Life cycle assessment of stainless-steel reusable speculums versus disposable acrylic speculums in a university clinic setting: a case study

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Abstract

The reusable versus disposable debate is frequently discussed with regards to health care sustainability. Vaginal speculums used in pelvic exams are available in both disposable and reusable material designs. A comparative cradle to grave life cycle assessment (LCA) was conducted to determine and analyze the environmental impacts of using disposable acrylic speculums versus using reusable stainless-steel speculums in a women’s university health clinic where around 5,000 pelvic exams are conducted on a yearly basis. Environmental impacts for the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) 2.1 categories were determined using process based LCA. The scope considered for the analysis includes the stages of raw materials, manufacturing, use, and end of life. The functional unit for all analyses is selected as 5,000 pelvic exams, which is equivalent to one year of clinic operation. The reusable stainless steel speculum system outperformed the acrylic speculum system in five impact categories: global warming, acidification, respiratory effects, smog, and fossil fuel depletion. There is one category, ozone depletion, where the acrylic speculum system performs better. When accounting for uncertainty, in the carcinogenics, non-carcinogenics, ecotoxicity, and eutrophication impact categories, there is no speculum system that outperforms the other. Overall, there is no speculum system that outperforms the other consistently across all TRACI impact categories, however, depending on the overall environmental objectives one may be preferable to the other.

Introduction

Pelvic exams are a routine part of many people’s annual health checkup. Vaginal speculums used in pelvic exams are available in both disposable and reusable configurations, making them part of the group of medical devices available in either reusable or disposable configurations that decision makers such as clinicians have available for their practice (Grimmond and Reiner 2012, Sørensen and Wenzel 2014, Sherman et al 2018, Donahue et al 2020, Leiden et al 2020). The bi-valve speculum, such as the Pederson, or the Graves model, which dates back to almost two hundred years, is still the most common type of vaginal speculum used (Rossmann 2008, Wong and Lawton 2021). There are however, other speculum configurations in existence, but these have not been widely adopted nor as extensively used in a clinical setting (Wong and Lawton 2021). There are however, other speculum configurations in existence, but these have not been widely adopted nor as extensively used in a clinical setting (Wong and Lawton 2021). Since speculums are frequently used, an understanding of the environmental impacts should be considered when deciding to increase a women’s health clinic’s sustainability efforts. During pelvic examinations, the speculums aid providers in collecting samples, in observing, and in placement and/or removal of contraceptive methods. The volume of pelvic examinations performed, which is around 37.3 million in the US (National Ambulatory Medical Care Survey: 2016 National Summary Tables 2016), raises the question of whether disposable or reusable speculums...
should be used in the context of sustainability. The purpose of this work is to determine the environmental impacts of using acrylic disposable speculums versus stainless steel reusable speculums in a university clinic setting to aid in decision making.

Health care spending in the US represents 17.7 percent of GDP as of 2019 (Martin et al. 2021). A 2016 study that used Economic Input-Output Life Cycle Assessment (EIO-LCA) revealed that the United States Health Care sector has significant environmental impacts. Overall it is responsible for 10% of greenhouse gas emissions, 10% of smog formation and 12% of acidification, among other impacts (Eckelman and Sherman 2016). Paradoxically, the environmental impacts of the health care sector cause human health damages. Eckelman and Sherman (2016) estimate these health damages to be equivalent to 470,000 disability adjusted life years (DALYs) lost from pollution related disease. Therefore, reducing the environmental impact of healthcare can increase overall population health outcomes. In this paper we address the environmental impacts of disposable and reusable vaginal speculums, including waste generated for each speculum system. There are various steps that could be taken to reduce this waste generation including sorting and/or reducing waste, material substitutions, among others (Kleber and Cohen 2020). In this paper we refer to waste, as the waste generated during the pelvic exam and subsequent disinfection process in the case of the reusable speculums. In the case of the disposable speculum the waste is the film packaging and the speculum itself. Further discussion of waste is included in the discussion in the section titled ‘Waste Management Alternatives Considerations.’

The University of Wisconsin’s (UW) Madison campus women’s health clinic is part of the University Health Services department. UW-Madison enrolls around 45,000 students annually, with around half being women, and about a quarter of the women belong to minorityized groups (Facts n.d.). The clinic serves about 10,000 patients on a yearly basis, around half of these patients require a pelvic examination as part of their visit (M Perez 2020). Reasons that a pelvic exam is required may be to conduct a Papanicolau (PAP) smear, sexually transmitted disease (STD) screening, to place an intrauterine device (IUD), to check on an IUD, or for ailments such as pain, bleeding and vaginal discharge (Bates et al 2011). Currently, the clinic may use either acrylic disposable speculums or reusable stainless-steel speculums for pelvic exams. The type of speculum ultimately used during a visit is at the provider’s discretion.

