceuticals (%)	(ranking)	Waste disposal (%)	(ranking)	Other (%)	(ranking)	Reference(s)
		Robot-assisted	—	—	—	—	80	(1)[g]	80	(1)[g]	20	(2)[a]	—	—	20	(2)[a]	—	—	
Outpatient consultations in multiple medical specialties	Face-to-face consultation	Geriatric Medicine clinic	60	(1)	35	(2)	1	(4)[g]	1	(4)[g]	3	(3)	—	—	—	—	1	(4)	Bartlett and Keir[90]
		Urology department	>99	(1)	—	—	—	—	<1	(2)	—	—	—	—	—	—	—	—	Filfilan et al.[91]
		Rehabilitation clinic	100	(1)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	Holmner et al., 2014[92]
		Speech therapy clinic	100	(1)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
		Psychiatry clinic	100	(1)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	Penaskovic et al.[93]
		Benign foregut clinic	99.5	(1)	—	—	—	—	0.1	(3)	0.5	(2)	—	—	—	—	—	—	Sillcox et al.[94]
			99	(1)	—	—	1	(2)	—	—	<1	(3)	—	—	<1	(3)	—	—	Thiel et al.[95]
	Neuroemergent consultation	Without telehealth	50	(1)	50	(1)	—	—	—	—	—	—	—	—	—	—	—	—	Whetten et al.[96]
		With telehealth	49.98	(1)	49.98	(1)	—	—	0.02	(2)	—	—	—	—	—	—	—	—	
	Preoperative screening	Before telehealth implementation	44	(2)	—	—	—	—	—	—	—	—	—	—	—	—	55	(1)	Wang et al.[97]
		After telehealth implementation	51	(1)	—	—	—	—	—	—	—	—	—	—	—	—	49	(2)	
	Virtual consultation	Geriatric medicine clinic	—	—	56	(1)	7	(3)[g]	7	(3)[g]	0	—	—	—	—	—	37	(2)	Bartlett and Keir[90]
		Urology department	—	—	—	—	—	—	100	(1)	—	—	—	—	—	—	—	—	Filfilan et al.[91]
		Rehabilitation clinic	—	—	—	—	—	—	100	(1)	—	—	—	—	—	—	—	—	Holmner et al.[92]
		Speech therapy clinic	—	—	—	—	—	—	100	(1)	—	—	—	—	—	—	—	—	
		Psychiatry clinic	—	—	—	—	—	—	100	(1)	—	—	—	—	—	—	—	—	Penaskovic et al.[93]
		Benign foregut clinic	—	—	—	—	—	—	100	(1)	—	—	—	—	—	—	—	—	Sillcox et al.[94]
		By phone	—	—	—	—	—	—	100	(1)	—	—	—	—	—	—	—	—	Thiel et al.[95]
		By video	—	—	—	—	—	—	100	(1)	—	—	—	—	—	—	—	—	

Note: Results should not be directly compared between studies and services owing to differing methodologies. Data on relative contributions were obtained from original studies. Results were summarized and reported in the following categories: patient travel; staff travel; facilities (e.g., heating, lighting, water use, construction and maintenance of building); medical equipment (e.g., MRI scanner, hemodialysis machine); medical consumables (e.g., disposable instruments, syringes, dressings, gloves, masks); pharmaceuticals (e.g., anesthetic gases, medical drugs, pharmaceutical packaging); waste disposal (e.g., waste incineration, landfill, recycling, wastewater treatment); other (e.g., nonmedical consumables, food, office supplies; nonmedical equipment, computers). For some services, it was not possible to group a factor to one category, because only aggregate percentages were presented in the original study. In those cases, the total contribution of this was attributed to each applicable category (i.e., double counting), meaning that row totals could be >100%. —, Not applicable; ABG, arterial blood gas; CABG, coronary artery bypass graft; COVID, coronavirus disease; CRP, C-reactive protein; CT, computerized tomography; DOAC, direct oral anticoagulant; ICU, intensive care unit; IMRT, intensity-modulated radiotherapy; LMIC, low- or middle-income country; MRI, magnetic resonance imaging; PD, peritoneal dialysis; TRUS, transrectal ultrasound; VMAT, volumetric modulated arc therapy.

[a]This percentage included both medical consumables and waste disposal.

[b]This percentage included both medical equipment and medical consumables.

[c]This percentage included both staff and visitor travel.

[d]This percentage also included nonmedical consumables (food).

[e]These studies quantified the carbon footprint of pharmaceuticals, but only presented results in separate analyses.

[f]This percentage included both patient and staff travel.

[g]This percentage both included facilities and medical equipment.

[h]This percentage included both medical equipment and medical consumables.

[i]This percentage included patient, staff, and visitor travel.

[j]This percentage also included both consumables and pharmaceuticals (non-injected medications).

[k]This percentage included both patient, staff, and visitor travel and transportation of consumables.

[l]This study also included variations to the care pathway, with different scenarios and prostate biopsy sampling approaches (not presented in this table).

