Review Article

Environmental Sustainability in Orthopaedic Surgery

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ABSTRACT

Climate change has been increasingly recognized in the healthcare sector over recent years, with global implications in infrastructure, economics, and public health. As a result, a growing field of study examines the role of healthcare in contributing to environmental sustainability. These analyses commonly focus on the environmental impact of the operating room, due to extensive energy and resource utilization in surgery. While much of this literature has arisen from other surgical specialties, several environmental sustainability studies have begun appearing in the field of orthopaedic surgery, consisting mostly of waste audits and, less frequently, more comprehensive environmental life cycle assessments. The present study aims to review this limited evidence. The results suggest that methods to reduce the environmental impact of the operating room include proper selection of anesthetic techniques that have a smaller carbon footprint, minimization of single use instruments, use of minimalist custom-design surgical packs, proper separation of waste, and continuation or implementation of recycling protocols. Future directions of research include higher-level studies, such as comprehensive life cycle assessments, to identify more opportunities to decrease the environmental impact of orthopaedic surgery.

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Climate change and environmental sustainability are topics of increasing importance and visibility in the public eye. Their presence in health care are growing but still nascent.[1] Health care is one of the largest sectors in the United States, and surgery is a particularly resource-intensive field within medicine.[2] In orthopaedic surgery, limited high-level evidence exists to guide best practices in reducing the field's environmental impact and associated carbon emissions. This review first provides context for the current state of climate change and environmental sustainability. Next, evidence is reviewed regarding environmental sustainability within the overall healthcare system, the operating room in particular, and finally orthopaedic surgery. A final discussion centers on the possible future directions for research into how the field of orthopaedic surgery may decrease its environmental impact and on how orthopaedic surgeons may navigate potential sustainability-related policy changes.

The State of the Environment

Climate change is increasingly recognized as a disruptive force. While recognition of a changing climate was present in the 20th century, research since the turn of the century has led to a growing sense of concern over the issue in the scientific community. The period from the early 1900s to the present is reported to be the warmest in the history of modern civilization, with evidence suggesting that human activities, particularly greenhouse gas emissions such as carbon dioxide, are the primary driver of this warming.[3] These conclusions are derived from US government research and from most of the scientific community.[4] The August 2021 United Nations Intergovernmental Panel on Climate Change report concluded that climate change is widespread, rapid, and intensifying, with the Secretary-General calling it a code red for humanity.[5] The report found that the past few decades have seen the fastest rise in global temperatures and sea level in at least the past 2,000 years. July 2021 was noted to be the hottest month in recorded history.[6] Because of warming, sea level rise, and increased extreme weather events, climate change is projected to adversely affect infrastructure, energy use and needs, trade, ecosystems, public health, and economies that rely on natural resources.[7]

The United States plays a significant role in global greenhouse gas emissions. In 2018, the United States was responsible for 6.02 million kilotons of carbon dioxide equivalents, which was 13.1% of the world's emissions, despite having 4.3% of the world population.[8,9] Solid waste production in the United States has risen from 243.5 million tons in 2000 to 251.1 in 2010 to 292.4 in 2018.[10] Owing to the magnitude of the US contribution to greenhouse gas emissions, a reduction in US emissions would have a marked effect on the global contribution to climate change.[11]

The Role of Healthcare in Climate Change

While much discussion of contributions to climate change focuses on the fossil fuel industry and the transportation sector, the healthcare sector is also an appreciable contributor given its size and resource use. The US healthcare sector is responsible for 10% of the nation's greenhouse gas emissions,[12] and emissions continue to increase.[13] By comparison, healthcare contributes 4% of the national greenhouse gas emissions in the United Kingdom and 4.6% in Canada.[12,14] The reason for these discrepancies is not established, but the fact that the United States spends far more on health care than other nations suggests a contribution from increased resource use.[15] The US healthcare sector contributes to 25% of global healthcare-related emissions.[13]

Of particular interest to physicians, public health is affected by climate change. Global temperature changes related to climate change cause more than five million deaths annually.[16] Warming contributes to extreme temperature-related deaths, impaired food and water supplies, increased risk of infectious disease, and indirect effects of economic disruption.[17] In 1 year, US healthcare emissions and environmental pollutants are responsible for 470,000 to 614,000 disability-adjusted life-years lost.[15,18] The low-end estimate encompasses more direct effects, such as those of particulates and smog on respiratory diseases.[15] The high-end estimate also includes indirect effects of greenhouse gases on climate-change related conditions, such as malnutrition and malaria.[18]