Materials and methods

System description
In this study six scenarios were considered, since the clinic currently employs both speculum types, reusable stainless steel and disposable acrylic speculum scenarios are included. Three scenarios correspond to the acrylic disposable speculums and three scenarios correspond to the stainless-steel reusable speculum system. For both speculum types, the raw materials and manufacturing, use phase, and end of life are considered. The reusable stainless-steel speculum system includes four metal speculums that range in size and shape depending on patient needs. The disposable acrylic speculum system is comprised of two sizes of acrylic speculums.

For the stainless-steel speculum system we have considered a range in lifetimes from 1 year up to 15 years, since the speculums may be in circulation for different time periods. In product descriptions there was no information related to the potential lifetime of a stainless-steel reusable speculum. For our study, the lifetimes of the speculums are based on personal communication with clinic personnel. According to the clinic, most of the speculums have been in the clinic for at least a decade. In addition, three different types of waste management are considered for both speculum systems as these may vary by region. In the case of recycling, it was included hypothetically since this alternative is available for medical equipment and waste on a limited basis, (Recycling Medical Equipment To Reduce Medical Waste 2021), and if available it is reserved for more durable single use medical equipment (Going Green in the Hospital 2010). The PPE used during disinfection, electricity of equipment, the water consumption and detergent use during the disinfection phase are included in the reusable stainless-steel speculum scenarios.

Goal and scope definition
In the current study, six total scenarios were considered, three for the reusable stainless-steel alternative and three for the disposable acrylic speculum alternative. These scenarios were analyzed and compared using a process based cradle-to-grave life cycle assessment (LCA) approach. The study was scoped to determine processes to be included, inventory data was gathered, analysis for cradle to grave process based LCA was done, and then all results were interpreted per ISO 14040 (ISO 2006, p. 14040). The functional unit used in this study is one year of clinic operation which is equivalent to conducting 5,000 pelvic exams per year. Impacts from transportation, labor and overhead within the clinic are excluded. Also excluded is the impact of manufacturing the autoclave machine used for sterilization. Transportation is excluded since the majority of the stainless-steel speculums are legacy speculums that have been in the clinic for a long time and vary widely. The most recent
acquisition of stainless-steel speculums was done more than four years ago and was for a limited number of speculums (less than 10% of existing clinic inventory). There is little information as to the specifications of the speculums acquired most recently (more than four years ago) as such we cannot include transportation in a comparative analysis if the transportation cannot be modeled accurately for all material alternatives considered. This will yield results that we cannot cross compare if there are varying scopes of the life cycle considered in the alternatives. This same argument is made for the cardboard packaging in which the speculums come to the clinic. The clinic is currently not procuring stainless steel reusable speculums as they have a very large existing legacy inventory. Overhead is not included as the clinic will be in similar layout for both material alternatives. There are differences in labor required, but these have more economic impacts rather than environmental impacts and would be appropriate to consider in a life cycle costing study.

**Inventory analysis**

Inputs were selected from Ecoinvent 3 databases, except for 10 inputs where data were not found in Ecoinvent 3. Nine inputs are from the European reference Life Cycle Database (ELCD) and one input is from United States Life Cycle Inventory (USLCI). Detailed description of input categories, database used and, values for each input are included in SI in tables S1 thru S11 (available online at stacks.iop.org/ERC/4/025002/mmedia).

To determine the environmental impacts of the systems considered in this study, the analysis starts at the raw materials acquisition phase. For the acrylic speculum scenarios, 5,000 individually wrapped speculums are purchased on a yearly basis. The disposable speculums presented in figure 1(a) which are used at UW Madison University Health Services (UHS) are manufactured by Welch Allyn. For the acrylic speculum system, the material composition is assumed to be polymethyl methacrylate (PMMA), the exact material composition is not provided by the manufacturer. The acrylic speculums contain a small part that is 13.2% by weight of the speculum that is what holds the speculum together and the opening in place, the material composition of this part is assumed to be polypropylene (PP). As per manufacturer indication, these speculums are not sterile (Allyn 2020). These speculums are available in four sizes, the clinic currently employs two sizes. The total weight of acrylic speculums purchased in a year is 274 kg, 75% of the speculums are the standard size while 25% of the acrylic speculums are the small size. In the case of the acrylic speculum, it comes wrapped in polyethylene film, each wrapper film weighs on average 3.46 g, which would equal 17.3 kg of this film disposed per year when using 5,000 acrylic speculums. This study excludes the additional packaging, such as cardboard boxes, in which each speculum type is shipped in.

