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Comparative Life Cycle Assessment of Reused Versus Disposable Dental Burs

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COMPARATIVE LIFE CYCLE ASSESSMENT OF REUSED VERSUS DISPOSABLE DENTAL BURS

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ABSTRACT

Healthcare infection control has led to increased utilization of disposable medical devices, which has subsequently led to increased adverse environmental effects attributed to healthcare and its supply chain. In dental practice, the dental bur is a commonly used instrument that can either be reused or used once and then disposed. To evaluate the disparities in environmental impacts of disposable and reusable dental burs, a comparative life cycle assessment (LCA) was performed. The comparative LCA evaluated a reusable dental bur (specifically, a 2.00mm Internal Irrigation Pilot Drill) reused 30 instances versus 30 identical burs used as disposables. The LCA methodology was performed using framework described by the International Organization for Standardization (ISO) 14040 series. Sensitivity analyses were performed with respect to ultrasonic and autoclave loading. Findings from this research showed that when the ultrasonic and autoclave are loaded optimally, reusable burs had 40% less of an environmental impact than burs used on a disposable basis. When the ultrasonic and autoclave were loaded to 66% capacity, there was an environmental breakeven point between disposable and reusable burs. Eutrophication, carcinogenic impacts, non-carcinogenic impacts, and acidification were limited when cleaning equipment (i.e., ultrasonic and autoclave) were optimally loaded. Additionally, the bur's packaging materials contributed more negative environmental impacts than the production and use of the bur itself. Therefore, less materially-intensive packaging should be used. Specifically, the glass fiber reinforced plastic casing should be substituted for a material with a reduced environmental footprint.

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LIST OF ABBREVIATIONS

Abbreviation	Name
ELCD	European Reference Life Cycle Database
FDA	Food and Drug Administration
GAO	Government Accountability Office
GHG	Greenhouse Gas
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
US	United States
USLCI	United States Life Cycle Inventory Database

1. BACKGROUND

The healthcare system in the US and its impact on the environment is gaining attention; it was estimated in 2009 that direct and total CO_2 emissions attributed to healthcare were approximately 253 and 545 million metric tons, respectively, which equates to 4.6% to 9.9% of the total US GHG emissions (Chung & Meltzer, 2009; EPA, 2009). In 2008, 73 billion kWh of electricity was used to support the healthcare system (WHO, 2008); and in the same year, four billion pounds of medical waste was sent to landfills and incinerators (DiConsiglio, 2008). Notably, there is also an inherent need for the healthcare industry to limit its potential for negative human health and environmental impacts caused by its consumption of goods and services, such as electricity as well as from the waste that it produces.

To date, sustainability efforts that focus on healthcare are limited (Kwakye, Pronovost, & Makary, 2010). For instance, the majority of sustainability efforts in healthcare have manifested as recycling (i.e., paper, plastic) initiatives, healing gardens, or programs that eliminate hazardous waste. While these programs are beneficial to healthcare's environmental profile, their impacts are not far-reaching. More significant environmental impacts can be achieved if sustainability efforts focus on the most inefficient elements related to healthcare.

Healthcare supply chains and their high utilization of single-use (i.e., disposable) medical devices is one of healthcare's most apparent inefficiencies (Kwakye et al., 2010; F. McGain, Sussex, O'Toole, & Story, 2011). Disposable medical devices became popular in the 1960s when concerns about pathogenic cross-contamination through device reuse were increasing (Greene, 1986). Even today, many healthcare providers cite infection liability as the principal reason for not electing to reuse their devices (GAO, 2008).

However, more studies are showing that the use of disposable devices do not correlate with a reduced infection risk (Favero, 2001; GAO, 2008). The Government Accountability Office (GAO) concluded in 2008 that "[the] FDA's analysis of reported device-related adverse events does not show that reused SUDs [single-use devices] present an elevated health risk" (GAO, 2008). This conclusion is based on the FDA's review of available adverse health events reported with reused SUDs, where no causative link was found between the adverse health events and use of reused devices. Accordingly, healthcare providers have recently responded favorably towards medical device reprocessing, as the number of US healthcare facilities who reprocess their medical equipment has risen by approximately 10% in the past five years (GAO, 2008).