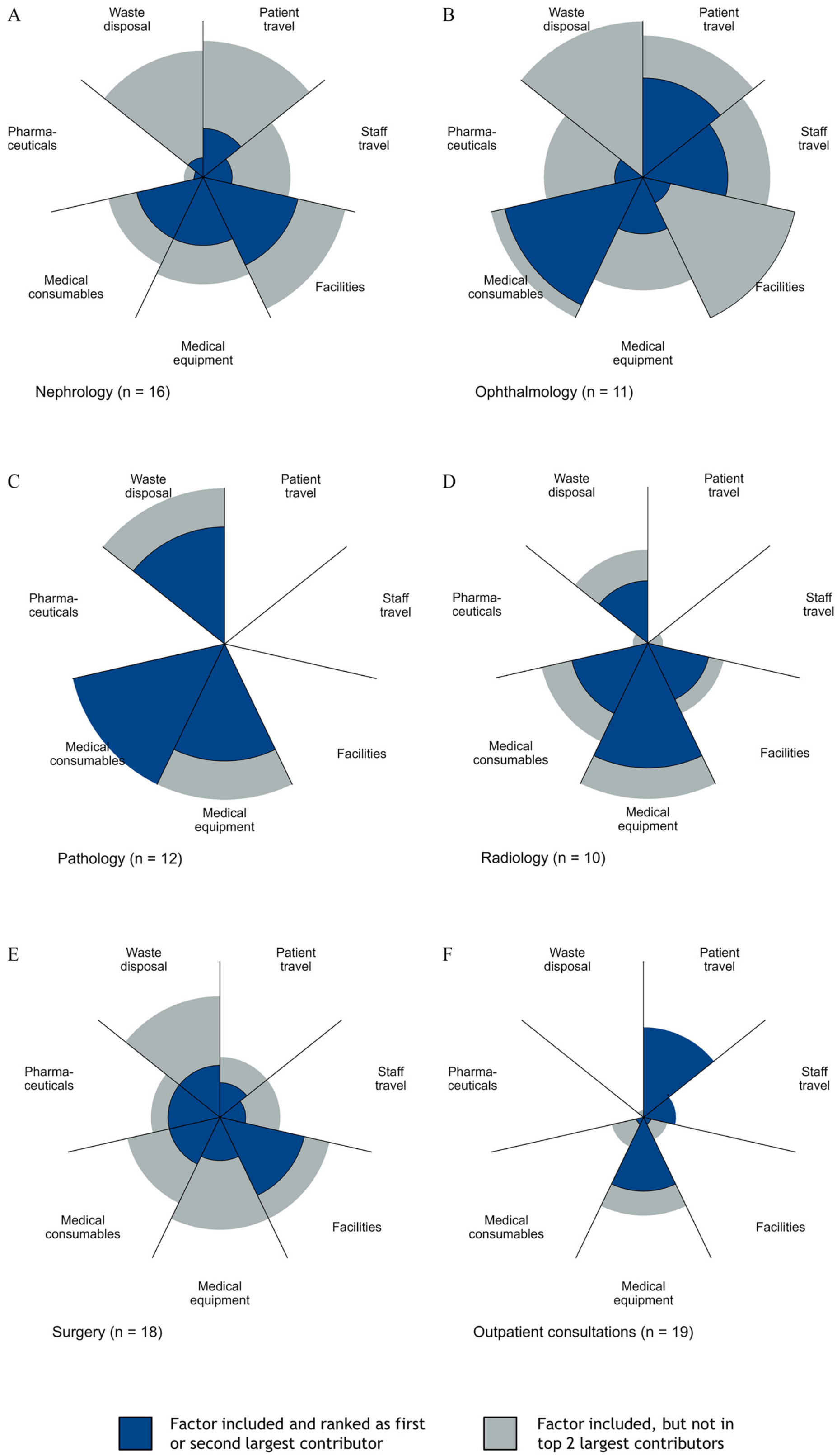

Figure 2. (A–F) Share of hospital services and care pathways that included specific contributors of the carbon footprint, presented for six different medical specialties. Medical specialties were graphically depicted if >9 individual services or pathways were studied among all sources identified. Data used for these graphs can be found in Table 4. The end of each black line indicates 100% of services/pathways represented in the figure. This figure should be interpreted with caution, given that it reflects only services/pathways that have currently been studied within these specialties and is likely not fully representative of these medical specialties as a whole. An empty area does not indicate that contributors had zero impact but only shows that it was not included for evaluation in the services/pathways studied within these specialties (i.e., missing data). Given that the chart represents individual services/pathways and not studies themselves, this figure also risks overvaluing those studies that included multiple services/pathways.

settings. These studies generated important insights about the variation in carbon footprints and hotspots, revealing differences in medical practice around anesthetic use and energy efficiency at different locations. Comparative studies provide a great opportunity for understanding what explains the variation, for identifying best practices to lower climate impact, and may also provide insights for potential transferability of results.

Although individual carbon hotspots differed per hospital service, care pathway, medical specialty, and setting, some common factors contributed to the footprint of many services and pathways, including travel, the facilities' and medical equipment's energy use, and medical consumables. Other research on national-level health systems shows that Scope 3 upstream supply chain emissions from pharmaceuticals, medical equipment, and private travel generally contribute most to the carbon footprint of hospital care, followed by Scopes 1 and 2 building emissions from energy use.[4,9,99] Our study results revealed similar hotspots, although the relative size and importance of their contributions varied from national estimations because of differences in methodologies, study scopes, and data availability. This suggests a dual-track approach is possible: We should target mitigation strategies based on both *a*) common patterns (e.g., greener forms of energy because of their large contribution to the carbon footprint of many hospital services), and *b*) specific hotspots within a certain service, pathway, specialty, or setting.[30,45] For example, stakeholders involved in organizing or providing services that require much patient travel, such as outpatient consultations, may prioritize initiatives that aim to reduce travel-related emissions. However, medical specialties that mostly provide services with a high contribution of facilities' energy use, such as surgery and nephrology, may better focus on reducing or optimizing energy use per service. Importantly, in both examples, the setting should also direct initiatives, because priorities may lie elsewhere in a modernized, well-isolated hospital building or in outpatient departments situated near public transportation.

Evidently, a hotspot can be found only if it was included in the first place. Pharmaceuticals were the least included category among the studies in this review, despite it being one of the major contributors to health care systems' national footprints.[4,10] This may be explained by a lack of life cycle inventory data for pharmaceuticals.[100] Not including potentially relevant factors may leave important contributors unseen or distort the analysis, making the relative share of certain contributors appear larger than it actually is. This in turn may direct carbon reduction efforts toward less impactful areas. On the other hand, including all products and processes may be very time consuming, and standards state that it can be justified to exclude an input if it is environmentally insignificant in the context of the study's goal.[101,102] Although it can be difficult to determine beforehand what inputs will not significantly change results, the studies included in our review showed which products and processes generally had marginal contributions to the carbon footprint of multiple hospital services and care pathways, such as paper and office supplies. Although ultimately also goal and context dependent, future footprint studies of hospital services and care pathways might better focus time and efforts on data collection for factors with generally larger contributions (e.g., facilities energy use, travel) or understudied but likely important contributions (e.g., pharmaceuticals) rather than counting every paper towel individually.

Our results show that carbon footprint studies within health care apply different methods and make different methodological choices (e.g., about functional units and system boundaries). In the majority of studies, the functional unit did not include the entire care pathway. In nonmedical sectors, extensive product rules and sector guidance documents exist to allow for a fair comparison across products. It is important to create consensus regarding used methodologies within health care as well, which has been argued by others before.[13] A first step toward methodological consensus is to develop a common vocabulary in health care LCA research. The currently prevailing use of different terminologies and abbreviations may create confusion. Furthermore, future studies should be more transparent regarding data sharing, especially life cycle inventory data, and their reporting on the influence of modeling choices on the study's outcomes and conclusions. Although it is imperative not to delay the reduction of the carbon footprint associated with hospital services and care pathways, establishing consensus and enhancing methodological quality is crucial. This is particularly important if we intend to use the climate impact of hospital services as a factor in selecting between clinical alternatives during medical decision-making.

