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Environmental Impacts of Surgical Procedures: Life Cycle Assessment of Hysterectomy in the United States

Cassandra L. Thiel,*[†,⊗] Matthew Eckelman,[§,⊗] Richard Guido,[‡,⊗] Matthew Huddleston,[†,⊗] Amy E. Landis,[⊥,⊗] Jodi Sherman,[‖,⊗] Scott O. Shrake,[⊥,⊗] Noe Copley-Woods,[‡,⊗] and Melissa M. Bilec[†,⊗]

[†]Department of Civil and Environmental Engineering, University of Pittsburgh, 153 Benedum Hall, 3700 O'Hara Street, Pittsburgh, Pennsylvania 15261, United States

[‡]Magee-Womens Hospital of UPMC, Department of Obstetrics and Gynecology, University of Pittsburgh School of Medicine, 300 Halket Street, Pittsburgh, Pennsylvania 15213, United States

[§]Department of Civil and Environmental Engineering, Northeastern University, 360 Huntington Avenue, Boston, Massachusetts 02115, United States

[‖]Department of Anesthesiology, Yale University School of Medicine, 333 Cedar Street, TMP 3, New Haven, Connecticut 06520, United States

[⊥]School of Sustainable Engineering and the Built Environment, Arizona State University P.O. Box 875306, Tempe, Arizona 85287, United States

Supporting Information

ABSTRACT: The healthcare sector is a driver of economic growth in the U.S., with spending on healthcare in 2012 reaching $2.8 trillion, or 17% of the U.S. gross domestic product, but it is also a significant source of emissions that adversely impact environmental and public health. The current state of the healthcare industry offers significant opportunities for environmental efficiency improvements, potentially leading to reductions in costs, resource use, and waste without compromising patient care. However, limited research exists that can provide quantitative, sustainable solutions. The operating room is the most resource-intensive area of a hospital, and surgery is therefore an important focal point to understand healthcare-related emissions. Hybrid life cycle assessment (LCA) was used to quantify environmental emissions from four different surgical approaches (abdominal, vaginal, laparoscopic, and robotic) used in the second most common major procedure for women in the U.S., the hysterectomy. Data were collected from 62 cases of hysterectomy. Life cycle assessment results show that major sources of environmental emissions include the production of disposable materials and single-use surgical devices, energy used for heating, ventilation, and air conditioning, and anesthetic gases. By scientifically evaluating emissions, the healthcare industry can strategically optimize its transition to a more sustainable system.

INTRODUCTION

The healthcare sector is a leading driver of economic growth and innovation in the U.S., with spending on healthcare in 2012 reaching $2.8 trillion, or 17% of the U.S. gross domestic product.[1] Globally, spending on healthcare services is expected to increase 4.4% a year with population growth and increased life expectancy.[2] Despite the significant local, national, and global impacts of healthcare procedures and facilities, the environmental costs are often overlooked. Resource consumption across this large industry has reached unsustainable levels in multiple areas, including energy consumption, material consumption, and emissions. Environmental campaigns within hospitals typically focus on waste reduction, yet with the size and interconnectedness of U.S. healthcare, supply chain impacts, energy use, and emissions are also significant.

There is no "magic pill" to reduce the environmental impacts associated with providing healthcare. Yet the current state of healthcare treatment across the U.S. and globally, offers significant opportunity for efficiency improvements, potentially leading to reductions in costs, resource use and waste, and environmental impacts.[3] U.S. hospitals are the second most energy intensive building type, cumulatively spending $8.8 billion per year on energy.[4,5] Hospitals generate 3.4 billion pounds of solid waste annually, relying on the $40.3 billion disposable medical supply industry.[6,7] Hospitals are beginning to scientifically evaluate the source of negative environmental