2. Reducing Environmental Impacts through Reuse

Recent studies are showing that utilization of single-use medical devices is increasingly considered to be materially and economically wasteful (Hailey, Jacobs, Ries, & Polisena, 2008; Rutala & Weber, 2001; Shuman & Chenoweth, 2012; Suter, Yueng, Johnston, & Suter, 2009). Therefore, reusing SUDs represents a pathway that can decrease healthcare's adverse environmental impacts. Through cradle-to-grave life cycle assessments (LCAs), the environmental impacts of a product over the product's entire lifetime can be determined. Healthcare LCA studies are relatively new and they offer unique insights that have not been fully developed. Additionally, although hundreds of devices are Food and Drug Administration (FDA)-eligible for reuse, LCAs published on healthcare products or devices are limited. These LCAs have studied healthcare products such as LMAs, medical waste containers, and catheter insertion kits (Eckelman, Mosher, Gonzalez, & Sherman, 2012; Forbes McGain, McAlister, McGavin, & Story, 2012; Overcash, 2012). In addition, others have utilized the LCA methodology to investigate hospital procedures, such as hysterectomies and C-sections (Bilec, Landis, Shrake, Thiel, & Woods, 2012; Campion et al., 2012). With regards to the LCAs on medical products, they have shown that reprocessed medical devices are environmentally favorable over disposable medical devices (Hailey et al., 2008; Rutala & Weber, 2001; Shuman & Chenoweth, 2012; Suter et al., 2009). It should be noted, however, that these results are predicated upon proper execution of reuse protocols and procedures (Hailey et al., 2008; Rutala & Weber, 2001; Shuman & Chenoweth, 2012; Suter et al., 2009).

3. TECHNOLOGY DESCRIPTION

In dental practice, the dental bur is a commonly used instrument that is used to: remove tooth decay, shape tooth structure, and drill cavities in teeth of a specific diameter and depth (where anchors that secure dental implants subsequently fill the cavities made by the dental burs). Dental burs are used in high quantity because nearly every dental procedure involves any number of the previously stated dental bur uses (Nathe, 2007). A typical dental bur is shown in Figure 1, which is a MIS Implants Technologies Ltd 2.00mm Internal Irrigation Pilot Drill; where, the 2.00 mm Internal Irrigation Pilot Drill was the bur used in this study’s analysis.

Figure 1: **Diagram of 2.00mm Internal Irrigation Pilot Drill**

Dental burs are suitable candidates for reuse in dental offices because: burs are able to be reused up to 30 instances (particular to this study); burs are materially intensive; the processes that define a reused bur and the processes defining a disposable bur are entirely different; the rate and effectiveness of reuse is variable based on either personal beliefs towards reuse, or lack of reuse protocols; and, burs are widely utilized in all dental offices across the US (Nathe, 2007).

Dental bur data was obtained from Deer Valley Smiles located in Phoenix, Arizona. Deer Valley Smiles indicated that reuse of dental burs is not consistently utilized in the dental community, and that infection liability is perhaps the most prominent reason for not reusing dental burs. Other, less-cited reasons for not reusing dental burs include: increased labor associated with reuse, decrease in bur efficacy (i.e., sharpness, width) as reuse instances increases; and, the fact that insurance will not cover any portion of a dental bur’s costs.

However, as stated earlier, more FDA studies are showing that reusing medical instruments does not present a significant risk for nosocomial infection; which has alleviated many healthcare providers’ concerns regarding disposable devices, as rates of reused medical devices has risen in recent years (GAO, 2008). And because dental burs are used in high quantities and are relatively costly, it is possible for dental practitioners to reduce both their environmental footprint and bottom-line costs if they reuse their dental burs.

To evaluate the environmental and economic trade-offs between reused dental burs and dental burs used as disposables, this study performs a comparative LCA of reused and disposable stainless steel dental burs.

4. Scope, System Boundary, and Inventory Analysis

A comparative life cycle assessment was conducted for reused dental burs and single-use dental burs. The LCA methodology was performed using the framework described by the International Organization for Standardization (ISO) 14040 series. System boundaries are illustrated in Figure 2, which depicts the cradle-to-grave aspects of both single-use and reused burs, including: extraction of raw materials, manufacturing, packaging, use, reuse, and disposal. The LCA system boundaries did not include the production of the autoclave or the ultrasonic cleaning device, since it has been shown that these types of equipment have negligible contribution to the overall outcome of LCAs (Hailey et al., 2008; Rutala & Weber, 2001; Shuman & Chenoweth, 2012; Suter et al., 2009). The functional unit was defined as one reusable dental bur, where the maximum number of uses was 30 (or in the case of a SUD, the equivalent functional unit would be 30 disposable dental burs).

