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Radiological Characteristics of 3D-Printed PETG and TPU at Different Infill Percentages for Breast Cancer Radiotherapy Bolus

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Abstract

Skin-sparing effect causes the radiation dose at a certain depth to be higher than at the skin surface. A tissue-equivalent material namely bolus is required to increase the radiation dose to the skin surface. Conventional bolus is widely used, it poorly conforms to irregular surface, leading to air gaps and compromising dose distribution accuracy. The three-dimensional (3D) printing technology enables the fabrication of 3D-printed boluses to minimize the air gap in conventional bolus applications. In addition, 3D printing is allowed to modify its infill percentage and infill patterns, minimizing both printing time and material usage but resulting in different radiological and dosimetric characteristics. Therefore, it is crucial to evaluate the radiological characteristics of 3D-printed bolus before its application in breast cancer radiotherapy. In this study, the radiological characteristics of 3D-printed Polyethylene Terephthalate Glycol (PETG) and Thermoplastic Polyurethane (TPU) boluses at different infill percentages have been evaluated. This research utilized eight plate-shaped 3D-printed bolus samples with dimensions of 12 cm × 12 cm × 1 cm, at the infill percentages of 20%, 40%, 60%, and 80%. Each bolus sample was scanned using a CT-Simulator to determine its Hounsfield Unit (HU) values and linear attenuation coefficients. The obtained HU values were compared with the HU values of human tissues. The results indicate that both 3D-printed PETG and TPU boluses demonstrate similar equivalency to adipose tissue. Consequently, based on radiological evaluation, PETG and TPU materials are suitable for use in fabricating 3D-printed bolus for breast cancer radiotherapy application.

Introduction

High-energy photon beam is used for cancer treatment on the depth or superficial target, challenging in radiation dose distribution due to the skin-sparing effect. This effect causes the radiation dose at a certain depth to be higher than at the skin surface, leading to increased radiation exposure to healthy tissues surrounding the target and reducing the target dose in superficial areas. [1]. Therefore, a tissue-equivalent namely bolus is a radiotherapy tool to increase the surface dose and improve dose distribution of superficial tumors [2, 3].

Bolus is a tissue-equivalent material that placed on the skin surface to increase the radiation dose to the skin surface [1], [4]. Conventional bolus is widely used, including superflab, dental wax, propylene glycol, silicone rubber, paraffin, gel bolus, and plasticine [2], [5-8]. However, it poorly conforms to the irregular skin surface, creating air gaps between the bolus and the skin surface. These air gaps lead to a reduction in the surface dose, affecting the dose distribution and increasing the radiation dose to healthy tissues surrounding the target [7], [9, 10].

The three-dimensional (3D) printing technology offers a solution to these problems by fabricating a 3D-printed bolus based on a patient's Computed Tomography (CT) images [3], [11, 12]. 3D-printed bolus have been shown to improve dose distribution accuracy compared to conventional boluses [13]. Previous studies have evaluated thermoplastic materials such as Polylactic Acid (PLA), Thermoplastic Polyurethane (TPU), Polyethylene Terephthalate Glycol (PETG), and High Impact Polystyrene (HIPS) for the fabrication of a 3D-printed bolus [14-18]. PETG and TPU materials are suitable for 3D-printed bolus due to their flexibility and tissue-equivalent densities [17].

Recent studies have reported that the 3D printing technology enables the modification of both infill percentage and pattern for the fabrication of 3D-printed boluses. Consequently, the infill percentage for a 3D-printed bolus can be reduced to under 100%, reducing the printing time and material usage [19]. However, reducing the infill percentage of the 3D-printed bolus, resulting in the formation of air pores within its structure and significantly changing its radiological and dosimetric characteristics [20, 21].

3D-printed boluses are required for both radiological and radiotherapy evaluations before their application in radiotherapy [19]. This study evaluated the 3D-printed PETG and TPU boluses at different infill percentages by radiological characterization. The gyroid infill pattern was chosen because it has demonstrated excellent performance as a 3D-printed bolus and is capable of increasing the surface dose [16]. The evaluation of the 3D-printed boluses was conducted by determining their linear attenuation coefficients and Hounsfield Unit (HU) values and comparing with the HU values of human tissues. This evaluation is crucial to ensure both the radiological characteristics and tissue equivalency of 3D-printed PETG and TPU, thereby confirming them for fabricating a 3D-printed bolus.