Strengths and Limitations

In this study, we focused on hospital care because this is one of the most energy- and carbon-intensive forms of health care delivery.[99] We conducted a complete state-of-the-science review of all carbon footprint studies of hospital services and care pathways, including gray literature. By including care from multiple medical specialties and extending the focus from individual hospital services to entire care pathways, we provided a more comprehensive overview of evidence compared with other studies that focused on a specific selection of hospital care, such as surgical and anesthetic care,[14,15,103,104] gynecology,[105] dermatology,[106] orthopedics,[107–109] and radiology,[110] or studies that did not include gray literature.[111] Furthermore, to our knowledge, this state-of-the-science review is the first study to assess the quality of many of these studies.[13,111]

A limitation of the current field of health care sustainability research is that meta-analyses cannot be undertaken, which is a common issue for LCA reviews.[12] Methods are heterogeneous, and results are inconsistently presented on, for example, different levels of aggregation. Although our review provided an overview of several methodological choices in LCA—including goal and scope definition, inventory analysis, and impact assessment—some important methodological choices remain to be researched. The identified footprints and hotspots each have numerous underlying data sources, assumptions, and allocation procedures. Further research is needed to develop a better understanding of these methodological choices and work toward methodological standardization.

A limitation of our study could be the relatively narrow focus on carbon footprint, which is only one environmental impact category. Basing sustainability decisions purely on one environmental impact risks aggravating other impacts, such as resource use or marine ecotoxicity. Despite the impact of hospital care on the environment being much broader than its carbon footprint, the majority of environmental impact studies within hospital care included only carbon footprint.[112] Given this lack of information on other important environmental impact factors, future studies should also address other environmental impact categories, such as those included in the ReCiPe 2016 method.[113] Furthermore, although our broad study scope extended the focus from individual hospital services to entire hospital care pathways, it must be mentioned that nonhospital care also carries a footprint.[99] Ideally, future research should include the whole patient trajectory, including relevant care provided outside of the hospital. Despite some limitations in the search process, where we could have included other search terms such as "climate change" or "waste," our search was sensitive to the relevant studies and even identified studies that were not included in the comprehensive Healthcare LCA database.[23] Finally, a limitation is that the *pro forma* tool[15] we used for quality assessment may not have been the most suitable for all footprint studies, given that it had a specific focus on attributional LCA methodology, and many studies applied different approaches and followed different protocols. As far as we know, no standardized assessment tool for the reporting of carbon footprint studies in health care exists to date, and further research should work on standardized transparency catalogs synthesizing multiple guidelines.[114]

Conclusion

This state-of-the-science review shows that the carbon footprint of an increasing number of hospital services and care pathways are being studied. These services and pathways play a central role in hospital care delivery. Factors that contributed most to the carbon footprint of hospital services varied per service, medical specialty, and setting, but generally travel, facilities, medical equipment, and consumables were important contributors. The variability in carbon footprints across different settings underlines the importance of conducting local studies in various settings and tailoring sustainability efforts accordingly. Standardization of carbon footprint methodologies, terminology, and reporting is needed to further develop the field of health care sustainability research.

Acknowledgments

L.H.J.A. Kouwenberg: conceptualization, methodology, investigation, data curation, formal analysis, writing–original draft preparation, writing–reviewing and editing, and project administration; E.S. Cohen: investigation, data curation, and writing–reviewing and editing; W.J.K. Hehenkamp: conceptualization, methodology, data curation, writing–reviewing and editing, and funding acquisition; L.E. Snijder and J. Kampman: investigation, data curation, and writing–reviewing and editing; B. Küçükkeles: data curation, writing–reviewing and editing, and funding acquisition; A. Kourula, M.H.C. Meijers, and E.S. Smit: writing–reviewing and editing and funding acquisition; N.H. Sperna Weiland and D.S. Kringos: conceptualization, methodology, data curation, writing–reviewing and editing, supervision, and funding acquisition.

This project was supported by a grant from the Amsterdam Public Health Research Institute and a Seed Grant from the University of Amsterdam. The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