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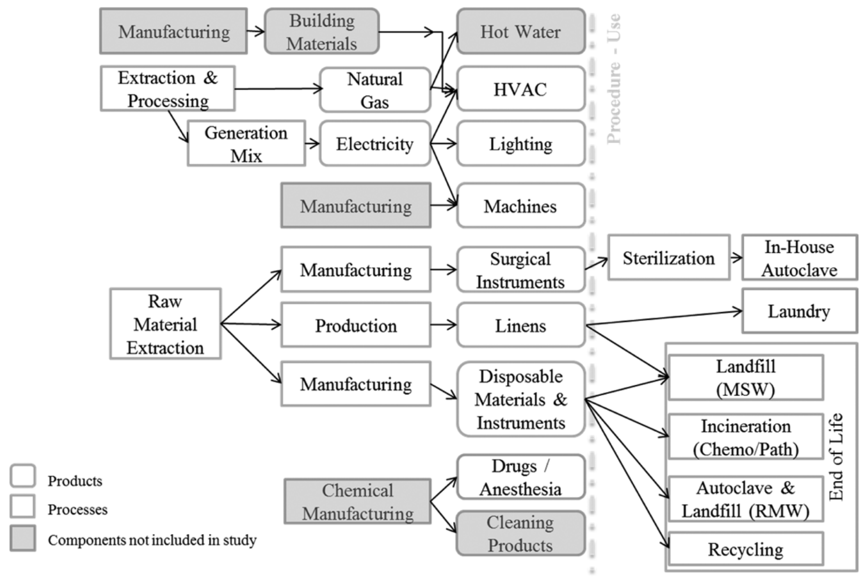

Figure 1. Boundaries for life cycle assessment of hysterectomy. HVAC = heating, ventilation, and air conditioning, MSW = municipal solid waste, Path = pathogenic, RMW = regulated medical waste.

impacts in current medical practice, specifically in regards to energy, but there is little research on environmental impacts. With better information, healthcare innovators can strategically optimize the transition to a more sustainable system, while maintaining or improving the safety, comfort, and health outcomes of patients.[8,9]

Though still rare, the adoption of life cycle assessment (LCA) is increasing as a tool to analyze the impacts of healthcare and health systems. As medical waste is the most visible form of healthcare's environmental impacts, many studies have focused on best-practices for proper treatment and disposal.[10−13] A burgeoning field set on reducing these long-term environmental impacts is developing methods and best practices to assess and ameliorate the impacts at multiple levels.[14−16] A study focused on the impacts of birth procedures, shows that multiple components of medical procedures have significant impacts, including: energy systems and material supply chain.[17] Other studies found that even aspects of procedures that may be commonly overlooked are found to have significant impacts, such as use of anesthetic gases (potent greenhouse gases), housekeeping routines, and potentially inefficient drug delivery methods.[18−20]

This paper presents a robust analysis of the life cycle impacts of a single surgical procedure, using four different surgical methods. Because the operating room (OR) is the most resource-intensive area of a hospital, understanding the environmental impact of surgery is critical to understanding healthcare-related emissions in general.[21−23] A hysterectomy, or the removal of a woman's uterus, is the second most common major surgery for women in the U.S.[24] and was chosen for this study based on the four surgical approaches broadly used to perform this procedure: vaginal, abdominal, laparoscopic, and robotic. These four approaches represent the evolution of modern surgery from larger incisions and small tools held in the surgeons hand to smaller incisions requiring more sophisticated technology, at times even physically separating the surgeon from the patient. The hysterectomy, still performed using vastly different technology, allows us a glimpse at how these developments might affect the resource use and environmental impact of surgery, at a time when many types of surgery now have, or are actively evolving toward, minimally invasive approaches. Medical advancements may improve patient outcomes or reduce surgical complications, but they may also have co-benefits and co-costs which, with thoughtful future development, could be modified to reduce future environmental burden. Without developing baselines, understanding the co-benefits and co-costs is difficult. Opportunities likely exist for improving design or use of these technologies that takes advantage of medical advances while reducing costs and impacts. The results of this study aim to provide an important profile of the emissions resulting from surgery, which are vital to consider at this important time in healthcare, as we make decisions about cost, reform, access, and the impact on future generations.

■ EXPERIMENTAL METHODS

This research utilized LCA to quantify the environmental emissions of a vaginal, an abdominal, a laparoscopic, and a robotic hysterectomy in the operating rooms (OR) at Magee-Womens Hospital (Magee) of the University of Pittsburgh Medical Center (UPMC). Magee is a top-ranked, 360-bed teaching hospital, which performs about 1400 hysterectomies annually.[25] The site was chosen based on the surgical volume and distribution. LCA is an assessment tool that analyzes the environmental impacts of a product or process by aggregating the emissions at all stages of the life cycle, including the raw materials production, manufacturing, use, disposal, and any transportation between these steps.[26,27] The functional unit for this study is one hysterectomy. The boundaries encompass the raw material extraction, production, use, and end-of-life of the processes and products required to perform each type of hysterectomy from the moment the patient enters the OR to the moment she leaves the OR, Figure 1. This research used a hybrid LCA framework developed for analyzing infant birthing procedures by incorporating process LCA data and Economic Input Output LCA (EIO-LCA) data.[16,17,28] Waste audits were conducted, and Monte Carlo simulations were used to quantify the variability and uncertainty in emissions for each component of a hysterectomy.