For the stainless-steel reusable speculum scenarios, it was assumed that 100 stainless steel speculums are employed in the clinic, based on approximate number provided in clinic communication. It is assumed that each reusable speculum is used 50 times throughout the course of a year for a total of the 5,000 yearly pelvic exams. There are multiple different lifetime acquisition and replacement options modeled in this work. There is one projection where the 100 stainless steel speculums are purchased every year (1 year reuse lifetime), while the rest of the projections consider that the 100 stainless steel speculums are purchased every certain number of years (from 2 years up to fifteen years), thus the impacts from raw materials, manufacturing and disposal of the stainless steel speculums are distributed and allocated throughout the years of use. This was done for a range of one year up to 15 years of stainless-steel speculum lifetimes. Reusable stainless-steel speculums, as mentioned in personal communication with the clinic, are kept in circulation for many years. In the case of the clinic there have been no replacement speculums purchased in more than four years and only a small percentage of the speculums currently in circulation were purchased that last instance.

Stainless steel reusable speculums figure 1(b) in the clinic vary in size. There are no records as to what size speculum is used in each patient visit, therefore, an assumption to find the weighted average of stainless-steel

![Figure 1. (a) Acrylic disposable speculum, (b) Stainless steel reusable speculums.](image_url)
speculum was made. This assumption consists of 45% of stainless-steel speculums will be medium sized, 25% small sized, 25% large sized and 5% extra-long. Assumptions were based on clinic communication, were the medium sized (numbered speculum #2 in table 1) was the most frequently used in the clinic. The mass of the different speculums considered in the study were the 6 listed in table 1. The total weight of stainless-steel speculums purchased in a year is 15.185 kg, for the stainless-steel scenario where 100 speculums are purchased yearly. Purchasing of metal speculums is infrequent since they are very durable, and the moving screws can be replaced as needed. The type of stainless-steel for the speculums could not be determined as the speculums have been in the facility for a long time. The only identifiable tag on some of the speculums was the word ‘stainless.’ On others the manufacturer’s name was visible but searching did not yield the exact type of stainless steel employed. ASTM standards do not exclude any type of stainless steel in a medical application, but 304 and 316 are explicitly listed as being used for speculums; therefore, the speculums are most likely made from 304 or 316 stainless steel (ASTM 2020). It was assumed that the speculums were made from stainless steel chromium alloy 18/8 and this was used for the input parameter category.

The use phase of each speculum system was considered. The acrylic speculum is single use; therefore, no use phase inputs were considered. After the acrylic speculum is used, the plastic film (#2 plastic HDPE) wrapper, which weighs 3.46 grams, and the used speculum are placed in the regular garbage bin located in the exam room.

Materials considered in the stainless steel use phase are included in table 1. After use in the exam room, the stainless-steel speculum is placed in a bin enclosed under the cabinet in the exam room, it is then collected by personnel. The used speculum is soaked in a solution made of water and a detergent (a proprietary nonionic surfactant), rinsed again, dried and autoclaved daily. The autoclave model used in the clinic is the Midmark M11-022. Stainless-steel speculums remain sterile if autoclaved inside a pouch that remains enclosed. A small percentage of the stainless-steel speculums in the clinic are used for procedures that require the use of sterile equipment per clinic guidelines, but the majority are not placed in bags as they are not required to remain sterile after autoclaving.

The autoclave at the clinic runs the sterilization cycle for one hour and then a dry mode cycle for 30 min (M. Perez, personal communication, April 2020). There is one cycle conducted per day for speculum disinfection, on average, 20 speculums are disinfected per cycle. For the energy consumption of the autoclave process for the reusable stainless-steel speculum disinfection, the energy for each cycle was found to be, through direct measurement, using Kill-A-WATT P3 model, up to 0.74 Wh/day, for a total of 185 kWh/year. This is for normal operations of using the autoclave once per day, 5 times a week for 50 weeks per year. The clinic’s autoclave equipment is unplugged when not in use, therefore standby electricity usage is not considered in our study. However, this practice may vary from clinic to clinic and could potentially change electricity consumption.

