

The feasibility of fabricated 3D-printed immobilization masks for radiotherapy: mechanical and dosimetric analysis

Kochakorn Phantawong^{1*}, Nongnat Singthuan¹, Kanjana Pinichsai¹, Somchat Taertulakarn²

¹Department of Radiological Technology, Faculty of Allied Health Sciences, Thammasat University, Pathum Thani Province, Thailand.

²Department of Medical Technology, Faculty of Allied Health Sciences, Thammasat University, Pathum Thani Province, Thailand.

ARTICLE INFO

Article history:

Received 30 May 2025

Accepted as revised 26 August 2025

Available online 29 August 2025

Keywords:

Radiotherapy, thermoplastic mask, 3D printing, infill pattern.

ABSTRACT

Background: 3D printing technology is becoming widely popular in the medical field, particularly in radiotherapy, where it is used to fabricate immobilization masks from thermoplastic materials because it can generate geometric figures and produce sophisticated templates eligible for individual patients.

Objectives: This study aims to evaluate the mechanical and dosimetric properties of three types of plastic: polylactic acid (PLA), polyethylene terephthalate glycol-modified (PETG), and acrylonitrile styrene acrylate (ASA) to identify an appropriate material for use as a 3D-printed thermoplastic mask in radiotherapy.

Materials and methods: The 3D-printed square plastic samples were designed with four infill patterns: triangle, honeycomb, gyroid, and honeycomb-gyroid, and were manufactured using fused deposition modeling (FDM) 3D printing technology. This study analyzed the characteristics regarding mechanics, uniformity, and radiation transmission.

Results: Mechanical testing demonstrated that PETG provided high strength (10.88 MPa with gyroid pattern) and flexibility (7.36% with honeycomb pattern). The mean uniformity across tests ranged from 84.80 to 85.03, with a standard deviation between 5.93 and 7.53. All plastic types have Hounsfield units (HU) ranging from -774.88 to -620.21. The 3D-printed plate demonstrated radiation transmission like the efficiency of a commercial thermoplastic mask, in the range of 99.30% to 99.91%.

Conclusion: All three types of plastic have proven to be appropriate alternative materials for the integration of an immobilization mask. PLA plates displayed advantageous results in terms of radiation transmission, while PETG emerged as the most balanced performer in terms of mechanical properties, showing high strength and flexibility. ASA, a polymer confirmed by FTIR analysis that contains a benzene ring, demonstrated that it is more resistant to radiation. The 3D-printed masks provide a viable alternative to traditional thermoplastic mask systems. Nevertheless, further investigation is required.

Introduction

Radiation therapy for cancer is typically divided into multiple doses known as fractionation. In daily irradiation treatment, the patient should constantly be positioned in the same way. Immobilization devices are used to help set up patient placement. The immobilization device aids in positioning the patient in a position that remains constant during treatment simulation. This allows the tumor to get precisely the dose of radiation required. It also decreases radiation exposure to adjacent normal tissue areas.

The fabrication of products by 3D printing is currently

* Corresponding contributor.

Author's Address: Department of Radiological Technology, Faculty of Allied Health Sciences, Thammasat University, Pathum Thani Province, Thailand.

E-mail address: kochakorn.pha@allied.tu.ac.th

doi: 10.12982/JAMS.2025.108

E-ISSN: 2539-6056

prevalent. This method can generate geometric figures and produce sophisticated templates. It is utilized as a material for fabricating thermoplastic masks to immobilize patients during radiation therapy. Carbon fibers are commonly used as the material for these masks. Nonetheless, carbon fibers are slightly costly.¹ In the last two decades, 3D printing has been used for medical purposes, such as surgical planning, dosimetry devices, and brachytherapy applications.² 3D printing of immobilizers has created a lot of interest in radiotherapy. The fabrication method was revealed to be essentially fused deposition modeling (FDM) printing, which continues to develop rapidly and seems to hold unlimited possibilities across numerous applications. Medical applications have applied the layer-by-layer approach of FDM to produce prosthetics, medical devices, and organ models. The capabilities of this technology are consistently growing due to ongoing advancements and findings, especially in the areas of materials and printing devices.³ The literature highlights several benefits of 3D-printed immobilizers, such as enhanced patient experience and comfort compared to traditional methods. Additionally, they illustrate high accuracy in fitting patients, allow for repeatable setups, and exhibit beam attenuation properties comparable to those of thermoformed immobilizers. The drawbacks included the slow production rate of 3D printing and the potential for inaccuracies in digitizing patient geometry.⁴