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Waste Audit. To quantify and characterize the products and materials entering Magee's municipal solid waste and recycling streams, detailed waste audits of 62 cases of hysterectomy were conducted (15 each abdominal, vaginal, and robotic, and 17 laparoscopic). The audits involved data collection from individual patients' medical cases; therefore, the project team applied for and received Institutional Review Board (IRB) approval under 45 CFR 46.110.(4) and 45 CFR 46.110.(5) (IRB#: PRO11010250). Patients undergoing vaginal, abdominal, laparoscopic, or robotic hysterectomies for noncancer related reasons were identified and approached for participation in the study. Waste audits were conducted over the course of 1 year, with the target goal of auditing the waste from at least 15 of each type of hysterectomy so that variability in material use could be included in the Monte Carlo Analysis. Once a patient consented to participate in the study, researchers conducted a visual inspection of the OR prior to the surgery to ensure all previously generated waste was eliminated. Immediately following the surgery, the municipal solid waste (MSW) and recycling was collected, labeled with the case identification number, and moved to a secure storage location for sorting and weighing. Regulated Medical Waste (RMW), which undergoes autoclaving prior to landfilling, was estimated by quantifying the type of "peel packs" or package labels found in the MSW. Chemo/Pathogenic waste was calculated using uterine weights, as described in the patient records. Quantities of anesthesia and abdominal insuflation were calculated from patient records, as described in the Supporting Information.

Life Cycle Inventory. To create a life cycle inventory of the data collected through waste audits and site assessment, unit processes were assigned to each data, with preference given first to U.S. based databases, i.e., USLCI[29] and then the most robust database, i.e., ecoinvent.[30] All database selections were determined by comparing the physical description and application of the material to the unit process description. Impacts due to the transportation of material wastes were calculated using distances from the hospital to the landfill and recycling facilities based on waste hauling quantity data provided by Magee's facility management. Database selection can be seen in the Supporting Information.

Certain unit processes were modified based on literature to more accurately reflect the product or process being represented. The USLCI electricity process was modified to match the energy mix of Pennsylvania for 2012.[31] Disposable gowns, drapes, and bluewrap from the OR are a type of polypropylene fabric also known as spunbond-meltblown-spunbond or SMS PP. As this material makes up a large portion of a hysterectomy's waste stream by weight, the USLCI unit process for PP production was modified to include the manufacture of the textile beyond pelletization of the plastic.[32]

Impacts due to production and disposal of reusable linens were allocated based on the estimated lifespan of each linen type, as listed in the Supporting Information. Reusable stainless steel instruments were estimated to have a lifespan of 300 uses, based on a 2012 study of reusable surgical instruments.[33] Previous literature was used to supplement gathered data on the sterilization process for reusable materials and linens, as seen in the Supporting Information.[17,34−37] Characterization factors for the global warming potential of anesthetic gases were taken from previous literature, as described in the Supporting Information.[19,38]

Hybrid LCA Approach. Certain medical equipment used in laparoscopic and robotic hysterectomies was too complex and expensive to be broken down accurately into representative components. To account for the manufacturing impacts from the medical equipment, this study utilized economic input-output LCA (EIO-LCA).[28] This combination of process LCA and EIO-LCA is called hybrid LCA and is used to address issues that may be encountered using each method alone.[39,40]

The price paid per unit for each piece of medical equipment was collected from Magee purchasing staff and matched to the number of medical equipment used in each hysterectomy based off of package labels (peel packs) found in the MSW. The monetary values were evaluated using the purchaser price model in EIO-LCA, as the prices were reflective of what the hospital paid, and not the cost to the manufacturer. For the production and disposal of complex medical devices, NAICS (North American Industry Classification System) sector 339112 *Surgical and Medical Instrument Manufacturing*, and sector 562000: *Waste Management and Remediation Services* were used, respectively. All monetary values were converted from 2012 U.S. dollars to 2002 dollars, the basis for the most recent EIO-LCA model.[41]

Life Cycle Impact Assessment. Environmental impacts from the inputs and outputs of the four types of hysterectomy were calculated using TRACI 2.1 for both process LCA and EIO-LCA.[42] Unit conversion was necessary to match the EIO-LCA results in impact categories Acidification, Carcinogenics, NonCarcinogenics, and EcoToxicity with the process LCA results, as seen in the Supporting Information. Embodied energy, or a summation of all energy used during the material's life cycle, was calculated using cumulative energy demand (CED) version 1.08 developed by ecoinvent version 2.0 and PRé Consultants for process LCA,[43,44] and the energy analysis function found on the EIO-LCA online tool.[28]

Monte Carlo Analysis of Variability and Uncertainty. Monte Carlo Analysis (MCA), or random number sampling, was used to account for the uncertainty inherent in life cycle inventory data and the variability of material and energy consumption for each type of hysterectomy at this hospital. It should be noted that material use will differ at other facilities, though most U.S. hospitals contract with the same material suppliers and utilize similar custom packs for a given procedure. The use of MCA allows this study to better understand the range of potential environmental impacts resulting from a typical hysterectomy.

