Assessment of 3D-Printed Bolus for Post-Mastectomy Breast Cancer Radiation Therapy

Urifa N. Aini,[1] Hayfa Annisa,[1] Diska Maharani,[1] Aditya P. Hariyanto,[1]
Agus Rubiyanto,[1] Nasori,[1] Aloysious Mario,[2] and Endarko*[1]
[1]Department of Physics, Institut Teknologi Sepuluh Nopember, Kampus ITS-Sukolilo Surabaya 600111
[2]Department of Radiotherapy, MRCCC Siloam Semanggi Hospital, Jakarta

Abstract: Breast cancer is a major health concern. Radiotherapy, while effective, faces challenges in delivering precise radiation doses, particularly in post-mastectomy patients. This research explores an innovative approach leveraging 3D printing technology to fabricate customized boluses. By tailoring boluses to individual patient anatomy, the study aims to improve radiation dose accuracy, spare healthy tissues, and ultimately enhance treatment outcomes for breast cancer patients. Therefore, this study focuses on creating a 3D printed bolus for post-mastectomy breast cancer patients. The fabricated 3D-printed bolus with 5 mm thick PLA and TPU materials was successfully used to analyze the air gap, relative electron density (RED), and mass attenuation coefficient values for Post-Mastectomy Breast Cancer Radiation Therapy (PMRT). The 3D bolus was designed using 3D-Slicer Segment Editor software according to the thickness used, then smoothed and finished using Autodesk Meshmixer software, and printed on a 3D Creality printer. The air gap value was then analyzed by taking images from the phantom and 3D-printed bolus on a CT-Scan, then processed on Radiant DICOM, and the air gap value for the two 3D bolus materials was obtained. Analysis of two 3D bolus materials, PLA and TPU, showed that TPU is more suitable for bolus use in postmastectomy breast cancer cases based on its material properties. In addition, TPU is also better in terms of the air gap value because it has a smaller air gap, an RED value that is almost close to that of breast tissue, and better mass attenuation. Therefore, the recommended 3D-printed bolus material is TPU with a thickness of 5 mm as a tissue substitute for postmastectomy breast cancer cases.

Keywords: 3D-printed bolus; Air Gap; Radiation therapy; Breast cancer; RED

*Corresponding author: endarko@its.ac.id

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I. INTRODUCTION

Breast cancer is one of the most common types of cancer and the leading cause of death among women worldwide. In 2021, 281,550 women in the United States were diagnosed with breast cancer. Radiotherapy is a frequently used treatment method, in which ionizing radiation is directed at the cancerous tissue to destroy it. This radiation can be in the form of gamma rays, X-rays, electrons, protons, or neutrons, depending on the location of the cancer [1].

For cancers near the skin surface, electron radiation with energy in the mega-electron volt (MeV) range is used, whereas for deeper cancers, photon radiation with energy in the mega-volt (MV) range is utilized. Postoperative radiotherapy is often performed after mastectomy to reduce local regional recurrence (LRR). Phantoms that resemble the human body are used to aid in more precise simulations and treatments [2].

Problems associated with radiotherapy include exposure of healthy tissues and insufficient surface doses for superficial cancers. Boluses, which are materials equivalent to human soft tissue, are used to increase the surface dose and protect organs from radiation exposure. However, commercial boluses often do not fit the patient's skin texture, leading to air gaps and an inaccurate dose distribution [3].

The requirements for a bolus are that it is not sticky, odorless, or safe for the skin [4]. Bolus materials often used in research include acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and superflabs [5]. Commercial boluses available in hospitals usually come in the form of plates of a certain thickness [6]. However, this type of bolus is less effective in cancer therapy, especially for breast cancer, because the area has an uneven texture, making it difficult to avoid air gaps between the bolus and the patient's skin surface [7]. Matching the bolus to the patient's skin texture is critical to ensure the accurate delivery of the dose to the target cells. A 3D bolus is required to overcome this problem. 3D printing is recommended for bolus fabrication because this technology has the advantage of shortening nurse preparation time, minimizing costs, and reducing air gaps [8].