This study examined three types of plastics: 1) polylactic acid (PLA), 2) polyethylene terephthalate glycol-modified (PETG), and 3) acrylonitrile styrene acrylate (ASA). All three sorts of plastics are classified as thermoplastics, yet they have different qualities. PLA is a highly potential biopolymer because its monomers may be derived from non-toxic resources, and it is a naturally produced organic acid. PLA is utilized for several applications in the medical

industry. PLA as an appropriate material for 3D printing in external beam radiotherapy.^{5,6} PETG is a material that is very reliable and flexible, resistant to chemicals, and frequently utilized in the medical industry since it can be sterilized without deforming the product. ASA material has properties like ABS plastic. However, ASA is more robust, resistant to UV radiation, and less expensive than ABS plastic.^{7,8}

The objective of this study is to identify a suitable material for a 3D-printed (additive manufacturing) thermoplastic mask in radiotherapy. This was assessed by looking at the strength and radiation properties of three types of plastic: polylactic acid (PLA), polyethylene terephthalate glycol-modified (PETG), and acrylonitrile styrene acrylate (ASA), using different internal designs like triangular, honeycomb, gyroid, and a mix of honeycomb and gyroid patterns.

Material and methods

Manufacturing of the samples

The sample was designed using Autodesk Fusion 360 software. The design involved creating samples measuring 10 x 10 cm² with a thickness of 2 mm using three types of plastics (Ultramo, Thailand) : PLA, PETG and ASA (Table 1). All the materials are available in the form of filaments with diameters of 1.75 mm. Four internal structures were designed for each plastic: triangle, honeycomb (hexagon), gyroid, and honeycomb-gyroid, as shown in Figure 1. Models were exported to Stereolithography (STL) file format and converted to G-code in HP SmartStream 3D Build Manager software (HP, Palo Alto, USA). G-code is the low-level machine language that controls the printer.⁹ A 3D model is created layer by layer using the 3D printer (Flashforge, Model: Creator 3, China) based on the Fused Deposition Modeling (FDM) technique.

Table 1. Properties of plastic material and print setting.

Physical property	PLA	PETG	ASA
Chemical formula	$(C_3H_4O_2)_n$	$(C_{10}H_8O_4)_x(C_8H_{16}O_2)_m$	$C_{18}H_{23}NO_2$
Density (gm/cm ³)	1.25	1.27	1.08
Flexibility	Low	High	Medium
Durability	Medium	High	High
Printing temperature (°C)	190-210	190-210	240-260
Print speed (mm/sec)	50-80	40-60	30-50
Nozzle temperature (°C)	200	240	245
Bed temperature (°C)	50-60	50-60	75-95

Note: PLA: polylactic acid, PETG: polyethylene terephthalate glycol-modified, ASA: acrylonitrile styrene acrylate.

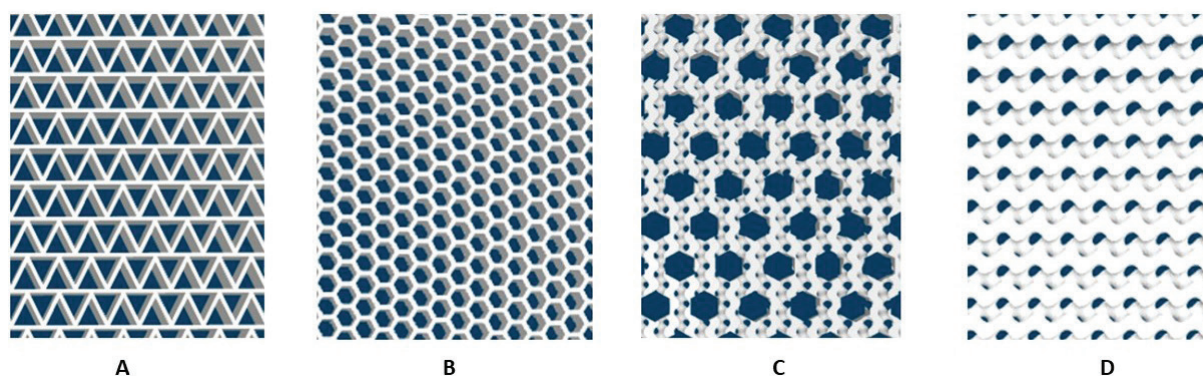


Figure 1. Infill pattern. A: triangle, B: honeycomb or hexagonal, C: honeycomb-gyroid, D: gyroid.