This MCA randomly sampled numbers from the probability distributions of materials and their impacts, resulting in an overall distribution of the impacts of a hysterectomy. Distributions of individual material processes in each type of hysterectomy were calculated from waste audit data using the Anderson−Darling test. More information on the MCA and distribution identification can be seen in the Supporting Information. The resulting distribution was calculated from 100 000 random samplings. The 5th, 50th, and 95th percentiles, as well as the means and standard deviation for all impact categories, were reported for each hysterectomy as a whole. The impacts due to recycling, because they were negative, were not included within the MCA, but were incorporated as averages in post-MCA results. MCA results are included as error bars in result figures.

■ RESULTS

The results are presented in two sections. The first shows the characterization and quantification of materials and waste from four types of hysterectomy, in order to better understand the

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resource use of current surgical practices and the effects of advancing technology. The second section details the life cycle environmental impacts of resource consumption and energy use in each hysterectomy, in order to help inform potential reduction strategies.

Material Footprint of Hysterectomy: Waste Audit Findings. Waste auditing of abdominal, vaginal, laparoscopic, and robotic hysterectomies determined the average material composition of MSW and recycling of each hysterectomy type. Across all four surgeries, SMS PP material, or gowns, bluewrap, and drapes, composed the majority of MSW by weight, from 22% by weight for robotic hysterectomies to 35% for laparoscopic. Gloves accounted for about 5% by weight of each surgery's waste stream. Other types of plastics, from thin film packaging wrappers to hard plastic trays, made up a minimum of 36% of MSW by weight for vaginal hysterectomies and a maximum of 46% for robotic procedures. Paper from package labeling and cardboard varied from 5% of MSW for abdominal hysterectomies to 18% for robotic. No correlation was found between duration of surgery and quantity of waste generated.

Robotic hysterectomies produced 30% more MSW than the average of other approaches at 13.7 kg per case, as seen in Figure 2. Of that quantity, 22% by weight were gowns, drapes,

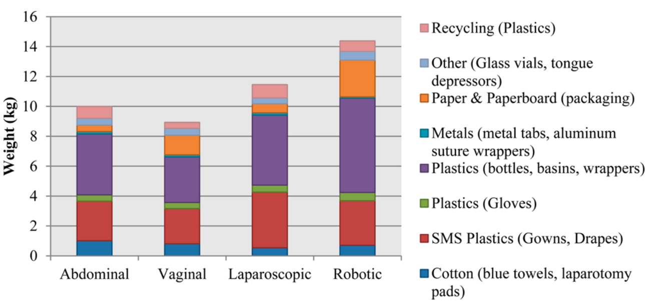

Figure 2. Average material composition of nonhazardous solid waste (municipal solid waste and recycling) from a single hysterectomy by surgery type. SMS = spunbond-meltblown-spunbond.

and bluewrap (SMS PP), 50% were gloves and other plastics, 18% was paper, and 5% was cotton. Abdominal hysterectomies, the most common form of hysterectomy in the U.S., had an average total MSW production of 9.2 kg. Abdominal procedures produced the largest amount of cotton waste at 1 kg per average surgery or 11% of the MSW by weight.

Recycling was variable for each case, ranging from 4% of total material disposal by weight (0.4 kg) for vaginal hysterectomies to 8% of total material disposal by weight (0.9 kg) for laparoscopic hysterectomies. Researchers discovered nonhazardous, nonrecyclable materials in the recycling waste in 1 out of 15 cases for vaginal and abdominal procedures, in 3 out of 16 cases for laparoscopic procedures, and in 6 out of 15 cases for robotic procedures. Based on estimated material type and observed quantities of noninfectious MSW, recycling rates could be increased by 45 to 60% by weight for each hysterectomy type, reducing the total amount of MSW to one-third of the current average quantity by weight. A 1992 study resulted in similar estimates of recyclability of surgical wastes.[45] Unfortunately, the time and associated costs often prohibit the manual sorting of waste within the OR; however, this presents an opportunity for improved waste management models and systems.