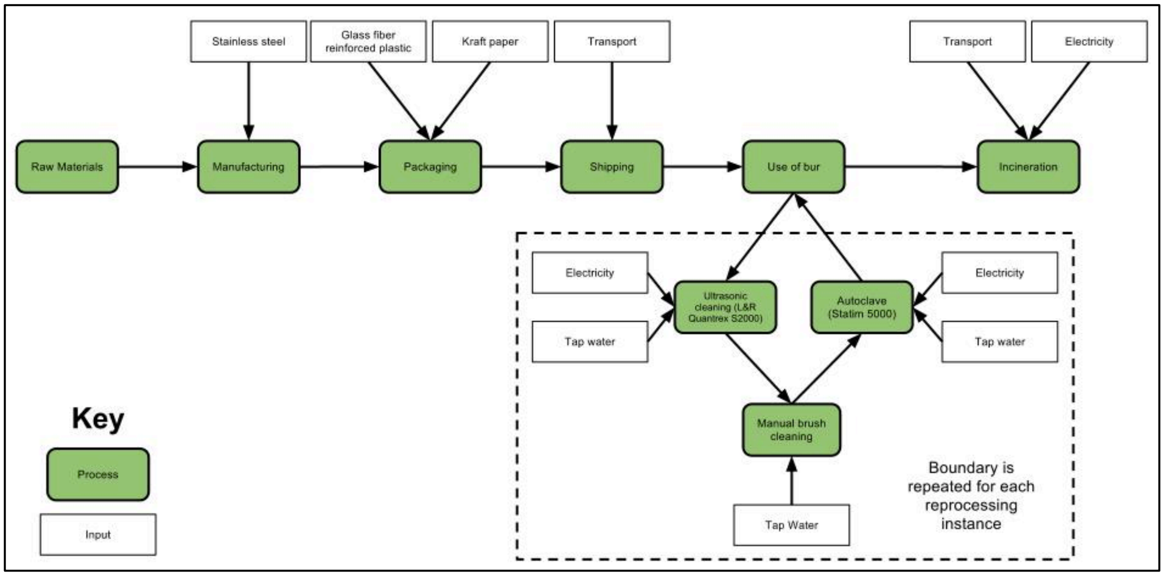

Figure 2: **System boundary showing processes included in the LCA.** (Caption text:) While not shown, the system boundaries include energy, materials, and emissions associated with each process.

Life Cycle Inventory (LCI) data were collected from different sources. Primary data were collected directly from the practices of the Deer Valley Smiles dental office. This primary data included: operating parameters for the ultrasonic cleaning such as volume of water used and energy consumed per cleaning; parameters for the manual washing including volume of water used; and operating parameters for the autoclave including water and energy used. To the extent possible, primary data was also collected from publicly available information from dental bur manufacturers. The secondary data for raw materials extraction and production of materials such as the dental bur, electricity, and packaging were obtained directly from life cycle inventory databases including: ecoinvent v2.2, and USLCI (United States Life Cycle Inventory), and ELCD (European Reference Life Cycle Database). Other secondary information (i.e., bur specifications, disposal methodologies) were obtained directly from their respective manufacturers or service provider. The LCI data is described in more detail in subsequent sections.

Certain operating parameters were specific to the Deer Valley Smiles dental office. These operating parameters included: form and method of reuse, instances reused per dental bur, and method of disposal. One model of dental bur is analyzed: the MIS Implants Technologies Ltd 2.00mm Internal Irrigation Pilot Drill. Material composition of the bur was determined from manufacturer information (MIS, 2013). The burs and their packaging were weighed using an analytical scale with a 0.01 gram detection limit. These weights are shown in Table 1. The materials and production processes were identified within the corresponding life cycle inventory records from the ELCD (European Reference Life Cycle Database) and USLCI (United States Life Cycle Inventory Database). The data used to construct the bur's life cycle inventory is shown in Table 2.

Figure 3: **Bur packaging materials**
(Caption text:) From Left to Right: Kraft Paper, Glass Fiber Reinforced Plastic, Kraft Paper

Table 1: **Weights of bur components**

Component	*Weight*
Stainless steel	1.05 grams
Glass fiber reinforced plastic	2.51 grams
Kraft paper	8.02 grams

Table 2: **Inventory data used to construct the dental bur life cycle inventory**

Material/Process	*Amount*	*LCI Database*	*Use*
Stinless steel hot rolled coil, annealed & pickled, elec. arc furnace route, grade 304, average European production mix	1.05 g	ELCD 3.0	Bur
Glass fiber reinforced plastic, polyamide, injection moulding, at plant, average European mix	2.51 g	ecoinvent v2.2	Packaging
Kraft paper, unbleached, at plant, average European mix	8.02 g	ecoinvent v2.2	Packaging
Transport, combination truck, average European fuel mix	0.7 tkm	ecoinvent v2.2	Transport
Transport, aircraft, freight, average European mix	0.01 tkm	ecoinvent v2.2	Transport
Tap water, at user, average European mix	5.8 kg	ecoinvent v2.2	Autoclave
Electricity, average US production mix	0.331 kWh	ecoinvent v2.2	Autoclave
Tap water, at user, average European mix	5.2 kg	ecoinvent v2.2	Ultrasonic
Electricity, average US production mix	0.172 kWh	ecoinvent v2.2	Ultrasonic
Transport, combination truck, average US fuel mix	0.0003 tkm	USLCI	Disposal
Disposal, steel, 0% water, to municipal incineration, average Chinese mix	8.7% of waste	ecoinvent v2.2	Disposal
Disposal, inert waste, 0% water, to inert material landfill, average Chinese mix	91.3% of waste	ecoinvent v2.2	Disposal

(Caption text:) ELCD: European Reference Life Cycle Database; USLCI: United States Life Cycle Database Inventory

Specific to this study, the burs were manufactured in Minden, Germany where the burs were transported via combination of transport truck and freight aircraft to the dental office in Phoenix. The burs were transported roughly a distance of 700km by transport truck from Minden, Germany to Paris, France. The burs were then transported roughly 8800km by freight aircraft from Paris, France to Phoenix, Arizona. Lastly, the burs were transported a distance of 35km from the Phoenix airport to the dental office. These distances were calculated using Google Earth v7 software. Upon arrival at the dental office, the burs were opened by the dental technicians, with the packaging materials (described in Table 2) being discarded into the municipal solid waste stream.