Environmental Sustainability in the Operating Room

Surgeons can have a substantive role in mitigating climate change. Operating rooms have a large environmental impact through energy use, single-use devices and supplies, medication production, and sterilization of equipment. Energy use is higher in operating rooms than that in many other rooms and buildings because of the strictly regulated air changes, temperature, humidity, and sterility.[2] In the United States, operating rooms generate 20% to 33% of total hospital waste.[15,19] Waste arises largely from disposable products such as gowns, gloves, surgical instruments and equipment, implants, and packaging. Biohazard waste, frequently generated in the operating room, requires particularly energy-intensive processing.[20]

Literature evaluating the effect of a surgical procedure often uses a basic waste audit or a more complex life cycle assessment (LCA).[21] A waste audit collects and weighs the disposed materials after a procedure, at times also recording how much is sent to a landfill or incinerator or recycling plant. LCA quantifies the overall environmental impacts of a product or process from raw material extraction, production, transportation, use, and disposal or reuse. LCAs can provide insight across a suite of environmental issues from water quality (eg, eutrophication) to resource use (eg, energy). LCAs are used to calculate total carbon emissions using carbon dioxide-equivalents (CO_2-eq). While used across a host of industries, in this case, a detailed map of the materials and processes of the surgery is created within predefined boundaries known as the scope, such as the beginning and end of the procedure (Figure 1). CO_2-eq used in each step are then calculated and summed to produce the carbon footprint of the procedure. This process allows for evaluation of the most carbon-intensive steps and thus those that may benefit the most from carbon-reduction efforts.

Because of limited literature on the environmental impact of orthopaedic surgery, examining literature from other surgical subspecialties is illustrative. Early attempts to comprehensively evaluate the environmental impact of surgical procedures occurred in the fields of ophthalmology and obstetrics/gynecology. In a study from the United Kingdom, Morris et al[22] reported the carbon footprint of 1 cataract surgery to be 181.8 kg CO_2-eq, noting that medical equipment contributed to 32.6% of emissions. The carbon footprint of this several minute-long procedure, was noted to be comparable with that of driving a car about 315 miles. A subsequent study by Thiel et al[23] used an LCA to determine the emissions from cataract surgery at a high-volume surgical facility in India. The authors found that efficiencies gained from a high-volume center, along with the use of reusable instruments, significantly reduced greenhouse gas emissions to 5% of the previous UK study from Morris et al.

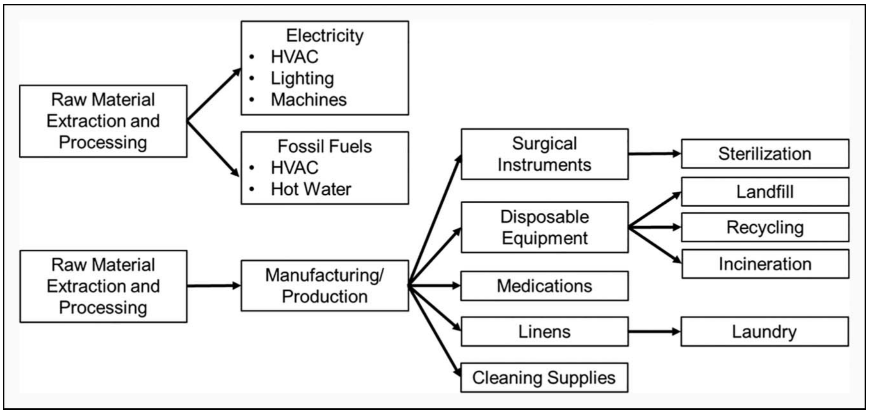
Thiel et al[24] used an LCA to evaluate four hysterectomy techniques, with a focus on laparoscopic and robotic techniques. The authors reported that single-use surgical devices, disposable materials, anesthetic gases, and building energy were significant contributors to emissions. A later study proposed interventions to mitigate the environmental impact of laparoscopic hysterectomies, using an LCA to estimate their efficacy.[25] Although recycling was noted to have minimal effect on emissions, several surgeon-controlled factors demonstrated promising results in decreasing the environmental footprint, including reusing instruments, limiting the use of operating room materials, and reprocessing single-use instruments.

While attention is often directed toward surgical materials and instruments, anesthetic gases have a large and variable effect on the carbon footprint of surgery because anesthetic gases are potent greenhouse gases. Desflurane has a greenhouse gas effect 15 times that of isoflurane and 20 times that of sevoflurane, largely because of the global warming potential of escaped gas.[26] Of note, desflurane has a faster induction time but is more expensive than isoflurane and sevoflurane. Use of desflurane led to a 10-fold difference in anesthesia-related emissions among hospitals in the United States, United Kingdom, and Canada and caused anesthetics to comprise most of the carbon footprint of the operating room at the two hospitals that used desflurane.[27] These findings illustrate the importance of analyzing all aspects of a surgical procedure, rather than just the surgical materials, when investigating the environmental impact.