### Table 1. Mass of Speculums Studied.

| Speculum       | Weights (g) |
|----------------|-------------|
| Stainless Steel |             |
| Speculum #1    | 134         |
| Speculum #2    | 143         |
| Speculum #3    | 181         |
| Speculum #4    | 175         |
| Acrylic        |             |
| Speculum #5    | 56          |
| Speculum #6    | 52          |

### Table 2. Reusable Stainless Steel Use Phase Materials (per autoclave cycle-20 stainless steel speculums disinfected on average).

| Material                                      | Weight          |
|-----------------------------------------------|-----------------|
| Nitrile Gloves                               | 7.31 grams      |
| Gown                                          | 83.81 grams     |
| Distilled Water for Autoclave Cycle           | 3 ounces        |
| Distilled Water for Autoclave Maintenance     | 6 gallons (used on a monthly basis, not per cycle) |
| Water for Soaking, Scrubbing and Rinsing      | 4 gallons       |
| Soaking Detergent (Sklar)                    | 7 ounces (avg)  |
| Scrubbing Detergent (Metriwash)               | 3.5 ounces (avg)|
| Electricity for Autoclave                     | 0.74 kWh        |
impacts if left plugged in. The energy composition of the UW Madison campus is shown in figure S1. More than half of the energy supplied to campus comes from coal while roughly 11% comes from wind, biomass and solar.

For water consumption, 1 gallon of water is used per soaking stage for disinfection and around 3 gallons total are used for both rinsing stages, daily. This was calculated with the volume of the soaking bin used for the soak stage, measuring the time the tap was open during the rinsing stage and the water flow of the faucet. The clinic uses MetriWash soap for cleaning prior to sterilization, the amount used per year is 10 gallons per year. This estimate was calculated by measuring the amount used in the cleaning cycle, this number may vary however, since the detergent is not measured in each cleaning, but hand poured by clinic personnel. The distilled water needed to run the autoclave ranges from 3 to 4 ounces per cycle and 6 gallons are used at the beginning of the month for maintenance of the autoclave equipment.

Medical products may be landfilled, incinerated, recycled, remanufactured or reused, depending on the hazard potential of the disposed products (McGinnis et al. 2021). For the waste disposal phase of this case study, landfill, recycling, and incineration were considered. The impacts of the bag that may be used to sterilize in some instances is omitted because it is used infrequently, overhead clinic impacts are also not considered in the analysis of this study. Transportation is not included in this study.

**Impact assessment**

To conduct the process based LCA, SimaPro (PRe Sustainability 2020) was used. Inputs were selected from EcoInvent 3, except for 10 inputs. All inventory inputs are included in the SI in the section titled ‘Inventory Data.’ The second version of the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) was used to determine environmental impacts. TRACI 2.1 (Bare 2011) categories used in the process based LCA include: acidification (AP in kg SO2-eq.), carcinogens (HHICP in CTUh), ecotoxicity (ETP in CTUe), eutrophication (EP in kg N-eq.), fossil fuel depletion (FFP in MJ surplus energy), global warming (GWP in kg CO2-eq.), non-carcinogens (HHNCP in CTUh), ozone depletion (ODP in kg CFC11-eq.), respiratory effects (RP in kg PM2.5-eq.), and smog (SP in kg O3-eq.).

**Sensitivity and uncertainty analyses**

A sensitivity analysis is conducted to determine the parameters to which the LCA results of the speculum system are sensitive to. Each parameter’s input value was increased by 20%. Afterwards, the environmental impacts of the speculum system are recalculated, with this it is determined how the change in the parameter’s inputs affects the overall system’s LCA results. Sensitivity factors were then calculated. If this factor was equal to or less than 2%, the parameter was not sensitive (Ghamkhar et al. 2020, Temizel-Sekeryan et al. 2021).

An uncertainty analysis was conducted using Monte Carlo simulations on SimaPro 8.5.2.0. These results are used to determine the maximum and minimum values of the environmental impacts of each scenario. The Monte Carlo simulation was done for 1000 repetitions and 95% confidence level was selected.