Experimental Method

Filament Density Measurement

The density of PETG (Shenzhen Esun Industrial Co., Ltd, China) and TPU (Sunlu, China) filaments were calculated using equation (1). Mass of PETG and TPU filament samples were measured using a digital scale (Tricle Brand, China) and these volume were taken from length, width, and height measurements using a clipper (Lanter, China) [22].

$$\rho = \frac{m}{V} \tag{1}$$

Where ρ is the filament's density (gram/cm^3), m is the filament's mass (gram), and V is the filament's volume (cm^3). These results were compared with the density of PETG and TPU filaments on the manufacturer's datasheet [23, 24].

Fabrication of 3D-printed Bolus

The boluses were designed using an open-source software, TinkerCAD (Autodesk Inc., USA), as plate-shaped objects with dimensions of 12 cm × 12 cm × 1 cm. The designs are in an.stl format exported to the 3D printer slicing software, Creatware version 7.2.0 (CreatBot, China), to set printing parameters, including temperature, speed, infill percentage, and infill pattern. The filaments used were PETG and TPU, with their densities are 1.27 g/cm^3 and 1.15 g/cm^3, respectively, with a diameter of 1.75 mm [23, 24]. An INOVA 3D i430 printer (PT Proinnov Teknologi Indonesia, Indonesia), utilizing Fused Deposition Modeling (FDM) technology, was used for printing. The plate-shaped boluses were printed according to the parameters specified in Table 1.

Table 1. Bolus printing parameter specifications.

Parameter	PETG	TPU
Nozzle Diameter (mm)	0.8	0.8
Layer Height (mm)	0.4	0.4
Number of Shells	2	2
Infill Pattern	Gyroid	Gyroid
Infill Density (%)	20%, 40%, 60%, 80%	20%, 40%, 60%, 80%
Extruder Temperature (°C)	220-230	195-215
Bed Temperature (°C)	75-85	30-40
Speed (mm/s)	40-50	15-20

Hounsfield Unit Analysis

The PETG and TPU boluses were scanned using a CT-Simulator (Siemens, Germany) with the following parameters are 120 kVp, 44 mAs, and a slice thickness of 2 mm. Table 3 shows the appearance of the infill percentage 3D-printed bolus based on CT-Simulator imaging. The purpose of scanning the boluses was to determine their HU values and linear attenuation coefficients. HU values represent the grayscale range obtained from the images. HU values were calculated as the average of 24 Region of Interest (ROI) points from each bolus image, processed using the software, Fiji (NIH, USA), in axial mode. The obtained average HU values of the materials were presented in a linear regression graph, where the x-axis represented the infill percentage and the y-axis represented the average HU value. Furthermore, the graph shows the correlation between bolus infill percentages and the HU values.

The HU value was calculated from the linear attenuation coefficient of water (μ_w) and the linear attenuation coefficient of the material (μ_t) using equation (2) [25]:

$$HU = \frac{\mu_t - \mu_w}{\mu_w} \times 1000 \quad (2)$$

The results were compared with the HU values of human tissues to evaluate the boluses' tissue equivalency, as shown in Table 2.

Table 2. The range of HU in human tissue [25, 26].

Tissue	HU Range
Air	-1000
Lung	-950 to -550
Adipose Tissue	-200 to -20
Fat	-100 to -80
Water	0
Muscle, Soft Tissue	20 to 100

Linear Attenuation Coefficient Analysis

The linear attenuation coefficient of the material (μ_t) was calculated based on the derivation of the HU formula on equation (2), and the following equation (3) was obtained:

$$\mu_t = \left(\frac{HU}{1000} + 1\right) \times \mu_w \quad (3)$$

where the linear attenuation coefficient of water is 0.060 cm^{-1} as measured by literature [5]. This reference was chosen because it was obtained under identical CT tube voltage settings is 120 kVp to those used in this study. This calculation is performed to determine the suitability of the 3D bolus for the photon energy used

Results and Discussion

The Density of PETG and TPU Filaments

The measured data for the density of PETG and TPU filaments are shown in Table 3. The data were compared with the theoretical density values from the manufacturer's datasheet [23, 24]. Relative differences between measured and theoretical values were calculated.

Table 3. Measured and theoretical values for the density of PETG and TPU filaments.

Filament	Density (g/cm³)		Relative Difference (%)
	Measured	Theoretical	
PETG	1.258	1.270	0.910
TPU	1.130	1.150	1.170

Based on the results, a discrepancy exists between the measured density values and the theoretical density in the filament manufacturer's datasheet. The PETG filament density from the datasheet is 1.270 g/cm^3 and the TPU filament density is 1.150 g/cm^3. In contrast, the measured density of PETG filament is 1.258 g/cm^3 and the measured density of TPU filament is 1.130 g/cm^3. The measured values are not significantly different from the theoretical values, with a relative difference of less than 3%. The density values of PETG and TPU filaments also indicate that both filaments are close to the density of water, which is 1.00 g/cm^3.