Life Cycle Impacts of Hysterectomy. Robotic hysterectomy was found, on average, to have the largest environmental footprint over other hysterectomy types in every impact category analyzed, as seen in Figure 3. There is, however, significant overlap with laparoscopic, abdominal, and vaginal hysterectomies in the categories of smog, carcinogens, noncarcinogens, and ecotoxicity. The upper range of laparoscopic hysterectomy's 90% confidence interval overlaps with average impacts of robotic hysterectomies in every category. Abdominal and vaginal hysterectomies show significantly smaller impacts than laparoscopic and robotic techniques in ozone depletion (ODP), acidification, respiratory, and cumulative energy demand. It should be noted that the error bars in greenhouse gas emissions (GHG) are largely influenced by anesthetic choice, which varies based on anesthesiologist preference and is not indicative of the type of hysterectomy performed. Without anesthetics, abdominal and vaginal hysterectomies emit significantly less greenhouse gases, with a narrower confidence interval, than laparoscopic and robotic hysterectomies.

Disposable Materials. Cotton production has the largest footprint of all disposable materials, especially in toxicity and human health categories, despite cotton products making up less than 5% by weight of municipal solid waste streams. Production of SMS PP, the material used for gowns, drapes, and bluewrap, makes up about 25% by weight of an abdominal hysterectomy's embodied energy and accounts for 1−24% of all other impact categories. Impacts of vaginal surgeries are similar, but with 20% less cotton by weight and roughly 3 times the quantity of paper, the impacts associated with the production of paper products such as paper labels and cardboard packaging makes up 1−7% of every impact category for vaginal hysterectomies. Disposal of MSW to a landfill or to an autoclave facility prior to landfilling accounts for over 40% of eutrophication and 8% of noncarcinogenic impacts for all hysterectomy types.

Anesthetics. Anesthetics are potent greenhouse gases. Selection of anesthetic varies based on anesthesiologist preference, per routine, and, as such, the results reported here are the averages of all cases surveyed. Selection of anesthetic can drastically affect the footprint of hysterectomy, as shown with the large error bars for GHGs in Figure 3. On average, anesthetic gases contributed to a third of the greenhouse gas emissions of robotic and laparoscopic hysterectomies and two-thirds of abdominal and vaginal hysterectomies. For abdominal and vaginal hysterectomy, anesthetic use contributed to 98% of the ozone depletion potential. The types of inhalation anesthetics used, sevoflurane or desflurane either with or without nitrous oxide (N_2O) as a carrier gas, are themselves greenhouse gases with ozone depletion potential. Desflurane has a global warming potential 20 times that of sevoflurane, as shown in Figure 4. Intravenous propofol was administered in 4 vaginal cases, and is not a greenhouse gas. As such, greenhouse gas emissions for vaginal hysterectomy from anesthetics varied drastically from case to case, from as low as 0.001 kg CO_2-eq/case to 505 kg CO_2-eq/case.

Reusable Instruments. Reusable stainless steel instruments produce 8−25% of impacts for all hysterectomy types in the categories of smog, carcinogenic, noncarcinogenic, and ecotoxicity. They also account for 7−12% of respiratory impacts, acidification potential, and embodied energy of abdominal and vaginal hysterectomies. For toxicity and

