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Review Article

Reducing the Impact of Perfusion Medical Waste on the Environment

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Abstract: The U.S. healthcare system generates more than five billion pounds of waste each year. Waste disposal has become a serious environmental problem facing healthcare institutions. The operating room is the second largest source of hospital waste, and no current standards exist regarding perfusion waste reuse or recycling. A typical perfusion circuit produces approximately 15 pounds of plastic that ends up incinerated once used. Contaminated perfusion circuits consisting primarily of polyvinyl chloride (PVC) and polycarbonate are difficult to sterilize, reuse, or recycle. A literature review of Internet-based and peer-reviewed publications was conducted to identify all resources that describe sterilizing, dechlorinating, reusing, and recycling of medical-grade disposable products. There are several chemical methods available to re-harvest PVC after it has been properly decontaminated and melted down. Dichlorination by near-critical methanol shows promise in the recovery of additives such as plasticizers, stabilizers, and lubricants. The reinjection of PVC may have ecological and economic advantages. Dechlorinated PVC also creates a less toxic by-product when incinerated. Although this process is not recycling, it lessens the impact of poisonous chlorine gas release into the atmosphere. Sterilizing, dechlorinating, and recycling the perfusion circuit may be a promising avenue for reducing the ecological impact of perfusion waste. Although an economically sensitive mode of reusing, reducing, and recycling a circuit does not currently exist, this presentation will explore the perfusion waste dilemma and present potential solutions in hopes of promoting future reuse and recycling opportunities. **Keywords:** medical waste, biohazard waste, dichlorination, incineration, perfusion circuit waste. *J Extra Corpor Technol. 2020;52:135–41*

Every year, the U.S. hospital system produces more than five billion pounds of waste (1). The disposable, single-use circuits used by perfusionist are made mostly of polyvinyl chloride (PVC), a plastic that is difficult to incinerate of because of its high chlorine concentration (2), which contributes to the waste problem. As waste keeps growing and landfills keep filling, it is vital to understand the impact the field of perfusion has on the environment. To minimize waste burden, key stakeholders across the cardiothoracic surgical industry should consider the environmental harms of extracorporeal disposal and benefits of waste minimization program. These benefits of waste minimization include, but are not limited to, environmental protection and cost reduction in the long term. Such programs are not easy to implement because of initial expenses, institutional support, and industry-wide education (3). This review presents a background on infectious medical waste as it pertains to perfusionists, the current disposal methods of the extracorporeal circuit, and the innovative research that may hold the key to sustainability in the future.

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BACKGROUND

In the United States, 49–60% of medical waste is incinerated, 20–37% is autoclaved, and 4–5% is treated by other technologies (4). Incinerated infectious waste releases toxic gases into the atmosphere (5). Autoclaving is

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not always possible for plastic devices, and the remaining percentage that is otherwise treated is not currently applicable to the extracorporeal circuit (6). An average of 28.5 pounds of infectious waste is produced per cardiac surgical procedure (7), including 15 pounds of perfusion waste (8), primarily consisting of PVC and polycarbonate. This makes the operating room the second largest source of hospital waste, with no current standards in terms of perfusion waste for recycling or reuse. More than 500,000 cardiopulmonary bypass (CPB) procedures are performed annually (9) and generate 7.5 million pounds of waste in the United States per year.

The most common practice for disposal of the CPB circuit is incineration. Incineration releases carcinogenic dioxins into the atmosphere, affecting the health of the environment and the people living near incineration plants (5). One alternative to incineration is disposal in a landfill. However, landfilling biohazardous waste is against the law. Because of its hazardous properties, sanitizing PVC for reuse in other applications is expensive, although emerging research may yield additional alternatives.

One step toward sustainability may be to partner with manufacturers to establish buy-back programs for unused damaged circuits, sturdy plastic bins, and sterile caps. This may be achieved through the establishment of a recycling system in operating rooms where recycling is a priority. Recycling uncontaminated pieces of the circuit (hard plastic bins) has already begun and reduces the amount of non-hazardous waste in biohazardous bags and, consequently, the amount of incinerated plastic (10). New research suggests the possibility of chemically breaking PVC into its component parts for re-harvest as a means of recycling. Although it has not been applied to medical waste, this technology has been successful in other industries.