**Results**

LCA results are shown in figure 2, using TRACI 2.1 impact categories, these are presented using a breakeven analysis for 100 speculum uses. The breakeven analysis presented in figure 2 includes 5 environmental impact categories, graphs for the breakout analysis of remaining TRACI impact categories are included in SI in section titled ‘TRACI Impacts Breakeven Graphs.’ The breakeven analysis conducted yields nine impact figures where scenarios cross (meaning that a true breakeven point occurs), in one category, ozone depletion, there is no breakeven point. In the ozone depletion category, the stainless-steel speculum systems have more impacts consistently throughout the lifetime arising from the use phase, specifically from the nitrile glove production, therefore the slope of the line is higher than the acrylic scenarios and never gets close to the acrylic speculum impacts. For global warming, the acrylic speculum if incinerated surpasses impacts of all stainless-steel scenarios at the 3rd use. If landfilled or recycled the acrylic speculum system surpasses global warming impacts of all stainless-steel scenarios in the 4th use. In fossil fuel depletion, if recycled the acrylic speculum breaks even with stainless steel scenarios in the 2nd use. While incineration and landfill of acrylic speculums have initially similar impacts to all stainless-steel scenarios in the fossil fuel depletion impact category. For smog, the acrylic scenarios breakeven with the stainless-steel scenarios in the 5th and 6th use. In acidification, the acrylic speculums breakeven with the stainless-steel speculum systems in the 4th use. In the eutrophication impact, the acrylic speculum systems breakeven with the stainless-steel speculum systems in the 17th, 18th and 19th use. In the respiratory effects the acrylic scenarios break even with the stainless-steel speculum in the 15th to 17th use. In the non-carcinogenics impact category, the acrylic speculum system breaks even in the 44th-47th use. In ecotoxicity, the acrylic speculum scenarios breakeven with the stainless-steel scenarios on the 40th to 42nd use. In carcinogenics, the acrylic speculum scenarios breakeven with the stainless steel in the 59th, 60th and 61st use.
In the breakeven analysis the disposal of the stainless steel speculum is added in the 100th use, this could however change if the speculum lifetime decreases or increases and is subsequently allocated in another lifetime use value. Values of breakeven results are included in tables S15 thru table S24 in SI. The mathematical formulas used for breakeven analysis are included in the SI in section titled 'Breakeven Analysis.'

The stainless-steel reusable speculum system has fewer overall impacts for all scenarios considered (recycling, landfill and incineration) when considering the breakeven analysis, except in ozone depletion. Although the stainless-steel speculums outperform in 9 out of 10 TRACI impact categories in the breakeven analysis, when considering the uncertainty there is no alternative that outperforms the other in the carcinogensics, ecotoxicity, eutrophication and non-carcinogensics categories as seen in figure 4. In the ozone depletion impact category, the acrylic speculum system performs better, even when accounting for uncertainties, if the acrylic speculums are either incinerated or recycled. If the acrylic speculums are sent to the landfill they are worse than all stainless steel configurations but, by a small margin in the ozone depletion impact category.

In figure 4, 1-year, 3-years, 5-years, 10-years and 15-years stainless steel speculum lifetimes were selected for illustrative purposes to show uncertainty of impact results. For figure 4, the raw materials and manufacturing impacts are divided into the years of use to show the impact for one functional unit which is representative of one year of clinic operation. For example, if the stainless-steel speculum is used for three years, the impacts of raw
The use phase impacts in all stainless-steel speculum scenarios are the same since the cleaning and disinfection process does not change across scenarios. The stainless-steel speculums reuse phase contributes more to the total environmental impacts of the stainless-steel speculum systems in all impact categories except respiratory effects, eco-toxicity, carcinogens, and non-carcinogens, where raw materials and manufacturing have more impacts than the use phase in the scenarios where the speculums are kept in circulation for shorter time periods (for example in 1-year and 3-year scenarios). Overall, in the stainless-steel scenarios, the end of life had the least impact of the life cycle stages. In the case of the disposable acrylic speculum, the manufacturing phase contributed most to the impacts. The acrylic speculum recycling scenarios had the least impacts when compared with incineration or landfills of the disposable acrylic speculum across all impact categories. Tables with all values of SimaPro impact results are included in Tables S35-S47. Also in the SI, overall impact results summaries can be found in table S12, impacts by percentage in table S13 and percent reductions can be found in table S14.

The reuse phase of the stainless-steel speculums is graphed separately in figure 3 to allow for disaggregated visualization. The production of the nitrile gloves contributes the most to the ozone depletion impact category. The nonionic surfactant and nitrile gloves have almost equal major contribution to the respiratory effects impact category. The polyethylene used to make the protective gowning contributes the most to the fossil fuel depletion impact category.

The electricity produced from coal that is used during autoclaving contributes the most to the global warming, smog, acidification, eutrophication, carcinogens, non-carcinogens and eco-toxicity impact.
categories. For the non-carcinogenic impact category, the negative contribution arises from the soybean used in the nonionic surfactant’s manufacturing.

In summary, for the stainless-steel speculum reuse phase, the inputs that majorly contribute that are under the clinicians’ control are the nitrile gloves, the polyethylene gowning, and the nonionic surfactant. However, the electricity generated from coal, which cannot be necessarily substituted or controlled by clinicians, is dominant in almost all categories.

Uncertainty and sensitivity

Sensitivity results
A sensitivity analysis was conducted for all 10 impact categories, and Sensitivity Factors (SF) were calculated for all input categories used in the 6 scenarios considered in this study. For the stainless-steel speculum product system, as illustrated in SI, the steel production is overall the most sensitive impact. Steel production is very sensitive in the ecotoxicity, respiratory effects, carcinogenics and non-carcinogenics categories. It is also sensitive, to a lesser extent, in the global warming, smog and acidification categories. Meanwhile tap water use, if increased, had the least impact on outcome of all environmental impacts.