This study focuses on developing a 3D bolus specifically designed for post-mastectomy breast cancer patients. The bolus is intended to be elastic and adaptable to the shape of breast tissue. To achieve this, the bolus is fabricated using Polylactic Acid (PLA) and thermoplastic polyurethane (TPU) in accordance with the research reference of Gugliandolo *et al.* [9]. The primary objective of this study is to analyze the Air Gap, Relative Electron Density (RED), and mass attenua-

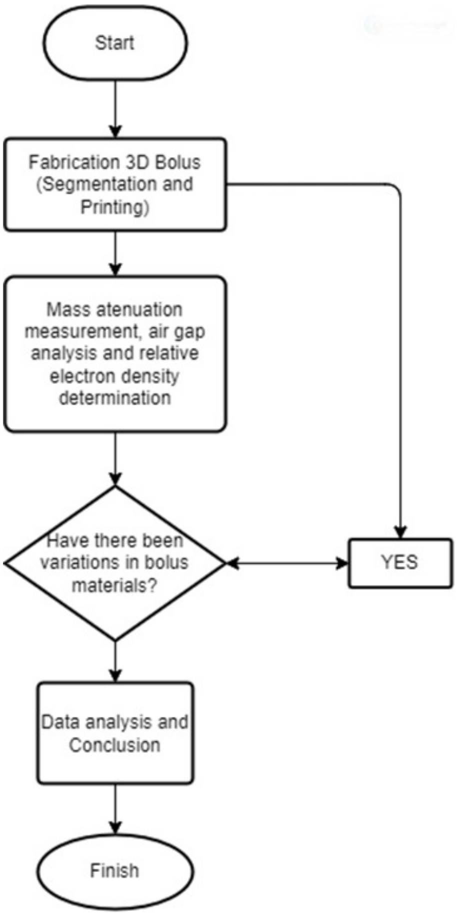


FIG. 1: Flowchart.

tion coefficient of these materials to determine their suitability as tissue substitutes in post-mastectomy breast cancer cases.

II. METHODOLOGY

Fig. 1 shows a flowchart of this research, with an explanation of each stage of the research given in this section.

A. Fabrication of 3D-printed Bolus

This research began with a post-mastectomy radiation therapy (PMRT) chest wall (thorax) phantom, which was designed as a 3D bolus that matches the shape of the patient's chest wall contour, using 3D Slicer Segment Editor software. The bolus was designed with a thickness of 0.5 cm. The bolus design was then adjusted to a predetermined thickness. Next, the bolus design was repaired and smoothed using Autodesk Meshmixer software to ensure that the 3D bolus design was not damaged or cracked when printed. Subsequently, the design was saved in a binary stereolithography (STL) format to print the file on a 3D printer, as shown in Fig. 2.

The printing parameters are listed in Table I. The 3D printing settings for the bolus were adjusted according to the filament materials used, namely, PLA and TPU. Once set, the STL file was transferred to the memory card and printed using a 3D printer, as shown in Fig. 3.

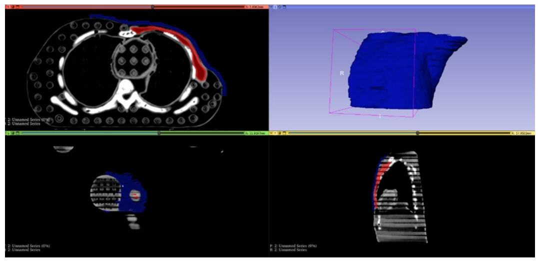


FIG. 2: Bolus segmentation PLA and TPU material.

TABLE I: Printed Parameters for PLA and TPU [7].

Data	PLA	TPU
Density	1.24	1.2
Nozzel (mm)	0.4	0.3
Extruder Temperature (°C)	205	215
Bed Temperature (°C)	60	70