During use, the burs were inserted into a dental handpiece which rotated the bur at high speeds ranging up to 400,000 rpm (Franzel, 2007). This process only involved energy input, as the handpiece was plugged directly into a standard US socket. The electricity consumed during bur use was not included in the analysis because the utilization of burs was identical for reused and disposable burs.

The burs required sterilization in order to be reused. First, excess debris was removed using an ultrasonic cleaner. After ultrasonic cleaning the burs were manually cleaned under tap water with a scrubbing brush. Lastly, the burs underwent autoclaving.

Ultrasonic cleaning prior to autoclaving is typical for many reusable dental instruments (Nathe, 2007). At the Deer Valley Smiles office, the reusable burs were placed into an L&R Quantrex S200 Ultrasonic cleaner (6,885cm^3 capacity) for approximately 30 minutes. The ultrasonic cleaner immersed the burs in a silver-based solvent and concurrently subjected the burs to ultrasonic waves produced by a transducer built into the device's chamber. The water element of the solvent was included in the analysis; however, silver was omitted due to lack of silver LCI data. The 30 minute time interval was recommended by the manufacturer, and was automatically controlled through the ultrasonic's integrated timer. The Deer Valley dental staff prepared, loaded, and eventually switched the ultrasonic into off-mode. The L&R Quantrex S200 Ultrasonic cleaner used at Deer Valley Smiles' office typically used 5.2L of water and 0.172 kWh of electricity. The water and electricity data were obtained from 10 independent trials, where electricity consumption was measured by a P3 International P4400 Kill-A-Watt Electricity Usage Monitor (i.e., Wattmeter) over the entire 30 minutes of the cleaning. After cleaning, the ultrasonic's water usage was measured directly by beaker. Based on capacities that ranged from 2,082 cm^3 to 24,683cm^3, Quantrex ultrasonic dental cleaners reported an energy usage ranging from 0.05 kWh to 0.41 kWh per cycle, and a water usage ranging from 2L to 26L per cycle (Company, 2013).

After a thirty-minute period in the ultrasonic cleaner, the burs were then manually cleaned with a scrubbing brush under tap water for approximately 30 seconds to one minute, and then placed into an autoclave-safe pouch. Time was measured directly as the Deer Valley Smiles staff cleaned the burs. Based on 10 independent trials measuring water usage by beaker, the median value for water used during manual cleaning was 1L.

After manual cleaning the burs underwent an autoclave cycle with a Statim 5000, Model #201103 Cassette Autoclave; where, the burs were autoclaved for 60 minutes. This time interval was based on recommended manufacturer's specifications, and was automatically controlled through the autoclave's integrated timer. Because the autoclave functioned by subjecting the burs (and other dental instruments) to high pressure saturated steam, both electricity and water inputs were associated with the autoclave's use. The manufacturer reported that the amount of water used by the autoclave in one cycle was 5.8L of water. Through direct measurement with a P3 International P4400 Kill-A-Watt Electricity Usage Monitor, the electricity requirement for one autoclave cycle was 0.315 kWh (which is summarized in Table 2). Electricity values were obtained from the average of 10 independent trials using the wattmeter to measure the autoclave electricity consumption.

In a typical autoclave cycle at Deer Valley Smiles, the autoclave load contents would consist of a range of other dental devices. On average, the autoclave was run by dental technicians either once or twice daily, with a maximum recorded daily usage being three instances. Although, the technicians indicated that three daily autoclave cycles was atypical. Additionally, autoclaves range in energy and water usage based on their respective capacities. Data provided by the manufacturer (i.e., Statim) showed that typical dental autoclaves water and energy usage ranged from 3L to 6.3L and 0.325 kWh to 0.425 kWh per cycle. Once the autoclave process was complete, the dental aid would mark (by hand) the number of instances the bur had been reused. Burs were tracked based on their assigned dentist and were disposed when they reached 30 instances of reuse.

Autoclave and ultrasonic LCA methodology are omitted from the system boundary because of complexity and lack of manufacturer data regarding material specifications of the autoclave and ultrasonic; and, because the autoclave and ultrasonic are simultaneously used with other devices not including burs. For the context of this analysis, it was assumed that autoclave and ultrasonic cycles consisted strictly of dental burs and no other dental devices. However, this practice is not typical for dental offices, as the office would simultaneously use the autoclave and ultrasonic on a variety of other dental instruments. Other instruments concurrently autoclaved with the burs included: scalpels, forceps, bone chisels, and scalers. Based on this assumption and the capacity/volume of the autoclave and ultrasonic, 30 burs could be loaded per autoclave and ultrasonic cycle.