In the case of the nitrile gloves, there is sensitivity in the ozone depletion impact category, which is significant as the nitrile gloves are the dominant input in the ozone depletion impact of the stainless-steel speculum system and is in fact what makes the reusable speculums have more total impacts in the ozone depletion category when compared with the disposable acrylic speculum. For the polyethylene gowning production, the most sensitive impact category is fossil fuel depletion which is of concern since the gowning is the dominant input in the fossil fuel depletion impacts of the stainless-steel reuse phase. For the electricity inputs the most sensitive is the electricity coming from hard coal. This is also significant as electricity from coal is the dominant input in all the use phase impact categories of the stainless-steel speculum system except in the ozone depletion, respiratory effects, and fossil fuel depletion categories. For the stainless-steel recycling scenario, the fossil fuel depletion impact category is sensitive in all inputs, this is due to the credit (negative values) of recycling.

For the acrylic speculum, the injection molding for making the acrylic speculums is sensitive in ozone depletion, eutrophication, ecotoxicity, non-carcinogenics and respiratory effects impact categories. The PMMA production is sensitive in all impact categories except ozone depletion. Overall, the most sensitive of the waste management alternatives for the acrylic speculum is the recycling of the polypropylene grip used to hold the speculum in place. However, the most sensitive input for the acrylic speculum system overall belongs to the recycling of the acrylic speculum itself. This is due to the negative values (credits) in each impact category caused by the recycling of the speculum.

Further information of sensitivity results can be found in the SI in figures S1 thru S7.

Uncertainty results
The uncertainty analysis was conducted using Monte Carlo simulations on SimaPro 8.5.2.0. The upper and lower bounds of these results are incorporated into the environmental impacts results graphs observed in figure 4. Values of results presented in figure 4 are provided in SI in Table S25 through Table S34.

Discussion

Given the healthcare sector’s environmental impacts, clinicians are considering sustainability more in their operations and decision making. As an outcome, studies that analyze reusable versus disposable medical device configurations are becoming more prominent.

A (LCA) that compared the carbon footprint of reusable stainless-steel speculums with disposable acrylic speculums has been performed in the past (Donahue et al 2020). Other medical devices have been compared in reusable versus disposable configurations. These include laryngoscopes (Sherman et al 2018), ureteroscopes (Davis et al 2018), sets of lumbar fusion surgery instruments (Leiden et al 2020), bedpans (Sorensen and Wenzel 2014), blood pressure cuffs (Sanchez et al 2020), and anesthetic equipment (McGain et al 2017). However, these devices vary in their complexity, for example the speculum has low complexity while the set of lumbar fusion surgery instruments is highly complex with multiple parts. In addition, the devices vary in their invasiveness/risk, for example a reusable bedpan has a lower risk whereas the set of lumbar fusion surgery instruments is highly invasive by coming into contact with internal tissues (high risk). Thiel et al (2015) analyzed the environmental impacts of various types of hysterectomies, a procedure common in gynecological care, and concluded that single use disposable materials contributed a majority of environmental impacts in almost all environmental impact categories, especially through the production impacts of these materials. However, in the case of reusable devices most of the impacts are driven by the cleaning and disinfection employed (McGain et al 2012, Donahue et al 2020). For example in the case of the blood pressure cuffs the GHG emissions are dominated.
by the production of the disinfection wipes used (Sanchez et al 2020). The loading practices when using autoclaving for disinfection can yield differing outcomes, if loading at equal or less than two thirds of the autoclave capacity, the disposable alternative may be favored, as was the case with disposable dental burs (Unger and Landis 2014).