Testing chemical properties

Fourier transform infrared (FTIR) analysis

Specimens of the 3D-printed plastic samples were investigated by Fourier-transform infrared (FT-IR) spectroscopy. The FTIR uses interferometry to encode information from a couple of materials placed within the IR beam. The profile was generated by the Nicolet iS50 FTIR Spectrometer (Thermo Scientific, USA) equipped with a rapid recovery deuterated triglycine sulfate (DTGS) detector. FTIR analysis could be conducted in Attenuated Total Reflection (ATR) mode, with a diamond as the crystal used. The obtained spectra were analyzed with the integrated OMNIC software (Thermo Scientific, USA). Spectra were collected between 4000 and 400 cm^{-1} , with a resolution of 4.0 cm^{-1} and 64 co-added scans.

Testing of the mechanical properties

Testing with simulation mode

Autodesk Fusion 360 software is used for the mechanical simulation step. Stress, tension, and flexibility tests were applied to the plastic plates. A force of 10 Newtons or 1.02 kilograms was applied, based on the average force applied to thermoplastic masks for head and neck.¹⁰ The software requires the specification of the sample material to mimic its mechanical properties. An attempt was made to reverse the g-code of each plate and utilize the STL format to acquire the various infills as an initial modeling approach for the plates. This approach, however, failed because the STL files lacked infill information about gyroid and honeycomb-gyroid.¹

Testing with universal testing machine (UTM)

Tensile testing was conducted with universal test machines (Lloyd Instruments LS 2.5, United Kingdom). All materials and infill patterns were subjected to tension testing at a speed of 20 mm/min, with a gauge length of

30 mm, a thickness ranging from 1.76 to 2.38 mm, and a cross-sectional area between 18.3 and 23.8 mm^2 . The tensile mechanical qualities, including maximum load and machine extension at maximum load, were examined. Following testing, the obtained data underwent analysis, and the results are provided through ultimate tensile strength, strain at maximum load, Young's modulus, and elongation.

Testing of the uniformity

The sample was x-rayed by a general x-ray machine (FDR Smart X, Fujifilm Medical System, Japan) with an exposure technique of 50 kVp, 3.2 mAs, and a source-to-image distance of 100 cm. The resulting images were examined for uniformity using ImageJ software, which included providing five same-size regions of interest (ROIs) and calculating both the mean and standard deviation. All regions of interest were clearly defined with an area of 5035-pixel². The measurement of uniformity for 3D-printed plastic sheets was illustrated in Figure 2 (A1-A5).

Testing of the density of samples using Hounsfield unit (HU) values

Samples of 10×10 cm^2 for Hounsfield unit (HU) assessments were scanned applying a Siemens SOMATOM Definition AS CT scanner (Global Siemens Healthcare, Erlangen, Germany) with 120 kVp tube potential, 270 mAs tube current and scan time, 500 mm field of view (FOV), 1.00 mm slice thickness, 0.4 pitch were used. The circular regions designated for measuring HU were precisely located at 1 mm^2 on middle axial slice CT images, with average HU values derived from five ROIs for each 3D-printed plate. The resulting images were evaluated for density by comparing the HU values of the sample plastic plates with those of a thermoplastic mask. Figure 2 (B1-B4).