Single-use burs and burs that had been reused 30 instances would undergo the same disposal process. When marked for disposal, the burs were placed into a general medical waste container, which typically contained other used medical items. Specific to the Deer Valley Smiles office, medical waste was handled by a medical and pharmaceutical recycling company, Stericycle. Waste for the dental office was transported 27 kilometers by truck to Stericycle's local handling facility. The burs would then undergo a medical incineration process.

Energy mixes, transportation mechanisms, and materials used were based on their respective life cycle process' location.   For example, because the bur was manufactured in Germany, a European electricity mix was utilized for the manufacturing component of the LCA. However, because the autoclave and ultrasonic are used in Phoenix, Arizona, the cleaning equipment LCI data utilized a US energy mix. Additionally, it was assumed that a European transport truck was used to transport the burs from Minden Germany (the point of manufacture) to the nearest international airport located in Paris, France. From Paris the burs were transported by a European aircraft to Phoenix, Arizona, where they were finally transported by a US-made transport truck to the Deer Valley Smiles dental office in Phoenix, AZ

The Life Cycle Impact Assessment (LCIA) was conducted using the TRACI v2.0 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) developed by the USEPA (EPA, 2013). The following environmental impacts were calculated and reported from TRACI: ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, and ecotoxicity.

5. Sensitivity Analyses

The results were divided into three scenarios: best-case, breakeven, and worst-case. These scenarios were derived based on ultrasonic and autoclave sensitivity analyses. The sensitivity analyses varied bur-loading of both the ultrasonic and autoclave. Because burs required sufficient distribution such that they were not touching and not stacked, the maximum assumed load for the ultrasonic and autoclave was 30 burs and was considered the best-case scenario. This was considered best-case because the ultrasonic and autoclave were most efficiently utilizing electricity and water relative to the number of burs being cleaned. To achieve the breakeven scenario of 20 burs, the loading capacity (in number of burs) was adjusted until four TRACI impact categories favored reusable burs, and four TRACI impact categories favored disposable burs. Lastly, the worst-case scenario of 10 burs per cycle was derived directly from personal consultation with the studied office's dental aides, who claimed that 10 was the lowest number of burs they had used in a single ultrasonic/autoclave cycle.

6. Results

Environmental impacts for disposable versus reusable burs varied depending on autoclave and ultrasonic loading. When the autoclave and ultrasonic were loaded to their highest capacities (i.e. 30 dental burs), reusable burs were environmentally favorable over single-use dental burs according to all nine TRACI impact categories (Figure 4). In this case, reused burs exhibited 33% less impacts in the following LCIA categories: ozone depletion, smog, respiratory effects, and ecotoxicity. In all nine of the impact categories, reused burs had less than a 61% overall impact than single-use burs. The global warming impact is characterized by CO_2 equivalent (eq) emissions, which is 1.19 kg CO_2 -eq and 0.42 kg CO_2 –eq for disposable and reused burs, respectively. Both the ultrasonic and autoclave were limited in their respective impacts because of their high operating efficiency. Glass fiber reinforced plastic used in bur packaging was a significant contributor to most impact categories, including: ozone depletion, global warming, eutrophication, and ecotoxicity. Bur disposal was also is the highest driver in acidification, and was significant in all impact categories.