**Comparison with existing literature**

The results of our LCIA quantify all reusable stainless-steel scenarios as having less global warming impacts than all three disposable acrylic scenarios, especially as the lifetimes are projected into the future. The carbon
footprint speculum study conducted by Donahue et al (2020) found that reusable speculums made of stainless steel 304 grade have a lower carbon footprint, followed by stainless steel grade 316 and the acrylic speculum having the highest impact. Through breakeven analysis, Donahue et al (2020) conclude that the acrylic speculum breaks even in the carbon footprint impact at 2 uses with the stainless-steel grade 304 and with the stainless-steel grade 316 at 3 uses. This is comparable to our results where we found that in the global warming impact category, if incinerated, the acrylic speculum breaks even with all stainless-steel scenarios in the 3rd use. If the acrylic speculums are recycled or landfilled they break even with all stainless-steel scenarios in the 4th use. The authors incorporated transportation which accounted for 14% of the global warming impact. When adjusting for our exclusion of the sterilization, the smaller speculums considered in our study and scaling to 5000 disposable speculums (our study’s functional unit) the global warming found by Donahue et al is 2,315 kg CO₂ eq. This result is comparable to the results obtained for the scenario of the acrylic speculum disposed in landfill in our study which totals 2,215 kg CO₂ eq. We have selected this scenario to compare with Donahue et al, as they use the Waste Reduction Model (WARM) (Waste Reduction Model WARM 2019) model and most waste in the US is landfilled (US EPA 2017). In their paper Donahue et al, determine that if reusable speculums had been employed in the clinic, assuming 100 reuses, there would have been global warming savings of 75%. In the case of the stainless-steel reusable speculum systems Donahue et al, obtain higher values for the carbon footprint (1,072 kg CO₂) versus the value we obtained for global warming potential, 443.41 kg CO₂ eq. Total impact differences may be due from differences in weight of the stainless-steel speculums modeled, material assumptions for the stainless steel composition, the disinfectant chemicals considered in their study, the inclusion of the pouch used in autoclaving which the clinic we study does not employ, different autoclave loading rates and our energy use is lower since the primary data we collected has electricity use at a lower value than the one modeled in Donahue et al (2020). We more specifically suspect that the differences arise in that Donahue et al utilizes a high-level disinfectant that could be the source of the higher environmental impacts. In addition, they consider a finishing process for the speculum that we did not consider, as we considered a coating/enameling for the stainless-steel speculum manufacturing. There is also the use of a Ecoinvent 2.2 in Donahue et al while we used Ecoinvent 3, this may be less significant since many inventory categories in Ecoinvent 3 were copied over from Ecoinvent 2. It is expected that more variability be found in the stainless-steel speculum scenarios as there are more difference in the use phase and the practices employed at particular locations. Donahue et al (2020) compared three product systems comparable to the two product systems considered in this study. However, Donahue et al focus on carbon footprint whereas in our study we consider the ten TRACI impacts. If focus is made on the global warming potential impacts obtained in our study which is analogous to carbon footprint, the same conclusion that the reusable stainless-steel speculum performs better is reached.

Significance of our findings
In our study the only impact category where the reusable stainless-steel speculums had more impact is in the ozone depletion category. In this category, the impacts are driven by the PPE used during stainless steel reusable speculums disinfection, specifically the nitrile gloves used, a possible area of improvement. In the case of fossil fuel depletion, the polyethylene gowning contributes the most to the use phase of the stainless-steel speculum. However total fossil fuel depletion impacts are higher for the acrylic speculum scenarios, but clinicians could address the type of gowning employed during disinfection if they wish to improve overall performance of the reusable stainless steel speculum system. In the respiratory effects impact category, the nonionic surfactant and nitrile gloves have an almost equal majority contribution. However, the total respiratory effects of the stainless-steel speculum system are less than the acrylic speculum alternatives. For all other environmental impact categories, the input that contributes the most is electricity used in the autoclave that is generated with coal. This is more difficult to address from a clinician standpoint as it is not directly controlled by the clinician. There is variability in the results of the various studies that compare reusable versus disposable devices in a medical setting. As observed, there is no determinate answer that one system configuration will always perform better across all of the environmental impact categories considered. The best option depends on the product systems analyzed, on the type of device themselves and the environmental objectives.

Patient safety considerations of reusable speculums
Although the vagina is not a sterile environment, there are instances where a sterile speculum is needed, such as during an IUD placement. But for many instances of pelvic speculum use, sterility is not needed. This does not mean that there is no need for sterilization after use. Through the autoclaving process the speculums are sterilized with steam, once they are removed from the autoclave if they are not inside a pouch, they remain clean but not sterile. Nosocomial infections are a risk if sterilization is insufficient and/or ineffective. Documenting and finding the culprit of a nosocomial infection is difficult, but, authors have analyzed this (Southworth 2014).
Studies have also analyzed the effectiveness of sterilization with autoclave. Panta et al. (2019) conducted a literature review and found various studies that analyze the effectiveness of autoclaving, most of the studies are for dental offices and there are very little studies in general healthcare facilities. Panta et al. (2019) find that the documented cases of sterilization failure are due to a variety of reasons, ranging from staff, management, equipment and/or the processes themselves (Panta et al. 2019).