A review of the literature was conducted to identify current practice and present future ideas about the disposal of CPB circuits. Without any current solution to lessen the impact of perfusion-generated medical waste, this study describes what happens to a typical CPB circuit: incineration, landfilling, reuse, and recycling. Hopefully, identifying the harmful effects of incinerated and landfilled PVC will increase awareness of manufacturers, hospitals, and individual perfusionists to develop recycling and reuse methods for the components in the CPB circuit.

PUBLIC HEALTH IMPACT OF MEDICAL WASTE

A CPB circuit is mostly made of PVC. Because the PVC is in contact with blood, it is considered biohazardous waste at the end of the procedure. According to the Environmental Protection Agency (EPA) standards, biohazardous waste must be either incinerated or sterilized before disposal in municipal waste. Incineration of biohazardous waste is the most common form of disposal and poses a serious threat to the overall health of the environment.

The main environmentally harmful component of PVC is the residual chloride that is released on incineration. According to the EPA, most chlorine released into the environment is from waste PVC (11). Burning PVC releases this chloride into the atmosphere, causing acid rain (12). Although fallen out of common discourse, acid rain still negatively impacts the environment. Acid rain is defined as precipitation that, given its acidic components, affects the ecosystem, the effects of acid rain most predominantly harming aquatic environments and the organisms that live in them. As the pH declines less than 5, fish eggs cannot hatch and begin to die. Beyond the marine life itself, acid rain has a tremendous effect on plants by leaching minerals from the soil needed for trees to grow (13), leading to the death of native species and decimated ecosystems.

More dangerous than acid raid are the dioxins released on incineration of chloride-containing compounds. According to the European Union Scientific Committee for Food, humans have a tolerable weekly intake of 14 pg per kilogram of body weight of dioxins, making it the "deadliest poison of all." Compared with sarin or potassium cyanide, the dioxins released because of the incomplete combustion of PVC have lower lethal-dose 50. Lethal-dose 50 describes the quantity of a chemical that is lethal to 50% of the population, meaning PVC dioxins are more toxic than sarin or potassium cyanide because a smaller quantity is required to be fatal. Chronic exposure can lead to severe skin diseases, changes in blood and urine because of hepatic damage, and hormonal disruption (14). The World Health Organization classifies dioxins as a class I carcinogen (15). In addition, vinyl chloride, the monomer that composes PVC, is formed by chlorinated hydrocarbons. Incineration of vinyl chlorides emits carbon dioxide, carbon monoxide, hydrogen chloride, and phosgene, which affect the peripheral and central nervous systems (16).

Directly related to the disposal of perfusion waste incineration is the release of 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). TCDD is one of the dioxins released with the incomplete combustion of fossil fuels, such as the crude oil, used to make PVC. It is formed both in the synthesis and combustion of PVC (17). In animal studies, TCDD changes the endothelium in the kidneys, heart, and aorta because of aortic superoxide. Superoxide is an anionic form of oxygen, which damages the endothelium and leads to dysfunction of the cells. This dysfunction increases the risk of hypertension, stroke, increased systemic arterial pressure, and coronary artery disease (18).

Aside from the dioxins released with incineration, landfilling the incinerated waste releases phthalate and other heavy metals into the earth, such as lead, cadmium, and tin. Phthalate is the main plasticizer in PVC, making up to 40% of the final product's weight (42), and improves the PVC's flexibility which is vital to bypass tubing. The phthalates are derived from the plasticizers and stabilizers that give PVC its strength and rigidity, but, when burned, it leaches into the ground and can disrupt endocrine function (19).

CURRENT PRACTICE

Medical waste is defined differently by state law (20), but blood and blood products are always considered infectious. The South Carolina Legislature, e.g., in Chapter 93, title 44, defines infectious waste as "human blood or blood products" and states that it must be treated with "incineration, steam sterilization, chemical disinfectant, or any other department-approved treatment method" (20). Steam sterilization, often achieved with an autoclave, requires exposing items to direct steam contact of at least 121°C for 30 minutes (21). The melting point of PVC is between 100°C and 260°C (22); therefore, steam sterilization is not an option because it would melt the material. Neither current practice nor studies were identified regarding rinsing the PVC circuit with chemical disinfectants. Although rinsing with saline has been shown to decontaminate the circuit for municipal waste (8), the common practice in operating rooms is to dispose of the entire perfusion circuit into biohazard bags for incineration.