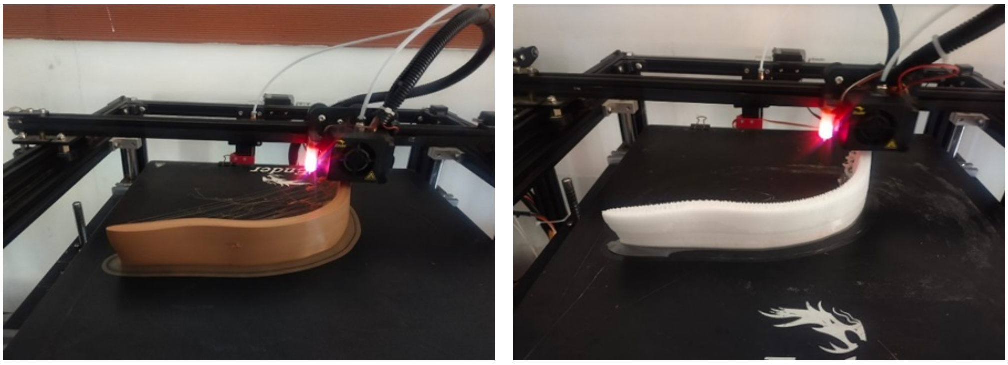
B. Air Gap

The density test involved measuring the air gap. The electron density was measured by first obtaining a tomography image using a CT-Simulator Philips Brilliance Big Bore from the MRCCC Siloam Hospital. With a voltage of 120 kV, tube current of 285 mA, and slice thickness of 3 mm, the voltage and current settings were adjusted according to the clinical examination requirements. The images from the CT-Simulator were sent to a computer for measurement using the RadiAnt DICOM program. Fig. 4 shows the measurement of the air gap between the phantom and bolus by measuring the distance in the gap at four points in 20 slices. After these measurements were made, the air gap values were entered into Excel and averaged.

C. Relative Electron Density (RED)

After measuring the air gap value, a second measurement was carried out to determine the Hounsfield Unit (HU) value, which was then used to calculate the Relative Electron Density (RED). In the Eclips Software (TPS), the CT number is obtained from the bolus image by creating a region of interest (ROI), as shown in Fig. 5.

The region of interest (ROI) was placed with the sample positioned axially. The CT image from the simulator was then sent to read the CT number using the DICOM program. The CT number data obtained were used to calculate the bolus density value using the following equation [10]:



(a) (b)

FIG. 3: (a) Bolus printing made with material PLA, (b) Bolus printing made with material TPU.

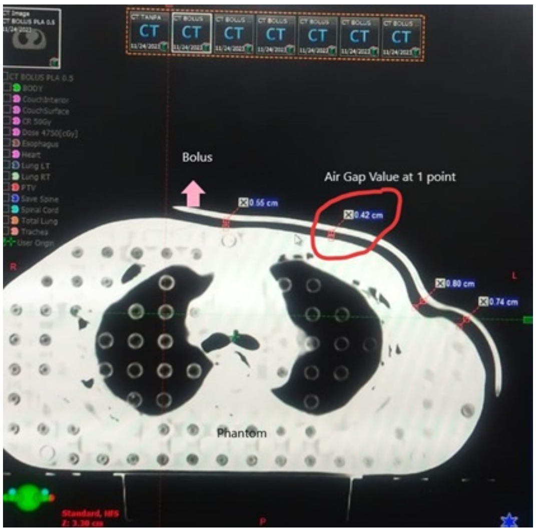


FIG. 4: Measured Air Gap Value.

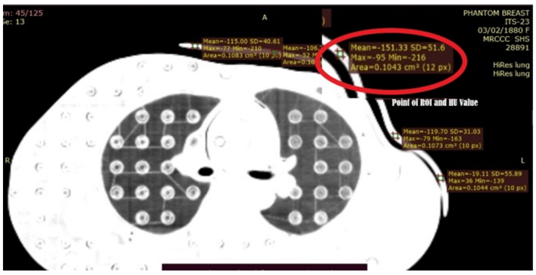


FIG. 5: ROI point for HU value.

$$\rho = \frac{(HU + 1000)}{1000} \quad \text{for } -100 \leqslant \text{HU} \leqslant 47 \qquad (1)$$

$$\rho = \frac{HU}{1827.15} + 1.0213 \quad \text{for } \text{HU} > 47 \qquad (2)$$

where ρ is the RED value and HU is the Hounsfield Unit for various tissue types obtained from the data pixels of DICOM. If the HU value is less than 47, we used Eq. (1), and HU values of more than 47 used Eq. (2).

D. Mass Attenuation Coefficient

The first test process for measuring the mass attenuation value was performed using treatment planning with a TPS-based system. The TPS can be created after obtaining the CT scan phantom results. TPS creation was performed using the Eclipse Treatment Planning System software The testing phase was conducted at the Radiotherapy Installation of MR-CCC Siloam Hospital Semanggi, South Jakarta. The initial step involved the use of a treatment planning system (TPS)-based planning approach. TPS can be created after obtaining the CT scan results of the phantom. The TPS was developed using the Eclipse Treatment Planning System software. Planning began with contouring and segmenting the necessary organs, specifically the target volume (cancer cells) and surrounding OARs such as the spinal cord, heart, and left lung. This process was performed to model the patients. The next stage is designing the TPS using a 6 MV photon beam modality for breast cancer cases, with a total prescription dose of 5000 cGy fractionated at 200 cGy over 25 sessions [11]. TPS was created using the VMAT technique with two arcs. The creation of the TPS is shown in Fig. 6, obtained directly from Eclipse Treatment Planning System software.