Environmental Sustainability in Orthopaedic Surgery

Limited literature is available pertaining to environmental sustainability in the field of orthopaedic surgery, with most studies consisting of waste audits rather than

Figure 1



Flow diagram showing example process for an environmental life cycle assessment to evaluate the carbon footprint of a surgery. HVAC = heating, ventilation, and air conditioning.

more comprehensive LCAs. In one of the earliest studies, Stall et al[28] performed a waste audit of 5 primary total knee arthroplasties (TKAs), dividing the waste into six categories: regular solid waste, recyclable plastics, biohazard waste, laundered linens, sharps, and blue sterile wrap. Excluding laundered linens, an average of 13.3 kg of waste was produced per procedure, with the largest contribution arising from regular solid waste (64.5%). Using similar methodology, de Sa et al[20] conducted a waste audit of five hip arthroscopy procedures for femoroacetabular impingement, reporting 9.4 kg of waste per procedure. This study noted the greatest contribution came from biohazard waste (45.7%), which necessitates expensive and energy-demanding treatment processes. Given that improper separation of waste can disproportionately increase biohazard waste and cost of disposal,[29] the authors suggested that adherence to proper waste disposal protocols may be an opportunity for improvement at their institution.

Kooner et al[30] performed a waste audit of 55 procedures in 6 different orthopaedic specialties, including arthroplasty (14), upper extremity (12), sports medicine (10), trauma (10), pediatrics (5), and foot and ankle (4). The waste was categorized during two perioperative periods: preoperative (recyclable and nonrecyclable) and intraoperative (recyclable, nonrecyclable, linen, and biologic). Although arthroplasty produced the highest total waste (8,779.3 g) per case across specialties, the authors noted that arthroplasty also had the highest average mass of recyclable waste (2,955.7 g), concluding that operating room recycling programs can substantially reduce the environmental impact of these procedures.

In another investigation of the environmental impact associated with arthroplasty, Lyons et al[31] used an LCA to evaluate the production of a TKA femoral implant with additive manufacturing (AM) versus conventional manufacturing (CM). In contrast to the AM process, which adds materials to a final product in successive layers, CM removes excess material from the implant, which can generate significant material waste in designs with complex geometries. This LCA found that 84.6% and 35% of material waste were produced during CM and AM of a TKA femoral implant, respectively.[31] Given that this waste consists of energy-intensive Ti-6Al-4V, the authors concluded that AM was a more environmentally sustainable method of TKA implant production.

Leiden et al[32] investigated the environmental impact of orthopaedic implants in an LCA comparing disposable and reusable surgical instrument sets for a single-level lumbar fusion. Although the disposable set had a greater environmental impact during the production phase of the materials, these adverse effects were offset by the high energy demand required for steam sterilization of the reusable instruments, which generates up to 90% of the associated greenhouse gas emissions. The authors suggested that reducing the number of reusable instruments undergoing steam sterilization would be more environmentally friendly. However, these results should be interpreted with caution because this study received industry financial support.

Wide-awake hand surgery (WAHS) has been recently popularized for hand procedures, providing a safe and cost-effective alternative to traditional sedative anesthesia.[33] Van Demark et al[34] analyzed the environmental impact of WAHS in combination with a minimal customized pack design, which used less surgical supplies for smaller procedures. When evaluating 1,099 hand procedures, the authors reported a decrease in 2.8 tons of waste and $13,250.42 of supplies in comparison with that in conventional surgery. Thiel et al[35] also investigated WAHS with minimal customized pack design in a waste audit of 178 hand surgeries, noting 0.3 kg (13%) less waste and $125 (55%) of materials cost-savings per case. The authors of both studies suggested that decreasing the environmental impact of surgery can occur in conjunction with cost-efficiency.

Table 1 summarizes the existing literature on environmental sustainability in orthopaedic surgery.

Future Directions

In the past decade, emerging literature has brought increased attention to the environmental impact of orthopaedic procedures, encouraging healthcare professionals to analyze their carbon footprint.[36-38] Few studies have investigated the environmental effects of orthopaedic surgery, limiting the conclusions that can be drawn now. However, the current evidence suggests that sustainability can be improved with the proper selection of anesthetic techniques that have a smaller carbon footprint, minimization of single use instruments, use of minimalist custom-design surgical packs, proper separation of waste, and continuation or implementation of recycling protocols. These strategies often have the added benefit of decreasing cost to the facility and system, which is an important incentive given the drive to lower cost in the healthcare system.[1] Future directions of research include higher level studies, such as comprehensive LCAs, to identify more opportunities to decrease the environmental impact of orthopaedic surgery.