Controlled air incineration is the most common form of waste removal for hospitals and other medical institutions. First, waste is fed into a primary combustion chamber with less air than stoichiometrically needed for combustion and burned at a relatively low temperature (760–980°C). Incineration occurs at .6–50 kg/min. The second stage of combustion occurs when excess air is added, which mixes with the volatile gases formed from the first stage, increasing the temperature from 908°C to 1,095°C. This type of incineration releases pollutants into the atmosphere, including acid gases, oxides of nitrogen, hydrochloric acid, and other harmful organic compounds (23).

Complete incineration breaks PVC into water, carbon dioxide, and hydrochloric acid. Although this process might not release the dangerous dioxins that incomplete incineration does, complete incineration is not feasible on a large, commercial scale because the heat and time required to incinerate PVC completely are beyond the scope of current commercial practice. PVC is also difficult to incinerate because of its high chlorine content. According to the EPA, solid PVC waste takes hours to be completely combusted at 450–1,600°C, although no specified time has been published. Even if complete combustion is achieved, dangerous hydrochloric acid is still released (15), and this highly corrosive acid corrodes and destroys furnaces (19).

CLEANER INCINERATION

Although no current research is identified on how to cleanly incinerate the PVC from a CPB pump specifically, advancing methods are being developed in other fields, such as the cable-wire industry in Japan. Because the raw materials used in cable wires is chemically similar to the PVC used on the bypass machine, the principles of incineration may be applicable across fields.

The main problem of incinerating PVC is the dioxins released because of the chlorine. Therefore, dechlorinating PVC before incinerating it lessens the health risks of dioxins in the atmosphere. Although this does not solve the ultimate waste problem, it does reduce dioxin levels. None of the following methods discussed are available on a commercial scale, but they exist to show that there is research being carried out, and, in the future, alternatives to the incomplete combustion of PVC may become more widespread.

The first method is to dechlorinate PVC before incinerating it. Sodium hydroxide (NaOH) is a highly corrosive solid that is used to neutralize acid by releasing heat, enough even to ignite combustible materials (24). It can also be used to turn PVC into carboxylic acid and eliminate the HCl generated with incineration. Although PVC is dechlorinated without NaOH, if burnt higher than 280°C, this is not commercially feasible. The addition of NaOH to PVC lowers the reaction temperature to 150°C and inhibits the generation of organic chlorides. The amount of NaOH changes the temperature. Adding the alkaline allows for plasticizers and chlorides to be selectively extracted (12). It was found to remove 99.5% of the chlorine at a milder temperature and to make the incineration of PVC a viable option for biofuel production.

Hydrothermal carbonization is used to convert waste into a biomass fuel called sterilized hydrochars, meaning could be a viable option for biohazardous waste. Elevated temperature and water pressure carbonize waste. When PVC and lignocellulose are combined, PVC is dechlorinated up to 89.5% effectively, without the use of NaOH. Lignocellulose is commonly found in all plants and is made up of a glucose matrix held in crystalline microfibrils, and it holds a distinct potential for being a new type of fuel (25). When combined with PVC in a 1:1 ratio, the waste produced when heated to 250°C creates a waste product that is dechlorinated (therefore not releasing harmful dioxins into the air) and a potential for a coal-alternative solid fuel.

These alternatives are far from being commercialized, but it is important to see that potentials exist for solving the crisis of incompletely incinerated PVC. The release of dioxins, heavy metals, and phthalates into the ground and atmosphere is creating a problem that is affecting people now. It is not a problem the perfusion field can ignore. The tubing used every day is creating an environmental and health dilemma that needs not only innovative research but also a strong commitment to resolve.