References

1. Romanello M, di Napoli C, Green C, Kennard H, Lampard P, Scamman D, et al. 2023. The 2023 report of the *Lancet* Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. Lancet 402(10419):2346–2394, PMID: 37977174, https://doi.org/10.1016/S0140-6736(23)01859-7.
2. Romanello M, di Napoli C, Drummond P, Green C, Kennard H, Lampard P, et al. 2022. The 2022 report of the *Lancet* Countdown on health and climate change: health at the mercy of fossil fuels. Lancet 400(10363):1619–1654, PMID: 36306815, https://doi.org/10.1016/S0140-6736(22)01540-9.
3. Pichler P-P, Jaccard IS, Weisz U, Weisz H. 2019. International comparison of health care carbon footprints. Environ Res Lett 14(6):064004, https://doi.org/10.1088/1748-9326/ab19e1.
4. Steenmeijer MA, Rodrigues JFD, Zijp MC, Waaijers-van der Loop SL. 2022. The environmental impact of the Dutch health-care sector beyond climate change: an input–output analysis. Lancet Planet Health 6(12):e949–e957, PMID: 36495889, https://doi.org/10.1016/S2542-5196(22)00244-3.
5. Lenzen M, Malik A, Li M, Fry J, Weisz H, Pichler P-P, et al. 2020. The environmental footprint of health care: a global assessment. Lancet Planet Health 4(7):e271–e279, PMID: 32681898, https://doi.org/10.1016/S2542-5196(20)30121-2.
6. Eckelman MJ, Sherman J. 2016. Environmental impacts of the US health care system and effects on public health. PLoS One 11(6):e0157014, PMID: 27280706, https://doi.org/10.1371/journal.pone.0157014.
7. ATACH (Alliance for Transformative Action on Climate and Health). 2024. Commitment tracker. https://www.atachcommunity.com/our-impact/commitment-tracker/ [accessed 18 June 2024].
8. Sherman JD, Thiel C, MacNeill A, Eckelman MJ, Dubrow R, Hopf H, et al. 2020. The green print: advancement of environmental sustainability in healthcare. Resour Conserv Recycl 161:104882, https://doi.org/10.1016/j.resconrec.2020.104882.
9. Tennison I, Roschnik S, Ashby B, Boyd R, Hamilton I, Oreszczyn T, et al. 2021. Health care's response to climate change: a carbon footprint assessment of the NHS in England. Lancet Planet Health 5(2):e84–e92, PMID: 33581070, https://doi.org/10.1016/S2542-5196(20)30271-0.
10. Malik A, Lenzen M, McAlister S, McGain F. 2018. The carbon footprint of Australian health care. Lancet Planet Health 2(1):e27–e35, PMID: 29615206, https://doi.org/10.1016/S2542-5196(17)30180-8.
11. Guinée JB. 2002. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Dordrecht, the Netherlands: Kluwer Academic Publishers.
12. Henriksson PJG, Cucurachi S, Guinée JB, Heijungs R, Troell M, Ziegler F. 2021. A rapid review of meta-analyses and systematic reviews of environmental footprints of food commodities and diets. Global Food Security 28:100508, https://doi.org/10.1016/j.gfs.2021.100508.
13. Drew J, Christie SD, Rainham D, Rizan C. 2022. HealthcareLCA: an open-access living database of health-care environmental impact assessments. Lancet Planet Health 6(12):e1000–e1012, PMID: 36495883, https://doi.org/10.1016/S2542-5196(22)00257-1.
14. Rizan C, Steinbach I, Nicholson R, Lillywhite R, Reed M, Bhutta MF. 2020. The carbon footprint of surgical operations: a systematic review. Ann Surg 272(6):986–995, PMID: 32516230, https://doi.org/10.1097/SLA.0000000000003951.
15. Drew J, Christie SD, Tyedmers P, Smith-Forrester J, Rainham D. 2021. Operating in a climate crisis: a state-of-the-science review of life cycle assessment within surgical and anesthetic care. Environ Health Perspect 129(7):076001, PMID: 34251875, https://doi.org/10.1289/EHP8666.
16. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Int J Surg 88:105906, PMID: 33789826, https://doi.org/10.1016/j.ijsu.2021.105906.
17. Zumsteg JM, Cooper JS, Noon MS. 2012. Systematic review checklist: a standardized technique for assessing and reporting reviews of life cycle assessment data. J Ind Ecol 16(suppl 1):S12–S21, PMID: 26069437, https://doi.org/10.1111/j.1530-9290.2012.00476.x.
18. Gatenby PAC. 2011. Modelling the carbon footprint of reflux control. Int J Surg 9(1):72–74, PMID: 20932944, https://doi.org/10.1016/j.ijsu.2010.09.008.
19. Morris DS, Wright T, Somner JEA, Connor A. 2013. The carbon footprint of cataract surgery. Eye (Lond) 27(4):495–501, PMID: 23429413, https://doi.org/10.1038/eye.2013.9.
20. Sehgal AR, Slutzman JE, Huml AM. 2022. Sources of variation in the carbon footprint of hemodialysis treatment. J Am Soc Nephrol 33(9):1790–1795, PMID: 35654600, https://doi.org/10.1681/ASN.2022010086.
21. Thiel CL, Eckelman M, Guido R, Huddleston M, Landis AE, Sherman J, et al. 2015. Environmental impacts of surgical procedures: life cycle assessment of hysterectomy in the United States. Environ Sci Technol 49(3):1779–1786, PMID: 25517602, https://doi.org/10.1021/es504719g.
22. Zhang X, Albrecht K, Herget-Rosenthal S, Rogowski WH. 2022. Carbon footprinting for hospital care pathways based on routine diagnosis-related group (DRG) accounting data in Germany: an application to acute decompensated heart failure. J Ind Ecol 26(4):1528–1542, https://doi.org/10.1111/jiec.13294.
23. Drew J, Rizan C. 2022. HealthcareLCA Database [Online Database]. https://healthcarelca.com/database [accessed 1 January 2024].
24. Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. 2016. Rayyan—a web and mobile app for systematic reviews. Syst Rev 5(1):210, PMID: 27919275, https://doi.org/10.1186/s13643-016-0384-4.
25. Penny T, Collins M, Whiting A, Aumônier S. 2015. *Care Pathways: Guidance on Appraising Sustainability*. New Abbot, UK: Sustainable Healthcare Coalition. https://shcoalition.org/wp-content/uploads/2019/10/Sustainable-Care-Pathways-Guidance-Main-Document-Oct-2015.pdf [accessed 1 August 2023].
26. Schneider CA, Rasband WS, Eliceiri KW. 2012. NIH image to ImageJ: 25 years of image analysis. Nat Methods 9(7):671–675, PMID: 22930834, https://doi.org/10.1038/nmeth.2089.
27. Weidema B. 1997. *Guidelines for Critical Review of Product LCA*. Brussels, Belgium: SPOLD. https://lca-net.com/files/critical_review.pdf [accessed 1 March 2023].
28. McGain F, Sheridan N, Wickramarachchi K, Yates S, Chan B, McAlister S. 2021. Carbon footprint of general, regional, and combined anesthesia for total knee replacements. Anesthesiology 135(6):976–991, PMID: 34529033, https://doi.org/10.1097/ALN.0000000000003967.
29. Sherman J, Le C, Lamers V, Eckelman M. 2012. Life cycle greenhouse gas emissions of anesthetic drugs. Anesth Analg 114(5):1086–1090, PMID: 22492186, https://doi.org/10.1213/ANE.0b013e31824f6940.
30. Ditac G, Cottinet P-J, Quyen Le M, Grinberg D, Duchateau J, Gardey K, et al. 2023. Carbon footprint of atrial fibrillation catheter ablation. Europace 25(2):331–340, PMID: 36107465, https://doi.org/10.1093/europace/euac160.