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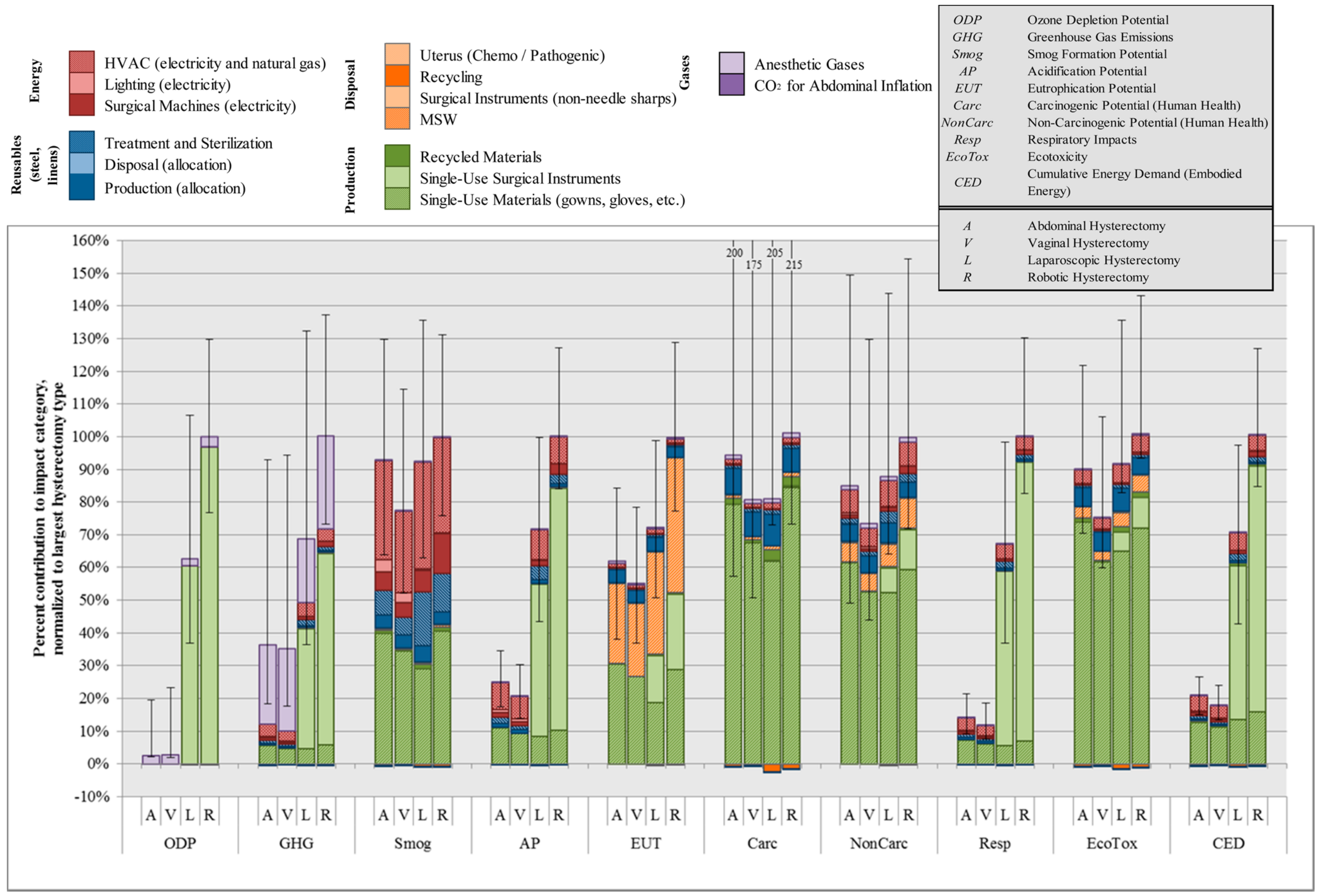

Figure 3. Total life cycle environmental impacts of an average hysterectomy by surgery type (normalized to highest hysterectomy type in impact category). Negative values reflect positive environmental impacts due to recycling; Error bars represent 90% confidence interval from Monte Carlo Analysis.

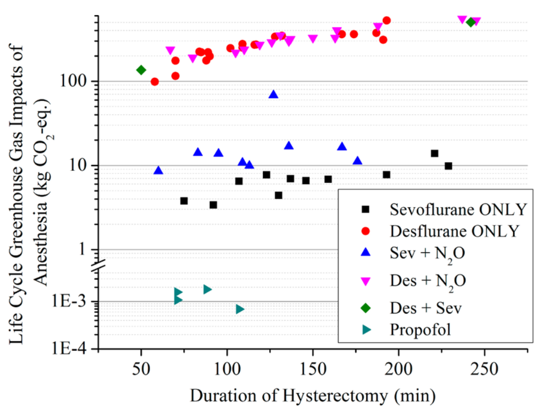

Figure 4. Life cycle greenhouse gas emissions of anesthetics used in all hysterectomy cases based on surgery duration. Sev = sevoflurane, Des = desflurane, N_2O = nitrous oxide.

human health categories, this is mainly due to the production of stainless steel instruments, whereas the treatment and sterilization of the instruments is the primary contributor to the other impact categories.

Energy. Natural gas and electricity use from all hysterectomies accounts for about 40% of smog, 15−40% of acidification, and 6−10% of noncarcingenic and ecotoxicity impacts for all hysterectomy types. Energy use contributes about 28% of cumulative energy demand in abdominal and vaginal hysterectomies, 9% for laparoscopic and 6% for robotic, as the materials used in the latter two hysterectomies have a higher embodied energy.