Two-arc VMAT was performed using clockwise (300170) and counterclockwise (170° - 300°) rotations. The EBT-3 film was placed nine points above the bolus and on the surface between the phantom and bolus and then irradiated, as shown in Fig. 7. The ROI and mass attenuation values were calculated using Eq. (3).

$$\frac{\mu}{\rho} = \frac{1}{\rho t} ln(\frac{D_\circ}{D}) \qquad (3)$$

where $\frac{\mu}{\rho}$ is the mass attenuation value (cm^2 /g), ρ is the bolus density (g/cm^3), t is the bolus thickness (cm), $D_\circ$ is the initial dose, and D is the final dose.

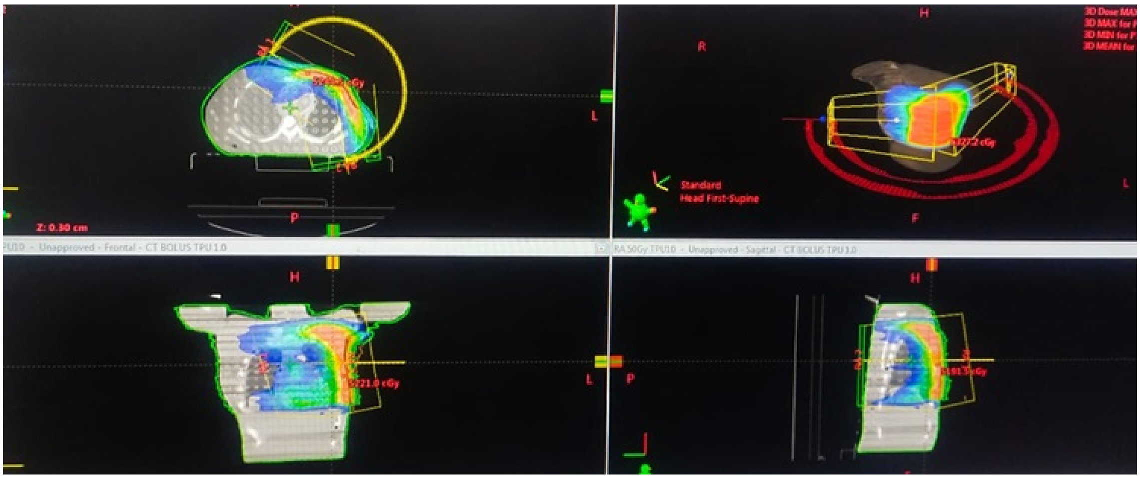


FIG. 6: VMAT Technique Treatment Planning.

FIG. 7: Positioning of the Gafchromic EBT-3 film to measure the mass attenuation coefficient.