31. Grinberg D, Buzzi R, Pozzi M, Schweizer R, Capsal J-F, Thinot B, et al. 2021. Eco-audit of conventional heart surgery procedures. Eur J Cardiothorac Surg 60(6):1325–1331, PMID: 34411226, https://doi.org/10.1093/ejcts/ezab320.
32. Orton A, Pierce JT. 2021. Elective DC cardioversion: a comparison of the carbon footprint of the care pathways for warfarin and DOAC treated patients. Future Healthc J 8(2):e330–e331, PMID: 34286211, https://doi.org/10.7861/fhj.Let.8.2.2.
33. Hubert J, Gonzalez-Ciccarelli LF, Wang AW, Toledo E, Ferrufino R, Smalls K, et al. 2022. Carbon emissions during elective coronary artery bypass surgery, a single center experience. J Clin Anesth 80:110850, PMID: 35525051, https://doi.org/10.1016/j.jclinane.2022.110850.
34. Grover S, Patel N, Tso S. 2024. Relative carbon footprint differences between National Institute for Health and Care Excellence melanoma follow-up pathways 2015 and 2022. Clin Exp Dermatol 49(6):633–635, PMID: 38345169, https://doi.org/10.1093/ced/llae043.
35. Hunfeld N, Diehl JC, Timmermann M, van Exter P, Bouwens J, Browne-Wilkinson S, et al. 2023. Circular material flow in the intensive care unit—environmental effects and identification of hotspots. Intensive Care Med 49(1):65–74, PMID: 36480046, https://doi.org/10.1007/s00134-022-06940-6.
36. Penny T, Collins M, Whiting A, Aumônier S. 2015. *Care Pathways: Guidance on Appraising Sustainability – Inpatient Bed Day Module*. New Abbot, UK: Sustainable Healthcare Coalition. https://shcoalition.org/wp-content/uploads/2019/10/Sustainable-Care-Pathways-Guidance-Inpatient-Bed-Day-Module-Oct-2015.pdf [accessed 19 May 2023].
37. Prasad PA, Joshi D, Lighter J, Agins J, Allen R, Collins M, et al. 2022. Environmental footprint of regular and intensive inpatient care in a large US hospital. Int J Life Cycle Assess 27(1):38–49, https://doi.org/10.1007/s11367-021-01998-8.
38. Penny T, Collins M, Whiting A, Aumônier S. 2015. *Care Pathways: Guidance on Appraising Sustainability—Emergency Department Visit Module*. New Abbot, UK: Sustainable Healthcare Coalition. https://www.shcoalition.org/wp-content/uploads/2019/10/6_3.-Sustainable-Care-Pathways-Guidance-Emergency-Department-Visit-Module-Oct-2015.pdf [accessed 19 May 2023].
39. McGain F, Burnham JP, Lau R, Aye L, Kollef MH, McAlister S. 2018. The carbon footprint of treating patients with septic shock in the intensive care unit. Crit Care Resusc 20(4):304–312, PMID: 30482138, https://doi.org/10.1016/S1441-2772(23)00970-5.
40. Elli L, La Mura S, Rimondi A, Scaramella L, Tontini GE, Monica F, et al. 2024. The carbon cost of inappropriate endoscopy. Gastrointest Endosc 99(2):137–145.e3, PMID: 37673197, https://doi.org/10.1016/j.gie.2023.08.018.
41. Zullo A, Chiovelli F, Esposito E, Hassan C, Casini B. 2023. Can gastric juice analysis with EndoFaster® reduce the environmental impact of upper endoscopy? Healthcare (Basel) 11(24):3186, PMID: 38132076, https://doi.org/10.3390/healthcare11243186.
42. Lacroute J, Marcantoni J, Petitot S, Weber J, Levy P, Dirrenberger B, et al. 2023. The carbon footprint of ambulatory gastrointestinal endoscopy. Endoscopy 55(10):918–926, PMID: 37156511, https://doi.org/10.1055/a-2088-4062.
43. Campion N, Thiel CL, DeBlois J, Woods NC, Landis AE, Bilec MM. 2012. Life cycle assessment perspectives on delivering an infant in the US. Sci Total Environ 425:191–198, PMID: 22482785, https://doi.org/10.1016/j.scitotenv.2012.03.006.
44. Woods DL, McAndrew T, Nevadunsky N, Hou JY, Goldberg G, Yi-Shin Kuo D, et al. 2015. Carbon footprint of robotically-assisted laparoscopy, laparoscopy and laparotomy: a comparison. Int J Med Robot 11(4):406–412, PMID: 25708320, https://doi.org/10.1002/rcs.1640.
45. Chen M, Zhou R, Du C, Meng F, Wang Y, Wu L, et al. 2017. The carbon footprints of home and in-center peritoneal dialysis in China. Int Urol Nephrol 49(2):337–343, PMID: 27848064, https://doi.org/10.1007/s11255-016-1418-5.
46. Connor A, Lillywhite R, Cooke MW. 2010. The carbon footprint of a renal service in the United Kingdom. QJM 103(12):965–975, PMID: 20719900, https://doi.org/10.1093/qjmed/hcq150.
47. Aspin J. 2018. *Continuous Renal Replacement Therapy (CRRT) with Prismaflex: Prodcut Case Study*. Deerfield, IL: Baxter International Inc. https://shcoalition.org/wp-content/uploads/2019/10/CRRT-with-Prismaflex.pdf [accessed 28 September 2023].
48. James R. 2007. Dialysis and the environment: comparing home and unit based haemodialysis. J Ren Care 33(3):119–123, PMID: 19160883, https://doi.org/10.1111/j.1755-6686.2007.tb00056.x.
49. Mtioui N, Zamd M, Ait Taleb A, Bouaalam A, Ramdani B. 2021. Carbon footprint of a hemodialysis unit in Morocco. Ther Apher Dial 25(5):613–620, PMID: 33159433, https://doi.org/10.1111/1744-9987.13607.
50. Lim AEK, Perkins A, Agar JWM. 2013. The carbon footprint of an Australian satellite haemodialysis unit. Aust Health Rev 37(3):369–374, PMID: 23731962, https://doi.org/10.1071/AH13022.
51. Newcastle upon Tyne Hospital. 2022. *In-Centre Haemodialysis at Newcastle upon Tyne Hospital. Care Pathway Case Study.* Newcastle upon Tyne, UK: Newcastle upon Tyne Hospitals NHS Foundation Trust. https://shcoalition.org/wp-content/uploads/2022/06/ICHD_CarePathway_-220610.pdf [accessed 28 September 2023].
