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STERILIZATION OF MEDICAL 3D PRINTED PLASTICS: *IS H_2O_2 VAPOUR SUITABLE?*

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ABSTRACT

3D printers that precisely fuse plastic filament are enabling the medical device manufacturing sector to produce high-quality plastic medical devices and implants. However, the low-temperature fusing process implies that post-production sterilization must also occur at a low temperature or destroy the precision of the product. This study characterizes the effects of hydrogen peroxide (H_2O_2) vapour sterilization on ASTM-compliant 3D printed tensile samples of polylactic acid (PLA), polycaprolactone (PCL), and polycarbonate (PC). The sterilization process caused physical deformations in PCL. Additionally, increases were observed in PCL and PC sample thickness, and in PC sample width. Decreases in Young's Modulus (*E*) were found in all three materials, while UTS decreased in PC, and strain at UTS increased in PCL. The findings demonstrate that the 3D printed materials can be compatible with H_2O_2 vapour sterilization, but products must be designed to accommodate for changes that occur due to sterilization.

INTRODUCTION

3D printing is a manufacturing technology that produces physical objects layer-by-layer through computer-guided material deposition[1]. This technology has seen use in the medical manufacturing sector in various capacities, including the production of custom implants, tissue scaffolds[1], and on-demand surgical instruments[2].

Fused deposition modelling (FDM) is a common approach to 3D printing with plastics[3,4]. In this approach, material is heated and extruded through a nozzle into a build tray, following a computer-guided path to produce each layer. First, the extrusion path produces a layer outline, which is then filled in. Once a layer is completed, the build tray lowers and the next layer is produced, with the layer infill oriented orthogonally to the layer before it[3]. FDM machines are typically compact and inexpensive, and have a wide variety of available biocompatible plastics to print with, including: polylactic acid (PLA), polycaprolactone (PCL), and polycarbonate (PC)[4]. 3D printed products differ physically when compared to conventionally manufactured products: they are typically porous, contain internal voids, and have rough surface finishes[5,6]. Mechanically, they are anisotropic, due to their layered composition[5]. Additionally, the elevated extrusion temperatures can be insufficient to ensure terminal sterility[2].

Regulatory bodies overseeing the medical manufacturing industry have imposed numerous guidelines and regulations to ensure that manufactured plastic goods remain sterile[7], but these guidelines do not address 3D printed plastic products[8]. When addressing sterility in plastic products, the selection of a low-temperature sterilization technique is important, as some materials are less thermally stable than others and can be physically deformed when sterilized. 3D printed products add additional complications, as defects associated with 3D printing could result in unintended subsurface sterilant penetration from surface-limited chemical sterilization techniques.[9] Furthermore, a rough external finish presents a larger surface area exposed to sterilant, potentially leading to an increased rate of material degradation[10]. With 3D printing gaining popularity in the medical manufacturing sector, products that undergo sterilization could be more susceptible to changes in material strength than those produced through conventional means, so the suitability of common sterilization techniques must be studied.

METHODS AND MATERIALS

The materials tested in this experiment were PLA, PCL, and PC, sourced from Stratasys®. The PLA and PCL were research-grade materials, containing 1% by weight gentamicin antibiotic. n=20 ASTM D638 Type IV samples of each material were produced. PLA and PCL samples were printed with a *Stratasys® Mojo™*, while PC samples were printed with a *Stratasys® Fortus™ 400mc*. Half of the samples of each material were selected at random for sterilization.

Bulk H_2O_2 vapour sterilization was performed on a *STERIS® Amsco® V-PRO® maX*, set to 'lumen cycle,' which exposed the samples to four cycles of 0.13 kPa pressure, at approximately 50 ºC over 28 minutes. Finally, ASTM D618, all samples were conditioned within a range of 22.27 to 23.33 ºC and 57.25% to 58.46% relative humidity for 40 hours.

Once conditioned, the tensile samples were tested using an *Instron® ElectroPuls™ E10000* load frame, on a material-by-material basis. To ensure test parity, there was no differentiation between the sterilized and unsterilized control samples, and test order was randomized. The strain rate for tensile loading was 5 mm/min.