LANDFILL

One alternative to incinerating hazardous waste is decontamination and burial, also called landfilling. Landfilling is problematic because even if decontaminated for municipal waste, there is diminishing land availability. Sanitary landfills are what we know today as landfills. They are regulated by the government to ensure safety to the public (26). To be considered safe, the location must be completely degraded biologically, chemically, and physically (27). Landfills are lined to prevent leachate from seeping into the soil, which can contaminate the local water supply. These landfills are also covered with soil every day to prevent animal infestation and reduce unwanted odors from contaminating the air (26).

The amount of waste produced in the United States is increasing with its growing population (28), meaning more landfills are needed to keep up (29). As a country, the United States cannot continue to bury, pile, and store waste in landfills that are already full. The plastic that is being dumped into landfills does not decompose quickly and does not provide a sustainable option. Increasing the number of landfills is only a temporary fix to the problem of waste buildup.

As mentioned, medical waste is separate from municipal solid waste and incinerated. Not only is this detrimental to the environment but also it is more expensive to send medical waste to incineration than it is to send municipal waste to landfills. The process in operating rooms to separate actual infectious waste (PVC that comes in contact with blood) from municipal waste (end caps and packaging) is not consistently performed. Without the infrastructure to separate infectious and noninfectious waste, more time and energy is spent treating "hazardous" waste than necessary (3). Recycling and separating waste during a single case can save more than $5.20 per bag (7). Hospital systems can turn their medical waste into municipal solid waste by developing sustainable methods to sterilize it (30).

One example of sustainable sterilization is achieved by a company called MedAssure (Lakewood, NJ). MedAssure takes medical waste and feeds it into a sterilization machine before decontamination. The waste is crushed down to very small pieces and further decontaminated in a hopper for over an hour at 212°F. The product is then available to be sent to an outside facility as solid municipal waste. The medical waste has been reduced by 80% (10).

One potential consideration not in current practice is to place all sterilized components of a bypass circuit that do not come in contact with blood into municipal waste: the caps, bags, some tubing, and the hard-plastic shell the circuits arrives in. Although burying this sterile waste is not the ultimate solution, it does keep some plastic out of the incinerators, preventing harmful dioxins from being released into the environment.

Plastic municipal waste does not disintegrate. It stays in the ground for many years. The degradation process for PVC municipal waste in landfills follows four phases. Phase I is the initial aerobic phase. The oxygen in waste is consumed by microorganisms and converted to carbon dioxide, taking around 14 days. Phase II is the anaerobic acidogenic phase where the pH is decreased in the waste, creating heavy metals that will be degraded over an unknown time. Phase III is the anaerobic methanogenic phase. This phase occurs with an increased production of carbon dioxide and methane. Because fatty acids are being consumed, the pH will increase. The range of time this occurs varies but can last hundreds of years. Phase IV is the final aerobic phase. Most current landfills have not reached this phase, but it is predicted that after the production of methane has ceased, air will be present for a conversion from anaerobic to aerobic conditions. This may lead to mobilization of heavy metals (32).

Plastics are sustainable because they last in the environment for a long time after being discarded. Adding to their chemical nature, the degradation time of plastics is extended when they are shielded from direct sunlight because of how waste is piled up on top of itself for decades at a time. This is exacerbated by the decrease in antioxidants commonly added to PVC to increase its acid resistance. Furthermore, decomposition of plastics is decreased by the antioxidants added to "enhance a container's resistance" to acidic contents (33).

REUSE

Reuse of the CPB circuit or portions of the circuit is an area that is not often discussed in the perfusion community. However, it may be a topic to consider as perfusion waste is brought to the forefront of an environmental conversation. Reuse could have a significant role in the reduction of the negative environmental impact that the CPB circuits currently pose with incineration and landfilling. In current practice, the CPB circuit is a single-use item and becomes infectious medical waste immediately after use (31).

Although uncommon in the United States, reuse has been a continuous practice in other countries. Currently, some nonprofit organizations and hospitals are spearheading the lead on reuse with medical waste. One particular nonprofit organization involved with reuse is REMEDY©2006–2019 (New Haven, CT) (35). REMEDY's ©2006–2019 mission is to provide international medical relief while reducing solid medical waste by sending various unused medical supplies to developing nations. REMEDY©2006–2019 has since extended this practice by obtaining single-use items from developed nations and supplying them to medical care facilities in developing nations for reuse. Without the reused equipment, facilities such as Hospital de San Jose' would be unable to operate. They reuse an extensive array of items that are considered single use in the United States such as perfusion cannulas, cautery pens, pace wires, and aortic punches. To reduce the risk of infection, REMEDY©2006–2019 provides hospitals participating in their reuse collection program with guidelines and training education on how to handle the reuse items.