52. Ferrero A, Thouvenin R, Hoogewoud F, Marcireau I, Offret O, Louison P, et al. 2022. The carbon footprint of cataract surgery in a French university hospital. J Fr Ophtalmol 45(1):57–64, PMID: 34823888, https://doi.org/10.1016/j.jfo.2021.08.004.
53. Goel H, Wemyss TA, Harris T, Steinbach I, Stancliffe R, Cassels-Brown A, et al. 2021. Improving productivity, costs and environmental impact in International Eye Health Services: using the 'Eyefficiency' cataract surgical services auditing tool to assess the value of cataract surgical services. BMJ Open Ophthalmol 6(1):e000642, PMID: 34104796, https://doi.org/10.1136/bmjophth-2020-000642.
54. Hong Z, Chong EW, Chan HHL. 2023. One step forward to sustainability: the carbon footprint of cataract surgery in Australia. Clin Exp Ophthalmol 51(2):180–182, PMID: 36478628, https://doi.org/10.1111/ceo.14193.
55. Latta M, Shaw C, Gale J. 2021. The carbon footprint of cataract surgery in Wellington. N Z Med J 134(1541):13–21, PMID: 34531593.
56. Pascual-Prieto J, Nieto-Gómez C, Rodríguez-Devesa I. 2023. The carbon footprint of cataract surgery in Spain. Arch Soc Esp Oftalmol (Engl Ed) 98(5):249–253, PMID: 36963485, https://doi.org/10.1016/j.oftale.2023.01.005.
57. Thiel CL, Schehlein E, Ravilla T, Ravindran RD, Robin AL, Saeedi OJ, et al. 2017. Cataract surgery and environmental sustainability: waste and lifecycle assessment of phacoemulsification at a private healthcare facility. J Cataract Refract Surg 43(11):1391–1398, PMID: 29223227, https://doi.org/10.1016/j.jcrs.2017.08.017.
58. Chandra P, Welch S, Oliver GF, Gale J. 2022. The carbon footprint of intravitreal injections. Clin Exp Ophthalmol 50(3):347–349, PMID: 35107201, https://doi.org/10.1111/ceo.14055.
59. Power B, Brady R, Connell P. 2021. Analyzing the carbon footprint of an intravitreal injection. J Ophthalmic Vis Res 16(3):367–376, PMID: 34394865, https://doi.org/10.18502/jovr.v16i3.9433.
60. Johnson & Johnson. 2018. Environmental Impact and Benefits of Care4Today® TKR Care Pathway. Care Pathway Case Study. New Brunswick, NJ: Johnson & Johnson. https://shcoalition.org/wp-content/uploads/2021/02/TKR-Care4Today-Case-Study_final-version.pdf [accessed 28 September 2023].
61. Delaie C, Cerlier A, Argenson J-N, Escudier J-C, Khakha R, Flecher X, et al. 2023. Ecological burden of modern surgery: an analysis of total knee replacement's life cycle. Arthroplast Today 23:101187, PMID: 37745969, https://doi.org/10.1016/j.artd.2023.101187.
62. Meiklejohn DA, Khan ZH, Nuñez KM, Imhof L, Osmani S, Benavidez AC, et al. 2024. Environmental impact of adult tonsillectomy: life cycle assessment and cost comparison of techniques. Laryngoscope 134(2):622–628, PMID: 37421241, https://doi.org/10.1002/lary.30866.
63. Budgen N. 2017. *Digital Adherence Monitoring in Poorly Controlled Paediatric Asthma. Care Pathway Case Study*. Durham, NC: AstraZeneca. https://shcoalition.org/wp-content/uploads/2019/12/Digital-Adherence-Monitoring-in-Poorly-Controlled-Paediatric-Asthma-Final.pdf [accessed 28 September 2023].
64. McAlister S, Grant T, McGain F. 2021. An LCA of hospital pathology testing. Int J Life Cycle Assess 26(9):1753–1763, https://doi.org/10.1007/s11367-021-01959-1.
65. Spoyalo K, Lalande A, Rizan C, Park S, Simons J, Dawe P, et al. 2023. Patient, hospital and environmental costs of unnecessary bloodwork: capturing the triple bottom line of inappropriate care in general surgery patients. BMJ Open Qual 12(3):e002316, PMID: 37402596, https://doi.org/10.1136/bmjoq-2023-002316.
66. Ji L, Wang Y, Xie Y, Xu M, Cai Y, Fu S, et al. 2022. Potential life-cycle environmental impacts of the COVID-19 nucleic acid test. Environ Sci Technol 56(18):13398–13407, PMID: 36053337, https://doi.org/10.1021/acs.est.2c04039.
67. Debaveye S, De Smedt D, Heirman B, Kavanagh S, Dewulf J. 2019. Human health benefit and burden of the schizophrenia health care pathway in Belgium: paliperidone palmitate long-acting injections. BMC Health Serv Res 19(1):393, PMID: 31217000, https://doi.org/10.1186/s12913-019-4247-2.
68. Patrucco F, Gavelli F, Balbo PE. 2023. Environmental impact of bronchoscopy: analysis of waste mass and recyclability of bronchoscopic equipment and consumables. Respiration 102(10):905–911, PMID: 37725933, https://doi.org/10.1159/000533706.
69. Budgen N. 2018. *Care Pathway for Monoclonal Antibody Therapy of Severe Eosinophilic Asthma*. Durham, NC: AstraZeneca. https://shcoalition.org/care-pathway-for-monoclonal-antibody-therapy-2/ [accessed 28 September 2023].
70. Martin M, Mohnke A, Lewis GM, Dunnick NR, Keoleian G, Maturen KE. 2018. Environmental impacts of abdominal imaging: a pilot investigation. J Am Coll Radiol 15(10):1385–1393, PMID: 30158086, https://doi.org/10.1016/j.jacr.2018.07.015.
71. McAlister S, McGain F, Petersen M, Story D, Charlesworth K, Ison G, et al. 2022. The carbon footprint of hospital diagnostic imaging in Australia. Lancet Reg Health West Pac 24:100459, PMID: 35538935, https://doi.org/10.1016/j.lanwpc.2022.100459.
72. Chua ALB, Amin R, Zhang J, Thiel CL, Gross JS. 2021. The environmental impact of interventional radiology: an evaluation of greenhouse gas emissions