A majority of the energy impacts, over 70%, are caused by the heating, ventilation, and air conditioning (HVAC) in the OR. Electricity required to run the machines in the OR makes up 10−30% of every impact category analyzed depending on the hysterectomy type. Lighting in abdominal and vaginal hysterectomies accounts for about 8% more of their environmental impacts in all categories, but only 1% in laparoscopic and robotic procedures. This is due to minimal use of OR lighting during laparoscopic and robotic hysterectomies.

■ DISCUSSION: IMPLICATIONS OF FINDINGS

Quantitative evaluations and data-driven solutions are needed to curb emissions and their resulting adverse health effects. Projecting the results of this study to the 500 000 cases of hysterectomy alone in the U.S. annually (assuming a mix of 40% abdominal, 20% vaginal, 30% laparoscopic, and 10% robotic[46]), the greenhouse gas emissions of U.S. hysterectomies is about 212 000 metric tons of CO_2-eq per year. There are over 51.4 million annual inpatient procedures in the U.S.[47] Although total numbers of open vs minimally invasive procedures are unknown, the trend is toward minimally invasive surgery that drives up the amount of pollution generated within the OR.

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Results of this study reveal a number of opportunities to improve the environmental sustainability of current surgical procedures, though it should be noted that the results of this study should not be used to dictate clinical care. This study considered only the narrow boundaries of the intraoperative period, without consideration for postoperative length of stay, which may be included in future studies. The footprint of specific procedures reported in this study appear to be less (and therefore preferable), but this study does not account for factors such as length of stay and postsurgical resource use, which may result in different emissions profiles.

As mentioned earlier, there is no single method to reducing environmental impacts associated with healthcare services. This study identifies aspects of surgical approaches with large environmental footprints so that informed and targeted reduction strategies may be implemented and future medical developments may be designed to minimize emissions. Table 1 lists the components of hysterectomy that contribute the most to specific impact categories as well as potential strategies to reduce surgery-associated emissions.

Table 1. Components of Hysterectomy Contributing Significantly to Environmental Impacts and Potential Impact Reduction Strategies, A = Abdominal, V = Vaginal, L = Laparoscopic, R = Robotic, all = All Hysterectomy Types

Issue	*Environmental Impact Categories*	*% of Total Impacts in Categories*	*Potential Reduction Strategies*
Energy used to run HVAC (heating, ventilation, and air conditioning)	• Greenhouse Gas Emissions, • Smog Formation, • Acidification Potential, • Respiratory Impacts, • Cumulative Energy Demand	10-35% (A&V) 5-30% (L&R)	• Regular maintenance of mechanical equipment, • Upgrade mechanical equipment and filters, • Reduce energy leaks in ducts and joints, • Reduced ventilation rates when OR not-in-use, • Use more renewable energy sources
Anesthetic Gases	• Greenhouse Gas Emissions	30% (L&R) 70% (A&V)	• Install waste gas capturing technology in OR, • Apply lowest fresh gas flow rates, • Avoid desflurane and N_2O
Production of Disposable Cotton	• Carcinogens, • Non-Carcinogens, • Ecotoxicity	25-60% (all)	• Reuse cotton, • Recycle cotton, • Use organic cotton, • Use other fibers (bamboo, hemp, etc.)
	• All other categories analyzed	15-40% (A&V)	
Production of Disposable Gowns, Drapes, and BlueWrap (SMS-PP)	• Non-Carcinogens, • Ecotoxicity, • Cumulative Energy Demand	10-30% (all)	• Recycle materials, • Replace with reusable materials
Disposal of PP (polypropylene)	• Eutrophication	10-20% (all)	• Recycle materials, • Replace with reusable materials
Production of Disposable Surgical Instruments	• Ozone Depletion Potential, • Greenhouse Gas Emissions, • Acidification Potential, • Eutrophication, • Respiratory Impacts, • Cumulative Energy Demand	20-99% (L&R)	• Encourage environmental manufacturing, • Utilize reusable instruments, • Utilize third-party reprocessing

Developing Best Practices and Training: Selection and Delivery of Anesthetics. Life cycle assessment and other sustainability tools have a role to play in identifying and developing best practices for minimizing emissions. For materials such as anesthetics, environmentally preferred substitutions already exist and are currently being used alongside options with larger impacts. By educating anesthesiologists and appropriate staff on environmentally preferred anesthetic choice and avoiding excessive fresh gas flow rates, the ozone depletion potential and greenhouse gas emissions of hysterectomies can be reduced 65−95% for abdominal and vaginal hysterectomies. Switching to propofol or other IV or regional anesthesia techniques where clinically indicated would reduce ODP 3% in laparoscopic and 28% in robotic hysterectomies.