Waste management alternative considerations
In our study, recycling was considered as a hypothetical waste management scenario. Used speculums do not technically constitute medical waste. The US EPA and state regulations address the degree or amount of contamination that would constitute characterizing a discarded waste from a medical facility as medical waste and not municipal solid waste (MSW). A speculum is a medical device that is no more dirty than a used condom or discarded feminine hygiene product, where we could argue that it can be discarded as municipal solid waste. Under the Wisconsin definition, in the Wisconsin Department of Natural Resources (WDNR) webpage it is stated that ‘items soiled or spotted, but not saturated, with human blood or body fluids, such as gloves, gowns, dressings, bandages, surgical drapes and feminine hygiene products’ are not considered infectious waste as per s.287.07(7)(c)1.c and is therefore not considered medical waste so long as it is not mixed with infectious waste. According to the WDNR, the items that come from a medical facility but are not medical waste or infectious waste should be reused or recycled (Wisconsin’s Infectious Waste Regulations | Wisconsin DNR 2021.). For this reason we are including recycling scenarios in case this alternative becomes more viable in the near future. The US EPA lists some of the potential alternatives to incineration of medical waste, which has become less frequent since more stringent regulations were put in place. These alternatives are other types of thermal treatment, steam sterilization, electropyrolysis, and chemical mechanical systems (US EPA 2016). But the speculum is technically not medical waste, therefore recycling could potentially be an alternative waste management route for the discarded speculums. However, recycling PMMA is difficult as there are no effective recycling systems for PMMA (Kikuchi et al. 2014), this would need to be addressed in order to recycle this waste stream.

Other considerations when recommending a speculum alternative
An important consideration to take is ease of use when working in more spartan locations and conditions. Lack of access to potable water or an unreliable electrical grid may make the reusable stainless-steel speculums less desired. For example, when serving an underserved population with a mobile clinic or in mobile clinics serving women in the armed services, it may be more practical to use the disposable speculums (Jones et al. 2013). However, mobile clinics could dock in a central location where disinfecting equipment could be available. Conversely, problems in accessing a reliable supply chain may make the acrylic speculum more difficult to consider. Considering a more contemporary topic, due to shortages in personal protective equipment (PPE) (Burki 2020, Ranney et al. 2020) and low volume of clinic patients caused by the COVID-19 pandemic, the UW-Madison clinic decided to use the disposable acrylic speculums for the duration of the shortage instead of reusable speculums due to the autoclave process for disinfection requiring the use of face shields, gowns and gloves by staff. There are possibilities to address the lack of disposable PPE. Reusable PPE could be considered such as washable gowns and reusable protective face masks. Disposable PPE reprocessing is an alternative that is being studied with increasing frequency due to the COVID-19 pandemic and design of more sustainable disposable PPE is a possibility (Rowan and Laffey 2021). However, many of the existing disinfecting technologies may not be suitable for reprocessing (Rowan and Laffey 2020). This decision lines up with what clinicians applied during the most critical supply chain shortages of the COVID-19 pandemic (Khot 2020). In the future, other considerations may come into play and shift the preference towards one system depending on needs. To make medical sustainability equitable, a holistic assessment of needs and accessibility is to be considered when making decisions and recommendations.

Conclusion

It is estimated that the health care sector generates around 10% of GHG emissions in the US. These emissions along with other environmental impacts from health care are detrimental to human health. Medical devices in disposable and reusable configurations have been compared as part of the efforts to increase the sustainability of healthcare. Through this work the impacts of stainless-steel speculums versus disposable speculums used in pelvic exams were calculated and analyzed through an LCA approach. All scenarios of the stainless-steel speculum system have less impacts in five TRACI 2.1 impact categories while acrylic scenarios outperformed stainless steel in one impact category, ozone depletion. Lastly, in four impact categories the results for which system had less impacts were inconclusive as there was overlap in the uncertainty of the impacts. Through breakeven analysis we found that the acrylic speculum surpasses global warming impacts of the stainless-steel speculum system.
speculums in the 3rd and 4th use. Our functional unit considers reusing each speculum 50 times in a year, meaning that the stainless-steel speculum would have less global warming impacts than acrylic in four weeks’ time or less in circulation at the UW Madison campus clinic. In the case of the acrylic speculums, the recurring expense of procurement should be considered, for the reusable speculums there are cost considerations as the disinfection requires labor from staff, which are outside the scope of this study but may be considered during implementation. Also, there may be increases in water use/footprint, which the TRACI method employed in this LCA study is not able to capture in its environmental impact categories. A water footprint analysis can be considered in the future to refine these results. Supply issues should be considered to increase resiliency of clinics, as was observed during the pandemic, PPE shortages caused the clinic to use disposable acrylic speculums since disinfection for reusables required use of PPE to protect employees. The optimal system recommended will depend on environmental objectives, accessibility to resources and supply chain, and the needs of the community and the clinic.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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