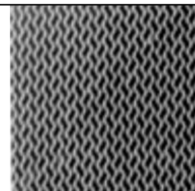
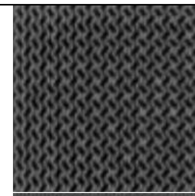
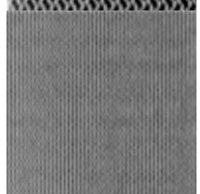
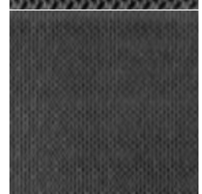
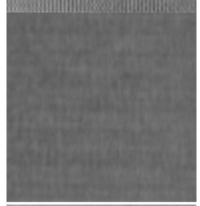
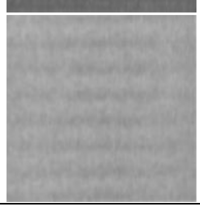
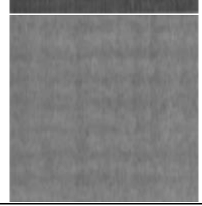
Hounsfield Unit Analysis

The coronal CT images of the 3D-printed boluses, presented in Table 4, show the internal structure and homogeneity of the bolus infill. At infill percentages of 20% and 40%, the infill pattern and the formation of air pores were clearly visible, indicated by the darker spots representing air pores in the CT images. Conversely, at infill percentages of 60% and 80%, the infill pattern exhibited less visibility due to the reduction of air pores, indicating the 3D-printed PETG and TPU boluses at 60% and 80% infill appeared more greyish in the CT images.

The air pores were not visible in the CT images because their sizes were smaller than the spatial resolution of 0,1 cm. This finding indicates that the infill patterns became denser and more compact as the infill percentages increased.

High homogeneity was observed in 3D-printed boluses at higher infill percentages. Homogeneous boluses possess higher densities, which in turn increase the interaction of photons with the atoms of the bolus, thereby increasing the attenuation in skin surface [1].

Table 4. Appearance of 3D-printed bolus at different infill percentages based on CT-simulator images in coronal mode.

Infill Percentage (%)	PETG	TPU
20		
40		
60		
80		

The HU value of each bolus was determined from the selected ROI. The HU values obtained are shown in Table 5.

Table 5. The calculated average Hounsfield Unit (HU) values for each bolus.

Material	Infill Percentage (%)	Mean HU Value
PETG	20	-290.08
	40	-252.88
	60	-191.67
	80	-113.13
TPU	20	-358.08
	40	-319.00
	60	-23.17
	80	-174.29

Based on Table 5, a correlation was observed between infill percentages and HU values. 3D-printed bolus at higher infill percentage increases in HU value, indicating that 3D-printed boluses at higher infill percentages are increasing attenuation of X-rays. Furthermore, HU values for 3D-printed PETG boluses ranged from -290 (at 20% infill) to -113 (at 80% infill), while 3D-printed TPU boluses showed a range from -358 (at 20% infill) to -174 (at 80% infill). The negative HU values indicate the material is less dense than water [12].

The 3D-printed PETG and TPU boluses at a 20% infill percentage exhibited lower HU values compared to those at higher infill percentages, attributing to the presence of larger air pores. A lower infill percentage is linearly correlated to a lower density. This finding aligns with the previous study, which demonstrated that 3D-printed structures at lower infill percentages exhibited larger internal air pores, consequently reducing the HU value [27]. Furthermore, a difference in the HU values was observed between 3D-printed PETG and TPU boluses due to their differing filament densities. TPU filament has a lower density compared to PETG [23], [28], consistently resulting in lower HU values for 3D-printed TPU boluses than for 3D-printed PETG boluses.

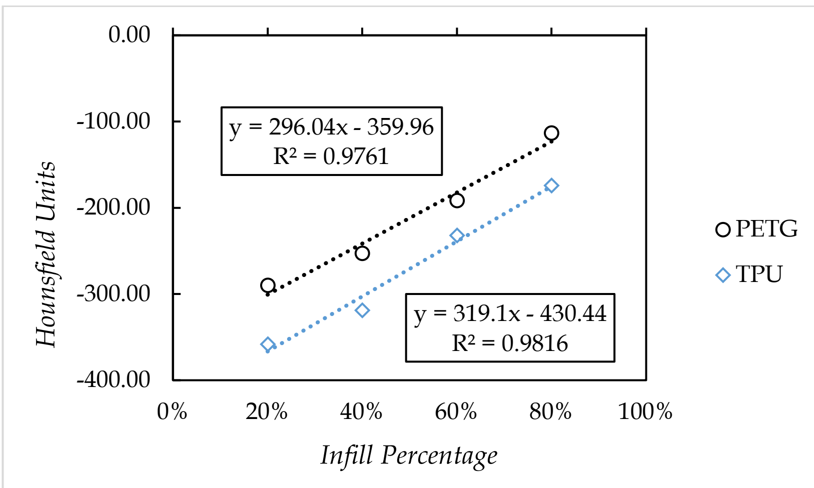


Figure 1. Linear regression of infill percentages versus HU value for 3D-printed PETG and TPU boluses.