RESULTS

Physical Changes

The colour of the PLA print filament was initially golden-brown in colour, and once printed, the tensile samples were significantly darker. Once exposed to a cycle of sterilization, PLA sample colour became bleached. Changes in colour were limited to PLA, as neither the PCL or PC materials displayed any noticeable pigmentation. While they did not change in colour, the PCL samples all experienced some degree of melting and bubbling in both the grip and gage sections.

Dimensions and Mass

The thickness, width, and mass measurements of all samples throughout the experiment were compared using paired t-tests. On average, the PCL samples increased in thickness by 1.60%, while the PC samples increased by 0.21%. PC sample width increased by 0.18%. Lastly, average mass of PLA, PCL, and PC, increased, respectively, by 0.24%, 0.36%, and 0.06%.

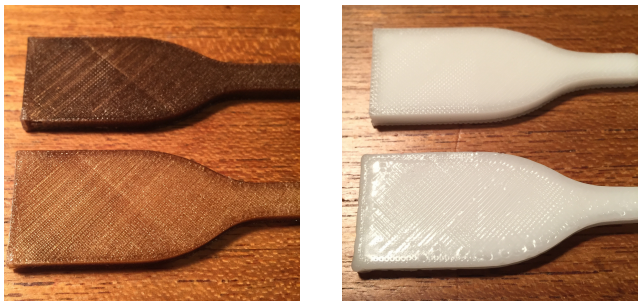

Figure 1: Left, colour difference between unsterilized control (top) and sterilized (bottom) PLA; right, PCL material deformation occurred in the sterilized samples (bottom).

Table 1: Average physical changes due to sterilization of n=10 samples of PLA, PCL, and PC. Statistically significant values are in bold.

Material	Physical Measurement		
	Thickness (mm)	***Width (mm)***	***Mass (g)***
PLA	-3.30×10^{-4} (0.0284)	-5.00×10^{-3} (0.0123)	**0.0180 (2.37×10^{-3})**
PCL	**0.0663 (0.0407)**	0.0123 (0.0187)	**0.0230 (3.00×10^{-3})**
PC	**8.00×10^{-3} (0.0106)**	**0.0107 (9.27×10^{-3})**	**3.82×10^{-3} (1.66×10^{-3})**

Table 2: Mean mechanical properties of n=10 samples of control and sterilized PLA, PCL, and PC. Statistically significant values are in bold.

Material	Mechanical Measurement		
	E (MPa)	***σ_{UTS} (MPa)***	***ε_{UTS} ($^{mm}/_{mm}$)***
PLA Control	**121 (4.72)**	38.8 (0.732)	0.0586 (3.15×10^{-3})
PLA Sterilized	**116 (4.14)**	38.9 (1.31)	0.0587 (2.63×10^{-3})
PCL Control	**121 (4.72)**	12.8 (0.496)	**0.333 (0.0154)**
PCL Sterilized	**116 (4.14)**	12.6 (0.342)	**0.378 (0.0193)**
PC Control	**595 (8.18)**	**42.4 (0.688)**	0.108 (1.06×10^{-3})
PC Sterilized	**584 (6.50)**	**41.8 (0.528)**	0.108 (1.53×10^{-3})

Mechanical Properties

A comparison of *E* between the control and sterilized samples revealed a statistically significant decrease in all three materials as a result of sterilization; the *E* of PLA, PCL, and PC decreased by an average of 2.15%, 4.13%, and 1.85%. In PC, σ_{UTS} saw a statistically significant change of 1.52%. The average ε_{UTS} only saw a statistically significant change in PLA, where it increased by 13.5%.

DISCUSSION

Physical Changes

H_2O_2 vapour sterilization affected the dimensional properties of PCL and PC, and the mass of all three materials. The sterilization cycle relied on heat, moisture, and vacuum to operate. The ten PCL samples that underwent sterilization had permanent deformation due to flow at the sample surfaces, becoming glossy and smooth, despite the sterilization method being low-temperature. These samples bubbled during sterilization around their periphery, indicating that either air was entrapped and escaped during the elevated chamber temperatures and low pressures, or a chemical reaction occurred. This deformation was the cause of the increase in PCL sample thickness.