Table 1. Selected Environmental Sustainability Studies in the Field of Orthopaedic Surgery

Author	Year	Journal	Country	Type of Study	Surgery	Cases (n)	Study Design	Key Findings
Lyons et al[31]	2021	*The International Journal of Advanced Manufacturing Technology*	Ireland	LCA	TKA	N/A	Compared the environmental impact of AM versus CM for the production of the TKA femoral implant.	AM was more environmentally sustainable than CM, mainly due to decreased material waste generated during the production process.
Kooner et al[30]	2020	*Canadian Journal of Surgery*	Canada	Waste audit	Assorted cases in 6 orthopaedic specialties	55	Categorized the weight of waste generated in two perioperative periods: preoperative (recyclable and nonrecyclable) and intraoperative (recyclable, nonrecyclable, linen, and biologic).	Arthroplasty produced the most average waste (8,779.3 g) compared with other specialties. Across all specialties, an average of 74% and 8% of waste was recyclable in the preoperative and intraoperative periods, respectively.
Leiden et al[32]	2020	*Resources, Conservation & Recycling*	Germany	LCA	Instrumented lumbar fusion	N/A	Compared the environmental impact of reusable and disposable lumbar fusion instrumentation and implant sets.	The reusable set had a higher overall environmental impact compared with the disposable set, which was largely due to the high energy demand of steam sterilization.
Thiel et al[35]	2019	*Hand (NY)*	USA	Waste audit; cost analysis	Hand surgery	178	Assessed the cost and waste savings for using WAHS with a minimal custom pack design of surgical materials compared with	Per each case, WAHS with minimal custom pack design generated 0.3 kg (13%) less waste and saved $125

(*continued*)

Table 1. *(continued)*

Author	Year	Journal	Country	Type of Study	Surgery	Cases (n)	Study Design	Key Findings
							traditional sedation anesthesia with standard surgical packs.	(55%) in supplies.
Van Demark et al[34]	2018	*Journal of Hand Surgery*	USA	Waste audit; cost analysis	Hand surgery	1,099	Assessed the cost and waste savings for WAHS with a minimal custom pack design of surgical materials compared with traditional sedation anesthesia with standard surgical packs.	Analysis of 1,099 cases showed that WAHS with minimal custom pack design generated 2.8 tons less waste and saved $13,250.42 in supplies.
de Sa et al[20]	2016	*Journal of Hip Preservation Surgery*	Canada	Waste audit	Hip arthroscopy	5	Sorted the weight of waste generated into six categories: normal/landfill waste, recyclable cardboards and plastics, biohazard waste, sharp items, linens, and sterile wrapping.	The average waste (excluding laundered linens) produced per procedure was 9.4 kg. The received the largest contribution was from biohazard waste (45.7%).
Stall et al[28]	2013	*Canadian Journal of Surgery*	Canada	Waste audit	TKA	5	Sorted the weight of waste generated into six categories: regular solid waste, recyclable plastics, biohazard waste, laundered linens, sharps, and blue sterile wrap.	The average waste (excluding laundered linens) produced per procedure was 13.3 kg. The largest contribution was from regular solid waste (64.5%).

AM = additive manufacturing, CM = conventional manufacturing, LCA = life cycle assessment, N/A = not applicable, TKA = total knee arthroplasty, WAHS = wide-awake hand surgery

On a larger scale, national organizations are moving to decrease healthcare's carbon footprint. The National Academy of Medicine has organized the Action Collaborative on Decarbonizing the US Health Sector, bringing together leaders from across public and private domains.[13] The National Health Service in the United

Kingdom aims to be carbon neutral by 2040.[14] Guided by recommendations from environmental experts, policy changes are no doubt a large component of decreasing the carbon footprint of the healthcare sector, and they will likely affect orthopaedic surgeons directly or indirectly.[39] Therefore, orthopaedic surgeons may benefit from anticipating and embracing these changes, helping integrate them into the operating room in a way that most benefits patients, surgeons, and the environment.

Summary

With the consequences of climate change increasingly demonstrated in the scientific literature, attention is shifting toward how to mitigate its effects and decrease the emission of greenhouse gases across all sectors. More than ever, private and public sectors alike are developing environmental practices and seeking to reduce their carbon footprint. The US healthcare sector has a large carbon footprint and is incentivized to reduce the negative public health effects of climate change, facilitating the spread of this movement into medicine. Literature has begun to assess the carbon footprint of surgery, as a resource-intensive field, and how to reduce that footprint. The same is true of the orthopaedic surgery literature, although to a more limited extent. Several studies demonstrate the benefits of implementing anesthesia and manufacturing techniques with a smaller carbon footprint, redesigning custom packs, limiting single-use devices and materials, minimizing equipment in trays, properly separating waste, and recycling. More high-level research is needed on best practices to reduce the carbon footprint of orthopaedic surgery, such as the principle of circular economy.[40] As policies take effect striving toward environmental sustainability, surgeons can help lead the way toward integrating them into orthopaedic surgery.

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