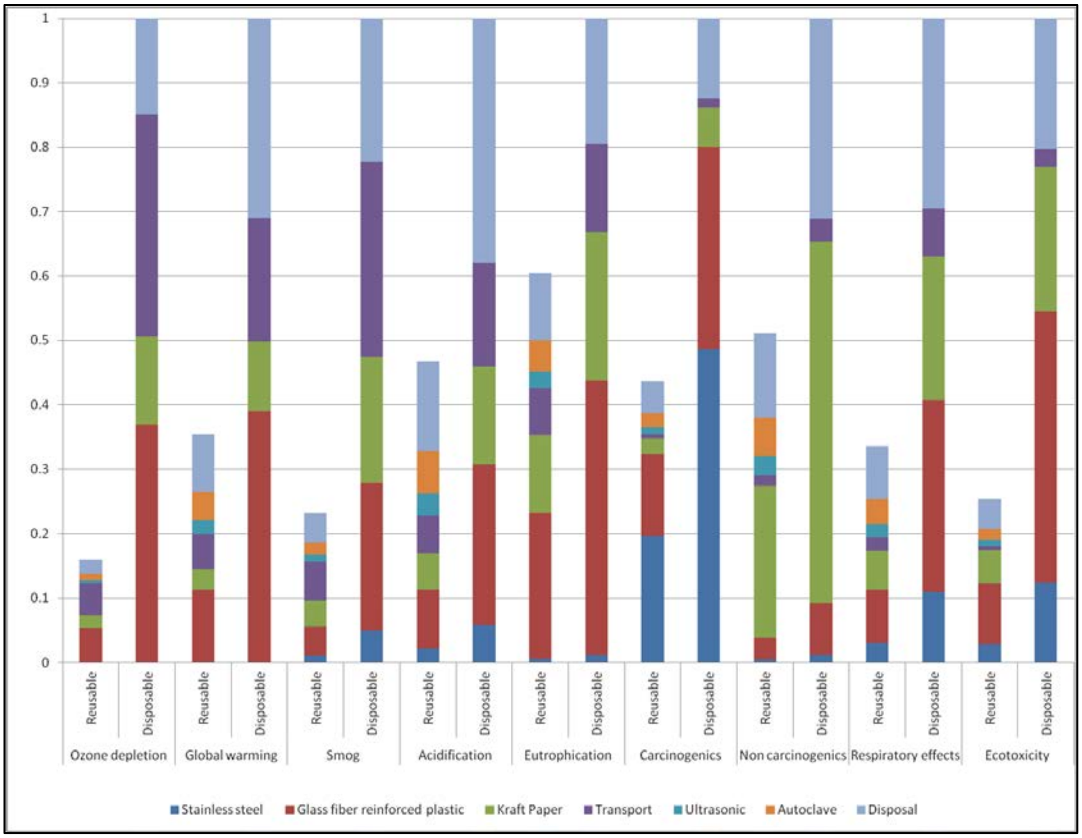

Figure 4: **Best-case scenario for 30 disposable burs versus 1 bur reused 30 instances**
(Caption text:) Impacts normalized to disposable burs; best case scenario represents autoclave and ultrasonic cleaning filled to highest capacity, or, 30 burs. Each entry in the legend represents the upstream data required for each process (e.g. 'Ultrasonic' includes water and electricity for operating the device).

These results in Figure 4 represent the best case scenario, and were associated with the ultrasonic and autoclave being used to their most effective extent. Effectiveness was based on their respective loading capacities, which were both assumed to be 30 burs per autoclave and ultrasonic cycle.

Figure 5 represents a breakeven scenario, which was determined as the sterilization load where reuse performed better than single use in four out of the nine TRACI LCIA categories. The breakeven scenario resulted in the ultrasonic and autoclave being loaded to 66% capacity, where 20 burs were loaded into the autoclave and ultrasonic per cycle. These impact categories include: acidification, eutrophication, carcinogenic, and non-carcinogenics. The global warming impact category values for reusable and single-use burs were similar, where they showed greater than 99.5% comparability (1.19 kg CO_2 and 1.18 kg CO_2 emitted for disposable and reusable, respectively). This was considered a breakeven scenario because four impact categories favored reusable burs (i.e., ozone depletion, smog, respiratory effects, exotoxicity), and four impact categories environmentally favored disposables (i.e., acidification, eutrophication, carcinogenics, and non-carcinogenics), and the final impact category, global warming, was nearly identical for reusable and disposable burs.

The breakeven scenario shown in Figure 5 represents a situation where the ultrasonic and autoclave increased considerably in their respective impact. The autoclave was the most significant driver in impact categories including: global warming, acidification, non-carcinogenics and respiratory effects.