III. RESULT AND DISCUSSION

A. Fabrication 3D Bolus

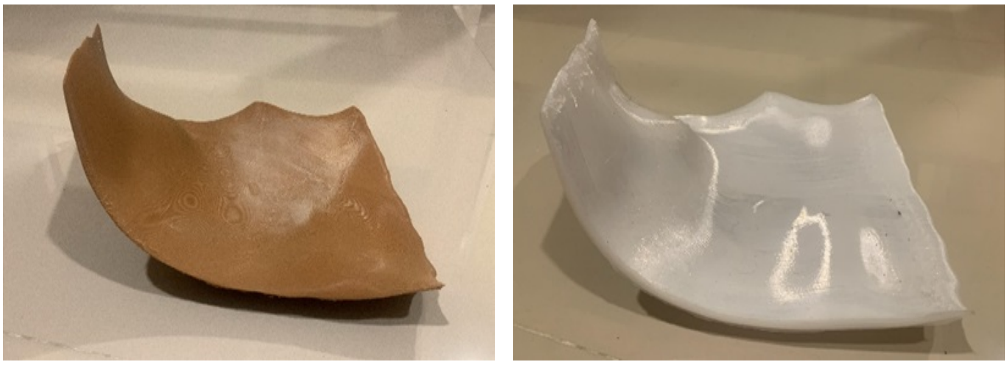
Fig. 8 shows the results of 3D bolus fabrication made from PLA and TPU, both with the same thickness of 5 mm. At first glance, no significant difference was observed between the two bolus materials. However, when handled, there is a noticeable difference in terms of elasticity and flexibility: TPU is more elastic and flexible than PLA. However, PLA is harder and denser than TPU, as can be seen from the density values of the two materials, where the density of PLA is higher than that of TPU. On the other hand, PLA material is harder and denser than TPU material, this can be seen from the density values of the two materials, where the density of PLA is higher than TPU, namely, PLA has a greater density, 1.24 g/cm^3, compared to TPU, namely 1.2 g/cm^3 [12]. Therefore, PLA is harder and more durable than TPU is. However, considering the eligibility requirements for boluses, they should be non-sticky, odorless, and harmless to the skin [13]. In addition, the bolus must conform to human skin tissue and be flexible (adaptable to the shape of the organ) [14]. Of the two materials, based on their properties, TPU better meets bolus requirements. TPU has many suitable properties that meet the bolus eligibility requirements. This result is the same as that of Gugliandolo *et al.*, where TPU material exhibited the best performance in terms of texture and properties [9].

TABLE II: Value of Air Gap.

Bolus Type	Air gap (mm)
PLA	2.89
TPU	2.43

B. Air Gap

The air-gap value of the bolus used in this study is shown in Table II. Based on the size of the air gap in Table II, the air gap value for a bolus made from PLA is 2.89 mm, and for a bolus made from TPU it is 2.43 mm. Table II shows that the air-gap value for boluses made from PLA is greater than that of boluses made from TPU. Another important bolus feasibility requirement is the density of the material to reduce the air gap [14], which is related to the air gap values analyzed for the two 3D bolus materials. As shown in Table II, the air-gap value was smaller for the TPU material. This is inconsistent with the mass density of the material. However, the elastic and flexible properties of TPU allow the 3D bolus shape to easily adapt to the shape of the breast, resulting in a smaller air gap value compared to PLA. Even though PLA has a greater density, its stiff and dense nature makes it difficult to shape, so PLA boluses are less able to conform to the shape of the breast and, as a result, have a greater air gap value compared to TPU. These air gap values are still within the clinically permissible range [15]. This is the same as research by Gugliandolo et al., which shows an air gap value for PLA of 1.2 mm and an air gap value for TPU of 1.05 mm; This shows that the PLA air



(a) (b)

FIG. 8: Bolus fabrication results with a thickness of 5mm (a) PLA Material (b) TPU Material.

TABLE III: Value of HU and RED.

Material	HU Value	RED
PLA	-58.85	0,94114
TPU	-29.36	0,97064
Breast	-100 until 50	0,976
Water	0	1,000
Fat	-100 until -50	0,92

gap value is greater than the TPU air gap value.

C. Relative Electron Density (RED)

The RED values are listed in Table III. The RED value obtained will be compared with the tissue reference value for clinical use of the bolus in external radiation therapy.

Based on Table III, the RED value for the PLA material was 0.94114 and that for the TPU was 0.97064. The RED value is very close to the value of breast soft tissue, namely TPU. The RED value in PLA is the same as the RED value found in the research of Van der Walt *et al.* [15]. The HU and RED values in Table III show that the HU values for both the materials were negative. This is in accordance with the reference HU value for soft tissue, which is negative, and for water, which is 0, as shown in Table III at the bottom [16]. The RED values in Table III show that the PLA and TPU materials used were equivalent to those of the breast tissue materials. Considering the properties of TPU, it is more suitable for soft tissue than PLA. This is also reflected in the RED value in Table III, where the RED value of TPU is closer to the RED value of breast tissue than PLA. This is because the TPU material is flexible, pliable, and thinner than the PLA.

D. Mass Attenuation Coefficient

The mass attenuation values for the PLA and TPU boluses are listed in Table IV. It can be seen in Table IV that the mass

TABLE IV: Value of Mass Attenuation Coefficient.