Based on Figure 1, a 3D-printed bolus at higher infill percentages correlates positively with an increase in HU value, attributing to the higher density of the bolus infill. This correlation is further supported by the R-squared fitting value (R^2) of 0.9761 for PETG boluses and 0.9816 for TPU boluses. These R^2 values are close to 1 that indicates the infill percentage is directly proportional to HU values [19]. These are consistent with previous research by Hariyanto et al. (2022), which reported an R-squared fitting value of 0.999 [26].

Tissue Equivalency Evaluation

The measured HU of 3D-printed PETG and TPU boluses in Table 5 were compared with the HU range of human body tissues in Table 2. This comparison aimed to evaluate the tissue-equivalency properties of PETG and TPU materials, one of the characteristics of the bolus.

The lowest HU values were measured for 3D-printed PETG and TPU boluses at 20% infill, which were -290.08 and -358.08, respectively. These values are higher than the HU range for lung tissue and air, indicating that the boluses possess greater density than these low-density tissues. Furthermore, 3D-printed PETG boluses with 60% infill (-191.67 HU) and 80% infill

(-113.13 HU), along with a 3D-printed TPU bolus with 80% infill (-174.29 HU), are similar within the HU range of adipose tissue. This finding demonstrated that 3D-printed boluses at 80% infill exhibited suitable equivalency to adipose tissue. However, since the HU value for water is zero and none of the measured HU values of 3D-printed boluses reached this value, indicating 3D-printed PETG and TPU boluses at 20%, 40%, 60%, and 80% infill percentage are suitable for low density tissues. Further exploration with higher infill percentages is necessary to achieve equivalency with water and other denser tissues.

Linear Attenuation Coefficient Analysis

The linear attenuation coefficient describes a material's ability to attenuate radiation and is directly related to HU, which was calculated and refers to equation (2). These linear attenuation coefficient values were compared with the linear attenuation coefficient of water [5], as presented in Table 6.

Table 6. The linear attenuation coefficients of water and 3D-printed PETG and TPU boluses.

Material	Infill Percentage (%)	Linear Attenuation Coefficient (cm^{-1})	Beam Energy (keV)
Water	-	0.060	120
PETG	20	0.043	120
	40	0.045	
	60	0.049	
	80	0.053	
TPU	20	0.039	120
	40	0.041	
	60	0.046	
	80	0.050	

The linear attenuation coefficients for both 3D-printed PETG and TPU boluses increased significantly with increasing infill percentages. This finding demonstrated that higher infill percentages increased the bulk density of the 3D-printed PETG and TPU bolus. The linear attenuation coefficients of 3D-printed PETG and TPU boluses with an 80% infill percentage approached that of water. In contrast, the linear attenuation values for both 3D-printed PETG and TPU boluses at the other infill percentages were below those of water. This suggests that 3D-printed PETG and TPU boluses are suitable for the 3D-printed bolus fabrication [5]. Furthermore, the linear attenuation coefficient of the TPU material was lower than that of PETG. It is consistent with TPU's greater flexibility compared to PETG. This finding also aligns with the previous study, which reported that flexible materials exhibited lower X-ray attenuation than rigid materials, due to their lower density [29].

Conclusion

This study has reported that the difference in HU values of 3D-printed PETG and TPU boluses with CT Imaging as a function of infill percentages. Higher infill percentages correspond to the increasing HU values, indicating a denser bolus structure. Similarly, the linear attenuation coefficient aligned with higher infill percentages.

Based on a tissue equivalency evaluation, PETG and TPU materials are similar to low density tissues, such as adipose tissue, at specific infill percentages of 60% and 80% for the 3D-printed PETG boluses, and 80% for the 3D-printed TPU bolus. These findings suggest that 3D-printed PETG and TPU boluses are highly suitable for use in breast cancer radiotherapy, as determined by radiological evaluation. However, radiotherapy evaluation is still required for these materials for 3D-printed breast cancer radiotherapy bolus fabrication.

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