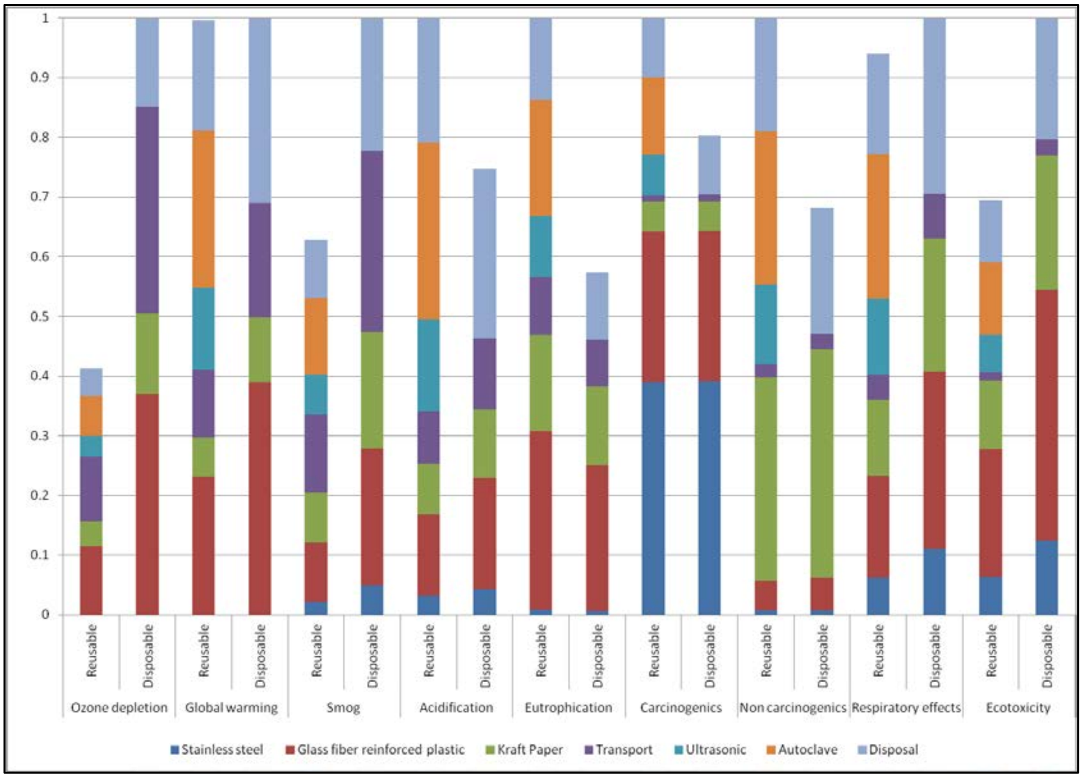

Figure 5: **Breakeven scenario for 30 disposable burs versus 1 bur reused 30 instances** (Caption text): Impacts normalized to the highest impact in each category; breakeven scenario represents the ultrasonic and autoclave being loaded to 66% capacity, where 20 burs are loaded into the autoclave and ultrasonic per cycle. Each entry in the legend represents the upstream data required for each process (e.g. 'Kraft paper' includes raw materials extraction, paper production, manufacture, and assembly of packaging).

Figure 6 illustrates what is considered a "worst-case scenario" for reusable dental burs. Figure 6 represents a situation where the ultrasonic and autoclave were used at 33% capacity, or 8 burs loaded per cycle. In eight of nine TRACI impact categories, reusable dental bur posed more negative environmental impacts than disposable burs. The largest disparity existed in the eutrophication impact category, with over a 60% differential. This situation was not ideal, as the ultrasonic and autoclave were utilized at particularly low operating efficiencies.

The worst-case scenario shown in Figure 6 is characterized by high autoclave impact. With the exception of carcinogenics, the autoclave was the most significant driver in all of the impact categories. And while fairly negligible in the best-case and breakeven scenarios, the ultrasonic was significant in many of the impact categories.

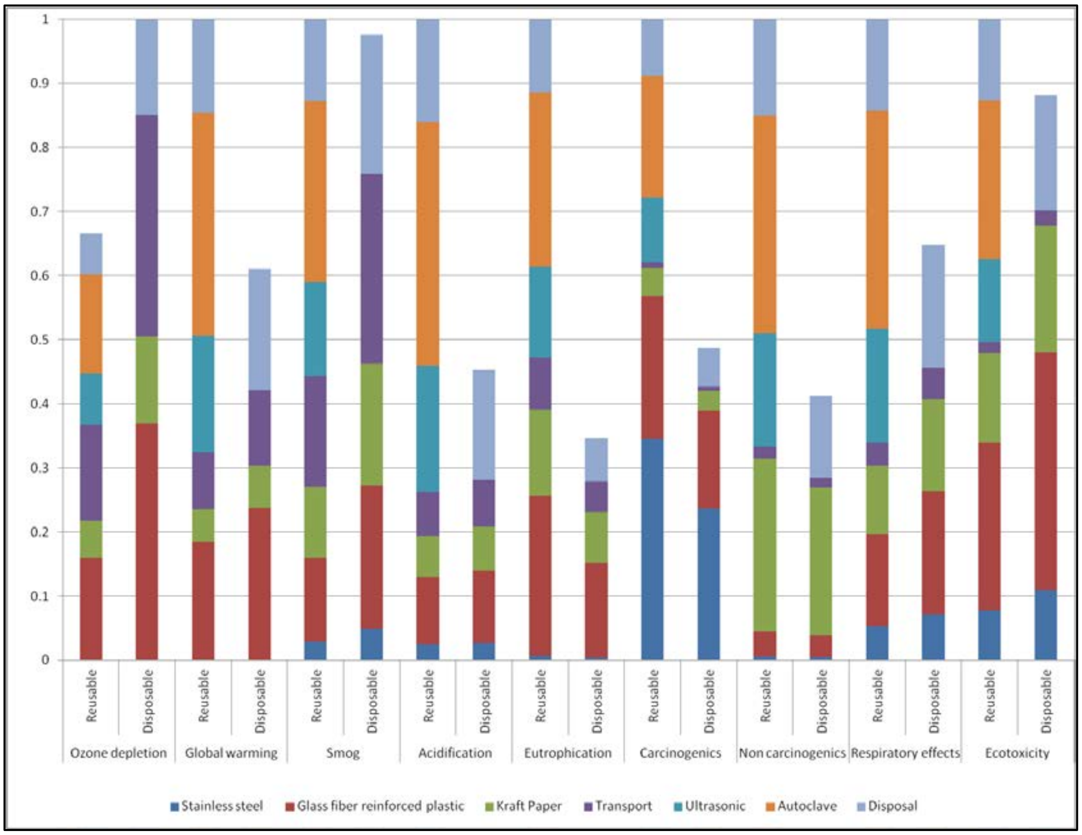

Figure 6: **Worst-case scenario for 30 disposable burs versus 1 bur reused 30 instances**