They also provide a list on how the different items should be separated for their program. REMEDY©2006–2019 differentiates between expired but never opened equipment or devices opened but never contaminated with patient use, even if just placed within a sterile field and never contaminated. Other materials include single-use items that have been used on patients but retain their ability to be used again. REMEDY©2006–2019 demonstrates waste can be reduced through reuse (36).

After all items have undergone sterilization, a visual and functional inspection is performed on each item. Then, each item is entered into a system which keeps track of the number of times each item has been reused. Because of Hospital de San Jose's meticulous reuse process, they report infection rates have not increased since the implementation of the reuse program (37).

Beyond outside aid from organizations such as REMEDY© 2006–2019, hospitals in parts of the developing world reprocess and reuse their own single-use items primarily to save money. Although becoming environmentally sustainable is not the intended outcome for these hospitals, the reuse of items previously thought to be "single use" shows an alternative for disposing of the entire circuit after one case. In some countries with limited resources, all portions of the circuit are reused, except the oxygenator and filters. Hospitals allow use of a sterilized and reused circuit that would not be permitted in the United States.

In more developed countries, such as Korea, steam sterilization is performed on all medical waste for potential reuse. Although this specific method is not possible for CPB circuits, it is a process to be considered for future research. Operating conditions for sterilization required by the Korean Ministry of Environment are 30 minutes of steam at 121°C and 1 atmosphere of pressure. This is similar to autoclaving requirements of the United States (34) and is an efficient method for sanitizing infectious waste, applicable to most types of microorganisms (38).

The reuse of CPB circuits or portions of it should be researched further, through either donation of specific parts to developing nations or methods of sterilization and reuse within the United States. Partnering with groups such as REMEDY©2006–2019 would allow us to help those countries in need of medical supplies and reduce the negative impact on the environment from perfusion waste.

RECYCLE

PVC is one of the most widely used plastics worldwide, and, therefore, recycling is a desirable outcome for end-of-life products. However, as previously stated, the high chlorine content and hazardous additives in PVC make recycling far more difficult. Most uses of PVC products have a useful life span of 30–50 years, and, thus, the volume of waste is expected to increase greatly soon as it gained mainstream usage in the 1970s (2).

Currently, two practices exist for the recycling of PVC: mechanical and feedstock. In mechanical recycling, the used product is ground into pellet-sized (or smaller) particles called granules. The granules are then heated to a liquid form and remolded into a new product. Because there is no chemical reaction occurring, the ground PVC will retain its original composition. This, however, poses the problem of varying mixtures of PVC all being combined into one pile of granules; most PVC requires a specific content of chloride and additives to create varying levels of flexibility, and to create a high level of recyclate, granules from varying backgrounds cannot be used. Therefore, mechanical recycling is most frequently used with large quantities of similar postindustrial waste to control the type of PVC being recycled (2,39,40).

Feedstock recycling has the potential to provide a much more usable source of recycled PVC. With this process, the PVC waste is heated past the melting point and reverts the material to its original chemical components. These basic components—namely, chlorides, hydrocarbons, and heavy metals in liquid or gas form—are scavenged and can then be used for a wider variety of new PVC products without worry of mixing uneven amounts of ingredients. Processes such as pyrolysis are at the forefront of this type of recycling. However, these processes incur higher costs, create less of a return on investment, and ultimately limit incentive for manufacturers to use such tactics (2,39,40).