H_2O_2 vapour sterilization caused the PLA samples to become noticeably lighter in colour. H_2O_2 is a known bleaching agent, used to decolourize products in several industries, and likely contributed to the breakdown of pigmentation from the sterilized samples[11]. Second, gentamicin is "freely soluble in water"[12]. Since water is a component in the H_2O_2 vapour sterilization process, its presence may have caused dissolution of the antibiotic from the plastic, causing loss of color and enlargement of voids within the samples.

The sterilization process also resulted in an increase in sample mass of all three materials. H_2O_2 vapour sterilization relies on the use of water to diffuse and condense sterilant on all surfaces within the chamber. As such, the sterilization cycle exposed the PLA, PCL, and PC samples to moisture. FDM printed products are highly susceptible to moisture absorption, resulting in the mass increase in all samples. This may have caused the increases in sample thickness and width, as some thermoplastics can swell in response to moisture absorption[13]. Additionally, FDM-produced products are anisotropic, and are weakest in tension transverse to the printed fibres[14]. This weakness may also explain the samples' susceptibilities to change in sample thickness. The increase in PC sample thickness after sterilization is likely attributable to a combination of moisture uptake and low chamber pressures 'pulling' outward.

Decreases in Mechanical Strength

H_2O_2 vapour sterilization had statistically significant effects on the material properties of PLA, PCL, and PC; each of the three materials decreased in *E*, while only PC saw a decrease in σ_{UTS}, and only PCL saw an increase in ε_{UTS}.

PCL was the only tested material with visible deformation resulting from sterilization, which contributed to decreased material performance. Those samples bubbled along their peripheral edges, including the gage regions. Fibrous materials have decreased properties when loaded in directions off-axis of their fibres, with more than half of the elasticity of the fibre lost at a loading angle of 15º[14]. The composition of each 3D printed sample layer was made up of an outline oriented in the direction of sample loading and an infill pattern oriented at 45º from loading. With this structure, the outline material in the gage sections provided the samples with a majority of their tensile strength, with the infill acting as a secondary support; the bubbling observed on the PCL samples caused localized disruptions to the axial orientation of the plastic fibres limiting their response to an axial load. Re-orientation of the fibres would not have occurred until sufficient sample elongation would 'pull' them straight, by which point mechanical failure in the samples would have already occurred elsewhere; these phenomena likely explain the decrease in *E* and significant increase in ε_{UTS} observed in PCL.

It is possible that low pressures within the sterilization chamber caused the change in mechanical performance of the PLA and PC samples, albeit on a smaller scale than the effects seen in PCL. The research literature has shown that both PLA and PC have high glass transition temperatures (T_g) of 60 to 65 ºC[15]

and 150 ºC[16] respectively, when compared to that of PCL, which is -60 ºC[16]. These temperatures indicate that PLA and PC would resist plastic flow when sterilized at 50 ºC. Instead, the low pressures of the sterilization chamber may have caused expansion of any entrapped air, causing internal material deformation before the air could escape. Additionally, the presence of moisture within FDM-produced products significantly decreased their mechanical strength, due to water acting as a plasticizer in polymers[6]. Regions within samples having contained entrapped air, or even washed-out gentamicin in the PLA samples, may instead absorb moisture and further impacting material performance.

Sterilization Suitability

H_2O_2 vapour sterilization caused changes in dimensions and mass, and some physical deformations, but none of the samples were unusable. The suitability of this sterilization technique is dependent on specifics of the applications. Changes in size, mass, and material strength can be anticipated and accounted for during the design process. Additionally, the physical deformations seen in PLA and PCL may not be of any significance to the performance of a 3D printed medical device, if the product's application allows for it.

CONCLUSIONS

Our review of the literature confirms a need for sterile medical manufacturing guidelines for 3D printing that provide insight into the effects of sterilization on material performance[7,8]. Sterile device design and production should be of utmost importance to this sector, as post-print microbial activity could compromise the well-being of patients who may rely on *in vivo* medical devices manufactured with this technology. This study explored how several common, biocompatible, printable plastics respond to exposure to a single sterilization technology. These findings can function as a building block for future work on other materials and sterilization technologies.

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