(Caption text): Impacts normalized to the highest impact in each category; worst-case scenario represents the ultrasonic and autoclave being loaded to 33% capacity, where 10 burs are loaded into the autoclave and ultrasonic per cycle. Each entry in the legend represents the upstream data required for each process (e.g. 'Glass fiber reinforced plastic' includes raw materials extraction, plastic production, manufacture, and assembly of packaging).

Note that for the bur itself, glass fiber reinforced plastic was the most significant driver for most impact categories. The glass fiber reinforced plastic was used in the packaging of the burs, where the bur was stored directly in a glass fiber cylindrical tube, which was sealed until the bur's use. In the non-carcinogenics impact category unbleached kraft paper was the driving factor. The kraft paper was also used in the bur's packaging. Transport by aircraft was significant to impact categories including: ozone depletion, global warming, smog, and acidification. For other impact categories, transport was fairly negligible. Stainless steel was also not significant for many impact categories. However, stainless steel was the predominant driver for the carcinogenics impact category.

Additionally, the most significant contributor to cradle-to-gate life cycle impacts of a dental bur was the packaging, and not the bur. This was because the packaging materials compromised over 91% over the bur's weight, and because the studied dental bur had limited material requirements. In the best-case, breakeven, and worse-case scenario, the packaging (i.e., kraft paper and glass fiber reinforced plastic) contributed 44.4%, 34.8%, and 28.7%, of the burs' total life cycle impacts, respectively. When the burs were used as disposables, the packaging contributed 51.9% of the burs' total life cycle impacts. These values were obtained by calculating the average of the nine LCI categories for each scenario. In the dental bur industry, many burs are comprised of varying quantities of precious metals, including tungsten carbide and diamond (Nathe, 2007). It is expected that the incorporation of such materials into the life cycle analysis would increase the environmental impacts attributed to the bur.

7. Conclusions

More geographically-specific inventory data could improve the accuracy of the results. For example, a European electricity mix (provided by ecoinvent v2.2.) was used for electricity generation in bur manufacturing. However, a German electricity mix, or even an electricity mix specific to Minden, Germany, could have given more accurate results. On the other hand, there are many dental practices in cities across the US and there are several bur manufacturers around the world. Future work might attempt to assess the average impacts from disposable dental products to evaluate representative industry standards. Additionally, all disposal methods are based on Chinese inventory records, which is due to lack of relevant US disposal life cycle inventory data. Specifically, there is no life cycle inventory database that lists disposal of steel (with 0% water) to a municipal incinerator located in the US, and there is no life cycle inventory that lists disposal of inert waste (with 0% water) to an inert material landfill located in the US.

Although the results show that optimized autoclave and ultrasonic loading are necessary for reduced environmental impacts, the drawbacks to autoclave and ultrasonic overloading should not dismissed. Previous studies have shown that overloading (in this case, more than 30 burs) of cleaning equipment is detrimental to the sterilization process (Nathe, 2007). Specifically, there is a correlation between increased residual protein levels and the extent to which the autoclave is over-filled (Nathe, 2007).

Additional sensitivity analysis regarding number of instances reused would have further illustrated the disparities in single-use versus reused dental burs. It is expected that as the number of instances of reuse decreases, the environmental impacts of reusable versus single-use devices will move closer. This would occur until instances of reuse equals zero, at which point the bur is considered a disposable. Therefore, environmental impacts decrease linearly until instances of reuse reaches 30. Upon reaching 30 instances of reuse, reuse has maximized its potential for limiting adverse environmental impacts. Future studies should include matrix analyses regarding the number of instances of reuse versus ultrasonic and autoclave loading. The analyses would further illustrate the effect of instances of reuse versus cleaning equipment loading.

This study finds that dental practitioners should reuse their dental burs in favor of using the burs as single-use disposables. Operational efficiency should be emphasized to enhance the environmental performance of reuse. Maximizing loading efficiency of the ultrasonic and autoclave is necessary for reduction of environmental impacts. In fact, improper loading of the ultrasonic and autoclave can lead to greater adverse environmental impacts than if the burs were treated as disposables.

Improvements to the environmental impact can be made by targeted improvements to bur packaging. With regards to the best-case scenario presented in Figure 6, the packaging materials proved to the most significant contributor to environmental impacts. Therefore, the next logical step after optimizing reuse protocols would be to optimize packaging. The glass fiber reinforced plastic contributed most to environmental impacts; other packaging materials or packaging methods might be able to provide similar product protection while using less material. Accordingly, future studies should especially focus on glass fiber reinforced plastic and its potential substitutes.

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