Impacts in the Supply Chain: Packaging and Purchasing. Most single-use disposable tools enter the OR in multiple layers of packaging. On average, about 20% by weight (∼2 kg) of the municipal solid waste for each hysterectomy originated as paper, plastic, and glass packaging for surgical supplies. This does not include plastic bluewrap, which is used to demark sterilized custom packs. Rethinking packaging strategies to reduce materials could have a significant impact.

Single-use disposable materials and tools accounted for a majority of environmental impacts in nearly every category. Over 95% of the single-use material impacts resulted from the production or manufacture of the items. The disposable surgical instruments used during minimally invasive surgery, in particular, incur a significant environmental and monetary cost, and health care professionals should carefully consider the impact of using increasingly disposable instruments. Reprocessing of single-use medical devices for reuse has been advocated as a strategy for cost and waste reduction. This may significantly reduce the environmental impact of surgical devices, although likely not to the same degree as reusable instruments. Approximately 3000 U.S. hospitals actively engage in third-party medical device reprocessing services, and the reprocessing industry is valued at roughly $400 million. The reprocessing industry's current valuation represents considerable growth within the past decade, where in 2000 the reprocessing industry was valued at $20 million.[48] It would be prudent to utilize LCA to compare single-use, reprocessed, and reusable versions to ascertain the preferable environmental and cost solutions for otherwise equivalent medical devices.[49]

Though a majority of a hysterectomy's impacts may be the result of decisions made in the product manufacturing and robotics industries, healthcare providers can drive positive change through their collective purchasing power.[50] For example, traditional cotton growing practices release many known carcinogens and toxic chemicals into the soil, air, and water. Though a hospital consumes only a handful of OR towels and laparotomy pads in a single surgery (cotton products represent only 5−10% of MSW in hysterectomies), the continued production from virgin, traditionally farmed cotton results in a quarter to half of the human health toxicity and ecotoxicity impacts in every type of hysterectomy. Hospitals can pressure their group purchasing organization (GPO) or material suppliers to manufacture OR towels with a reduced footprint or an environmentally preferred fiber.

Future of Technologies in the Surgical Landscape. Laparoscopic and robotic surgeries are minimally invasive, leaving patients with smaller incisions, less pain, and faster recovery times than patients undergoing open procedures. Although advancing medical technologies often means better outcomes, current laparoscopic and robotic hysterectomy also cost more and utilize more resources, especially packaging and plastics, and produce more waste, namely disposable electronic devices. The production of these disposable electronic devices results in significantly higher emissions related to ozone depletion, greenhouse gases, acidification, and respiratory impacts.

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As technological innovation continues to improve medical care, more research should be done to ultimately reduce the environmental emissions and human health impacts of these technologies at each stage in their life cycles, including medical product design to close the circular loop of product emissions and environmental and public health concerns. Currently, medical product innovation and approvals are complex endeavors, especially in the U.S., with minimal or no incentives to reduce environmental burdens. Continuing research, such as this study, may create awareness for product designers, device manufacturers, and policy makers to enable or incentivize reprocessing, reusability, energy efficiency, and substitution of deleterious materials.

Healthcare is ready for more rigorous measurement of both greenhouse gas emissions and environmental performance. Future studies that accurately and scientifically evaluate potential solutions will help the healthcare industry strategically optimize its transition to a more sustainable system. Quantification tools such as life cycle assessment provide needed information about the source of environmental impacts and are a great asset for hospital decision-makers to set priorities for hospital and clinician practices, equipment upgrades, product sourcing priorities, and waste handling protocol. Across the whole healthcare industry, there is a profound opportunity to make healthcare services more efficient environmentally and economically without compromising safety or efficacy.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Life cycle inventory: database selection and allocation details, economic input-output LCA setup and LCIA, Monte Carlo analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Cassandra L. Thiel, Ph.D. E-mail: clt31@pitt.edu. M: (608) 387-1985. O: (412)624-9870. F: (412)624-0135.

Author Contributions

⊗The paper was written through contributions of all authors. All authors have given approval to the final version of the paper. These authors contributed equally.

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Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

CED	Cumulative Energy Demand
Magee	Magee-Womens Hospital of UPMC
LCA	Life Cycle Assessment
MSW	Municipal Solid Waste
RMW	Regulated Medical Waste
GHG	Greenhouse Gas
SMS PP	Spunbound-meltblown-spunbound polypropylene
ODP	Ozone Depletion Potential
OR	Operating Room

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