Much effort has been spent researching pyrolysis of plastic wastes for energy conversion. Pyrolysis is a process where heat and pressure are applied to existing plastics, and, as a result, long-chain polymer molecules are thermally degraded into molecules with less complexity that are smaller in size. This breakdown of plastics results in three major products: oils, gases, and hydrocars. Hydrocars, as previously discussed, are waste products, but the other by-products can be of extreme value. Oils, e.g., can be burned in furnaces, boilers, and diesel engines, and are the main products desired most from pyrolysis. In Europe, the synthesis gas (syngas) obtained from PVC pyrolysis is used to replace coke, coal, or natural gas to fuel iron ore (and other oxidized metal) furnaces (2). However, the main product obtained from the pyrolysis of PVC is HCl, which is corrosive and toxic when heated moderately. A dechlorination process can occur first, but this includes an additional step—and an additional cost—and, ultimately, makes the overall process inefficient. Thus, pyrolysis of PVC is not feasible because of the minimal amount of oil being produced and the additional incurred costs (41).

Other research is being conducted for different methods of dechlorination or scavenging additives. In PVC, additives potentially make up 70% of the total mass of the product, with phthalate plasticizer being almost 40% of flexible PVC. In a 2018 study from China, a new process of dealing with PVC waste using near-critical methanol (NCM) has shown the ability not only to dechlorinate but also to recover additives that can be reused in the production of more PVC. Plasticizer, stabilizer, and lubricant have all been extracted from medical waste, including transfusion tubing and urine sample collection containers. The use of NCM as a treatment medium for PVC is milder than some other processes as the critical temperature is much lower than that of water. In addition, methanol can be recycled during the NCM process, and the process both retrieves additives and dechlorinates simultaneously. After the NCM treatment, the liquid–solid product can be separated by a centrifugal machine. The lower boiling point of methanol allows the chlorine to be removed (while bound to liquid methanol), and the plasticizers and stabilizers remain as solids. Next, those materials can be separated one at a time because of their varying boiling points. Ultimately, there is still much research to be carried out regarding dechlorination and additive recovery from PVC, but the current outlook is promising for success (4).

Ideally, in the future, the CPB circuit will be taken from the OR after each case, sent to a recycling facility where it is sanitized and dechlorinated, and then scavenged for molecular parts. The scavenged parts will then be used to create one of a variety of medical products including new CPB circuits or other medical tubing, or possibly even be used by others such as the cable, construction, or flooring industries. One day, the incineration of PVC should completely disappear as an option for eliminating medical waste.

CONCLUSION

The PVC contained in the CPB circuit contributes to the negative impact of the perfusion field on the environment. The perfusion community has a responsibility to investigate cleaner methods for PVC disposal. The harmful byproducts of incineration, dioxins, and phthalates cause cancer and cardiovascular disease. Burying sanitized waste is expensive and unsustainable.

There are two practical methods perfusionists can take now. The first is to make sure that there are established standards in the operating room where any uncontaminated perfusion waste is either recycled or put into municipal waste. This would include end caps, hard plastic bins, and any storage bags that tubing arrives in. By reducing the amount of biohazard waste, not only hospitals save money but also less plastic is incinerated, reducing harmful toxins in the environment. Second, partnering with groups such as REMEDY©2006–2019 will provide a new life to used perfusion equipment while helping hospitals in developing nations. Although there are currently limitations with how much perfusion equipment can be reused, partnering with REMEDY©2006–2019 might help discover the best ways for CPB tubing to be donated. We can also begin partnerships with different manufacturing companies. An example of a partnership with manufacturers could be the collection of all end caps on the CPB circuit that have not been contaminated. Once collected, the caps could be sent back to the company for re-sterilization and reuse. In addition, the large plastic packaging containers that CPB circuits come in could also be reused. Both of these small changes would serve as a cost-saving mechanism as pack companies would save by not having to repurchase end caps and plastic containers. Hospitals could in turn save because of the lowered costs of packaging. Ultimately, it would help with the overall environmental impact of CPB circuits.

Longer term solutions, in terms of cleaner incineration and recycling component parts of PVC, are possible if perfusionists start the conversation and support environmental sustainability. Although the current opportunities for recycling of the contaminated perfusion circuit and other medical waste are minimal, research is currently being conducted to create recycling possibilities for the future. By following the lead of other industries, the medical community could significantly lower its growing environmental impact in the coming years. Still, those opportunities have notable obstacles to overcome to be physically and monetarily efficient.

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