from an academic interventional radiology practice. J Vasc Interv Radiol 32(6):907–915.e3, PMID: 33794372, https://doi.org/10.1016/j.jvir.2021.03.531.
73. Esmaeili A, McGuire C, Overcash M, Ali K, Soltani S, Twomey J. 2018. Environmental impact reduction as a new dimension for quality measurement of healthcare services. Int J Health Care Qual Assur 31(8):910–922, PMID: 30415627, https://doi.org/10.1108/IJHCQA-10-2016-0153.
74. Leapman MS, Thiel CL, Gordon IO, Nolte AC, Perecman A, Loeb S, et al. 2023. Environmental impact of prostate magnetic resonance imaging and transrectal ultrasound guided prostate biopsy. Eur Urol 83(5):463–471, PMID: 36635108, https://doi.org/10.1016/j.eururo.2022.12.008.
75. Ali D, Piffoux M. 2024. Methodological guide for assessing the carbon footprint of external beam radiotherapy: a single-center study with quantified mitigation strategies. Clin Transl Radiat Oncol 46:100768, PMID: 38633470, https://doi.org/10.1016/j.ctro.2024.100768.
76. Cheung R, Ito E, Lopez M, Rubinstein E, Keller H, Cheung F, et al. 2023. Evaluating the short-term environmental and clinical effects of a radiation oncology department's response to the COVID-19 pandemic. Int J Radiat Oncol Biol Phys 115(1):39–47, PMID: 36309074, https://doi.org/10.1016/j.ijrobp.2022.04.054.
77. Chuter R, Stanford-Edwards C, Cummings J, Taylor C, Lowe G, Holden E, et al. 2023. Towards estimating the carbon footprint of external beam radiotherapy. Phys Med 112:102652, PMID: 37552912, https://doi.org/10.1016/j.ejmp.2023.102652.
78. Dvorak T, Meeks S, Dvorak L, Rineer J, Kelly P, Ramakrishna N, et al. 2023. Evaluating carbon footprint of proton therapy based on power consumption and possible mitigation strategies. Int J Radiat Oncol Biol Phys 117(1):22–30, PMID: 37244624, https://doi.org/10.1016/j.ijrobp.2023.05.022.
79. Berner JE, Gras MDP, Troisi L, Chapman T, Vidal P. 2017. Measuring the carbon footprint of plastic surgery: a preliminary experience in a Chilean teaching hospital. J Plast Reconstr Aesthet Surg 70(12):1777–1779, PMID: 28655513, https://doi.org/10.1016/j.bjps.2017.06.008.
80. Bischofberger S, Adshead F, Moore K, Kocaman M, Casali G, Tong C, et al. 2023. Assessing the environmental impact of an anastomotic leak care pathway. Surg Open Sci 14:81–86, PMID: 37528919, https://doi.org/10.1016/j.sopen.2023.07.001.
81. MacNeill AJ, Lillywhite R, Brown CJ. 2017. The impact of surgery on global climate: a carbon footprinting study of operating theatres in three health systems. Lancet Planet Health 1(9):e381–e388, PMID: 29851650, https://doi.org/10.1016/S2542-5196(17)30162-6.
82. Penny T, Collins M, Whiting A, Aumônier S. 2015. *Care Pathways: Guidance on Appraising Sustainability – Surgical Procedure Module*. New Abbot, UK: Sustainable Healthcare Coalition. https://shcoalition.org/wp-content/uploads/2019/10/Sustainable-Care-Pathways-Guidance-Surgical-Procedure-Module-Oct-2015.pdf [accessed 19 May 2023].
83. Umo I, Pangiau M, Kukiti J, Ona A, Tepoka S, James K, et al. 2023. Estimating the carbon emissions from a resource-limited surgical suite in Papua New Guinea: the climate change potential. Dialogues Health 2:100108, PMID: 38515480, https://doi.org/10.1016/j.dialog.2023.100108.
84. Kodumuri P, Jesudason EP, Lees V. 2023. Reducing the carbon footprint in carpal tunnel surgery inside the operating room with a lean and green model: a comparative study. J Hand Surg Eur Vol 48(10):1022–1029, PMID: 37226468, https://doi.org/10.1177/17531934231176952.
85. Zhang D, Dyer GSM, Blazar P, Earp BE. 2023. The environmental impact of open versus endoscopic carpal tunnel release. J Hand Surg Am 48(1):46–52, PMID: 35123818, https://doi.org/10.1016/j.jhsa.2021.12.003.
86. Sénémaud J, Gouel-Chéron A, Tesmoingt C, Barret E, Montravers P, Castier Y. 2023. Carbon footprint of elective endovascular abdominal aortic aneurysm repair. Eur J Vasc Endovasc Surg 66(6):877–878, PMID: 37647983, https://doi.org/10.1016/j.ejvs.2023.08.062.
87. Power NE, Silberstein JL, Ghoneim TP, Guillonneau B, Touijer KA. 2012. Environmental impact of minimally invasive surgery in the United States: an estimate of the carbon dioxide footprint. J Endourol 26(12):1639–1644, PMID: 22845049, https://doi.org/10.1089/end.2012.0298.
88. Tan E, Lim D. 2021. Carbon footprint of dermatologic surgery. Australas J Dermatol 62(2):e170–e177, PMID: 33277919, https://doi.org/10.1111/ajd.13522.
89. Fuschi A, Pastore AL, Al Salhi Y, Martoccia A, De Nunzio C, Tema G, et al. 2024. The impact of radical prostatectomy on global climate: a prospective multicentre study comparing laparoscopic versus robotic surgery. Prostate Cancer Prostatic Dis 27(2):272–278, PMID: 37085603, https://doi.org/10.1038/s41391-023-00672-4.
90. Bartlett S, Keir S. 2022. Calculating the carbon footprint of a geriatric medicine clinic before and after COVID-19. Age Ageing 51(2):afab275, PMID: 35134839, https://doi.org/10.1093/ageing/afab275.
91. Filfilan A, Anract J, Chartier-Kastler E, Parra J, Vaessen C, de La Taille A, et al. 2021. Positive environmental impact of remote teleconsultation in urology during the COVID-19 pandemic in a highly populated area. Prog Urol 31(16):1133–1138, PMID: 34454847, https://doi.org/10.1016/j.purol.2021.08.036.
92. Holmner A, Ebi KL, Lazuardi L, Nilsson M. 2014. Carbon footprint of telemedicine solutions—unexplored opportunity for reducing carbon emissions in the health sector. PLoS One 9(9):e105040, PMID: 25188322, https://doi.org/10.1371/journal.pone.0105040.
93. Penaskovic KM, Zeng X, Burgin S, Sowa NA. 2022. Telehealth: reducing patients' greenhouse gas emissions at one academic psychiatry department. Acad Psychiatry 46(5):569–573, PMID: 35997996, https://doi.org/10.1007/s40596-022-01698-x.
94. Sillcox R, Gitonga B, Meiklejohn DA, Wright AS, Oelschlager BK, Bryant MK, et al. 2023. The environmental impact of surgical telemedicine: life cycle assessment of virtual vs. in-person preoperative evaluations for benign foregut disease. Surg Endosc 37(7):5696–5702, PMID: 37237107, https://doi.org/10.1007/s00464-023-10131-9.
95. Thiel CL, Mehta N, Sejo CS, Qureshi L, Moyer M, Valentino V, et al. 2023. Telemedicine and the environment: life cycle environmental emissions from in-person and virtual clinic visits. NPJ Digit Med 6(1):87–88, PMID: 37160996, https://doi.org/10.1038/s41746-023-00818-7.
96. Whetten J, Montoya J, Yonas H. 2019. ACCESS to better health and clear skies: telemedicine and greenhouse gas reduction. Telemed J E Health 25(10):960–965, PMID: 30359184, https://doi.org/10.1089/tmj.2018.0172.
97. Wang EY, Zafar JE, Lawrence CM, Gavin LF, Mishra S, Boateng A, et al. 2021. Environmental emissions reduction of a preoperative evaluation center utilizing telehealth screening and standardized preoperative testing guidelines. Resour Conserv Recycl 171:105652, https://doi.org/10.1016/j.resconrec.2021.105652.
98. Connor A, Lillywhite R, Cooke MW. 2011. The carbon footprints of home and in-center maintenance hemodialysis in the United Kingdom. Hemodial Int 15(1):39–51, PMID: 21231998, https://doi.org/10.1111/j.1542-4758.2010.00523.x.
99. Weisz U, Pichler P-P, Jaccard IS, Haas W, Matej S, Bachner F, et al. 2020. Carbon emission trends and sustainability options in Austrian health care. Resour Conserv Recycl 160:104862, https://doi.org/10.1016/j.resconrec.2020.104862.
100. Parvatker AG, Tunceroglu H, Sherman JD, Coish P, Anastas P, Zimmerman JB, et al. 2019. Cradle-to-gate greenhouse gas emissions for twenty anesthetic active pharmaceutical ingredients based on process scale-up and process design calculations. ACS Sustain Chem Eng 7(7):6580–6591, https://doi.org/10.1021/acssuschemeng.8b05473.
101. Bhatia P, Cummis C, Draucker L, Rich D, Lahd H, Brown A. 2011. Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard. Washington, DC: World Resources Institute. https://www.wri.org/research/greenhouse-gas-protocol-product-life-cycle-accounting-and-reporting-standard [accessed 4 July 2023].
102. ISO (International Organization for Standardization). 2006. *ISO 14044. Environmental management—life cycle assessment—Requirements and guidelines*. Geneva, Switzerland: ISO. https://cdn.standards.iteh.ai/samples/38498/17324bfe9ec44e27a2f84e1a8ac3ca26/ISO-14044-2006.pdf [accessed 4 July 2023].
103. Shoham MA, Baker NM, Peterson ME, Fox P. 2022. The environmental impact of surgery: a systematic review. Surgery 172(3):897–905, PMID: 35788282, https://doi.org/10.1016/j.surg.2022.04.010.
104. Papadopoulou A, Kumar NS, Vanhoestenberghe A, Francis NK. 2022. Environmental sustainability in robotic and laparoscopic surgery: systematic review. Br J Surg 109(10):921–932, PMID: 35726503, https://doi.org/10.1093/bjs/znac191.
105. Cohen ES, Kouwenberg LHJA, Moody KS, Sperna Weiland NH, Kringos DS, Timmermans A, et al. 2024. Environmental sustainability in obstetrics and gynaecology: a systematic review. BJOG 131(5):555–567, PMID: 37604701, https://doi.org/10.1111/1471-0528.17637.
106. Allwright E, Abbott RA. 2021. Environmentally sustainable dermatology. Clin Exp Dermatol 46(5):807–813, PMID: 33215752, https://doi.org/10.1111/ced.14516.
107. Engler ID, Curley AJ, Fu FH, Bilec MM. 2022. Environmental sustainability in orthopaedic surgery. J Am Acad Orthop Surg 30(11):504–511, PMID: 35412500, https://doi.org/10.5435/JAAOS-D-21-01254.
108. Saleh JR, Mitchell A, Kha ST, Outterson R, Choi A, Allen L, et al. 2023. The environmental impact of orthopaedic surgery. J Bone Joint Surg Am 105(1):74–82, PMID: 36574633, https://doi.org/10.2106/JBJS.22.00548.
109. Smith JT, Boakye LAT, Ferrone ML, Furie GL. 2022. Environmental sustainability in the orthopaedic operating room. J Am Acad Orthop Surg 30(21):1039–1045, PMID: 36007200, https://doi.org/10.5435/JAAOS-D-22-00247.
110. Woolen SA, Kim CJ, Hernandez AM, Becker A, Martin AJ, Kuoy E, et al. 2023. Radiology environmental impact: what is known and how can we improve? Acad Radiol 30(4):625–630, PMID: 36400705, https://doi.org/10.1016/j.acra.2022.10.021.
111. Alshqaqeeq F, Amin Esmaeili M, Overcash M, Twomey J. 2020. Quantifying hospital services by carbon footprint: a systematic literature review of patient care alternatives. Resour Conserv Recycl 154:104560, https://doi.org/10.1016/j.resconrec.2019.104560.