Bolus Type	Density Material	Mass Attenution Coefficient
PLA	1.24	0.4357
TPU	1.20	0.6458

attenuation coefficient value for the PLA material is higher, namely 0.6458, compared to the mass attenuation coefficient value for TPU material, namely 0.4357. However, when compared with the TPU material, the mass attenuation value of the TPU is greater. This shows that the amount of incoming light is reduced after passing through the TPU bolus media compared with the PLA bolus. This is because the attenuation coefficient (μ) is influenced by the density of the bolus material and the number of atoms that make up it [16]. There was no linear relationship between density and mass attenuation coefficients. However, the densities of PLA and TPU were not significantly different. Considering the atomic number of its constituent elements, TPU has a larger atomic number than PLA, as shown in Table IV. Therefore, TPU is more effective in absorbing and transmitting the received dose, thereby helping control the distribution of the dose to the organs. This shows a linear relationship between the constituent atomic values and mass damping as well as a linear relationship with the mass damping value of TPU, which is greater than that of PLA.

IV. DISCUSSION

At first glance, no significant difference was observed between the two bolus materials. However, when handled, there is a noticeable difference in terms of elasticity and flexibility: TPU is more elastic and flexible than PLA. However, PLA is harder and denser than TPU, as can be seen from the density values of the two materials, where the density of PLA is higher than that of TPU. The fabrication results showed that TPU 3D-printed boluses were more elastic and flexible compared to PLA boluses. This makes TPU a more suitable material for radiotherapy applications as it can better conform to the patient's anatomy and meet other medical requirements. These findings are consistent with previous research by Gugliandolo *et al.*, which demonstrated the superior performance of TPU in terms of texture and properties [9]. In addition to the fabrication results, the RED values obtained in this study also indicate that the RED value for PLA material is 0.94114, while for TPU it is 0.97064. The RED value of TPU is closer to the value of breast soft tissue compared to PLA. The RED value for PLA is consistent with the findings of Van der Walt *et al.* [15]. The HU and RED values presented in Table III show that the HU values of both materials are negative, aligning with the reference HU value for soft tissue (negative) and water (θ). The RED values in Table III demonstrate that both PLA and TPU materials are equivalent to breast tissue material. Considering its properties, TPU is more suitable for soft tissue applications compared to PLA. This is also evident in the RED values in Table III, where the TPU RED value is closer to the RED value of breast tissue than PLA. This is attributable to TPU's flexibility, thinness, and overall suitability for soft tissue applications.

When comparing the air gap values, the PLA bolus exhibited a larger air gap of 2.89 mm compared to the TPU bolus, which had an air gap of 2.43 mm. A smaller air gap is often associated with a higher material density [15]. However, in this case, the TPU bolus, despite having a lower density, achieved a smaller air gap. This can be attributed to TPU's elastic and flexible properties, which allow the 3D bolus to conform more easily to the breast's shape, reducing the air gap. Although PLA has a higher density, its rigidity and density make it less adaptable to the breast's shape, resulting in a larger air gap.

Nevertheless, both air gap values fall within the clinically acceptable range [15], aligning with the findings of Gugliandolo et al. (PLA: 1.2 mm, TPU: 1.05 mm). Regarding the mass attenuation coefficient, PLA has a higher value (0.6458) compared to TPU (0.4357). However, TPU's higher mass attenuation coefficient suggests that it absorbs and distributes the received dose more effectively, contributing to better dose control. This is likely due to TPU's higher atomic number compared to PLA, which influences the attenuation coefficient (μ) and the material's ability to absorb and distribute the dose [16]. While a linear relationship between density and mass attenuation coefficient doesn't always exist, the higher atomic number of TPU is a contributing factor to its superior mass attenuation properties.

V. CONCLUSION

From the density analysis of the two materials, it can be concluded that between PLA and TPU, TPU is more suitable and feasible to be used as a bolus in cases of post-mastectomy breast cancer. This conclusion is based on the analysis of the flexible and elastic properties of the material and the RED value of TPU of 0.97064 which is closer to breast tissue than PLA of 0.94114. In addition, the analysis of the air gap and mass attenuation shows that the air gap value of TPU (2.43 is smaller than that of PLA (2.89), resulting in an increase in the mass attenuation for TPU of 0.6458, and PLA shows a smaller mass attenuation value of. This is in line with the feasibility of the bolus, because a smaller air gap value results in greater attenuation of the radiation received. When passing through a material with a large atomic number, radiation is absorbed and transmitted to the organ with an appropriate dose. Therefore, the most suitable and feasible 3D bolus fabrication material is TPU.

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