112. Seifert C, Koep L, Wolf P, Guenther E. 2021. Life cycle assessment as decision support tool for environmental management in hospitals: a literature review. Health Care Manage Rev 46(1):12–24, PMID: 31116121, https://doi.org/10.1097/HMR.0000000000000248.
113. Huijbregts MA, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, et al. 2016. *ReCiPe 2016: A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. Report I: Characterization*. RIVM Report 2016–0104. Bilthoven, the Netherlands: National Institute for Public Health and the Environment. https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf [accessed 9 November 2022].
114. Lange O, Plath J, Dziggel TF, Karpa DF, Keil M, Becker T, et al. 2022. A transparency checklist for carbon footprint calculations applied within a systematic review of virtual care interventions. Int J Environ Res Public Health 19(12):7474, PMID: 35742724, https://doi.org/10.3390/ijerph19127474.
115. Sulbaek Andersen MP, Nielsen OJ, Karpichev B, Wallington TJ, Sander SP. 2012. Atmospheric chemistry of isoflurane, desflurane, and sevoflurane: Kinetics and mechanisms of reactions with chlorine atoms and OH radicals and global warming potentials. J Phys Chem A 116(24):5806–5820, PMID: 22146013, https://doi.org/10.1021/jp2077598.
116. Sulbaek Andersen MP, Nielsen OJ, Wallington TJ, Karpichev B, Sander SP. 2012. Assessing the impact on global climate from general anesthetic gases. Anesth Analg 114(5):1081–1085, https://doi.org/10.1213/ANE.0b013e31824d6150.
117. Ashby M. 2013. *Materials and the Environment, Eco-Informed Material Choice*, 2nd ed. Oxford: Butterworth Heinemann.