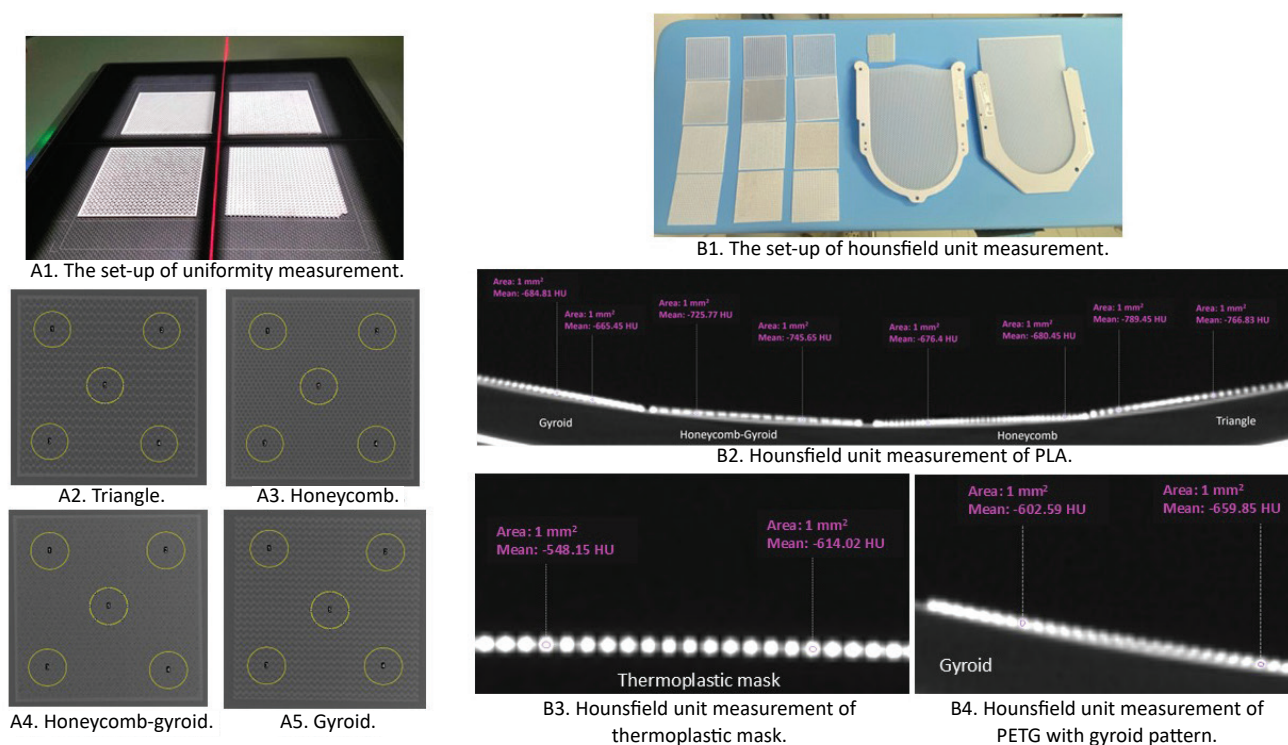


Figure 2. The measurement of uniformity and density for 3D-printed plastic sheets. A1-A5: measurement of uniformity for 3D-printed plastic sheets, B1-B4: testing the density of the samples using Hounsfield unit (HU) values

Testing of the radiation transmission

The sample irradiation was performed in the Radiation Oncology Center at Thammasat University hospital, Pathum Thani, Thailand. TRS-398 guidelines were followed in the calibration output, as recommended by the International Atomic Energy Agency (IAEA). The radiation dose was determined by inserting a 0.6 cm³ Farmer-type ionization chamber (PTW 30013, Freiburg, Germany) into a plastic slab phantom (Virtual Water™, Med-Cal, Tennessee, USA). The dose of radiation was measured at a depth of 5 cm from the surface of a 30 cm tissue-equivalent material (density was 1.04 gm/cm³, and a 30x30 cm size) or the surface-to-ionization chamber distance was 5 cm. The field size was 10x10 cm², and the source-to-skin distance

(SSD) was 95 cm. The radiation was delivered at a dose of 2 Gy (600 MU/min) using a 6 MV photon beam on the Elekta Versa HD linac (Elekta Oncology Systems, Crawley, UK). The radiation passing through the object was measured using a Farmer-type ionization device with a volume of 0.6 cm³. The object was placed on the tissue-equivalent material. The dose was quantified using an ionization chamber, followed by a comparison with a conventional immobilization thermoplastic mask of approximately 2 mm thick. The setup for testing radiation transmission was shown in Figure 3. The transmission of radiation emerges as it passes each plate, calculated as follows:

$$\% \text{ of transmitted dose} = \frac{\text{plastics sample measurement}}{\text{dose from control reading}} \times 100$$

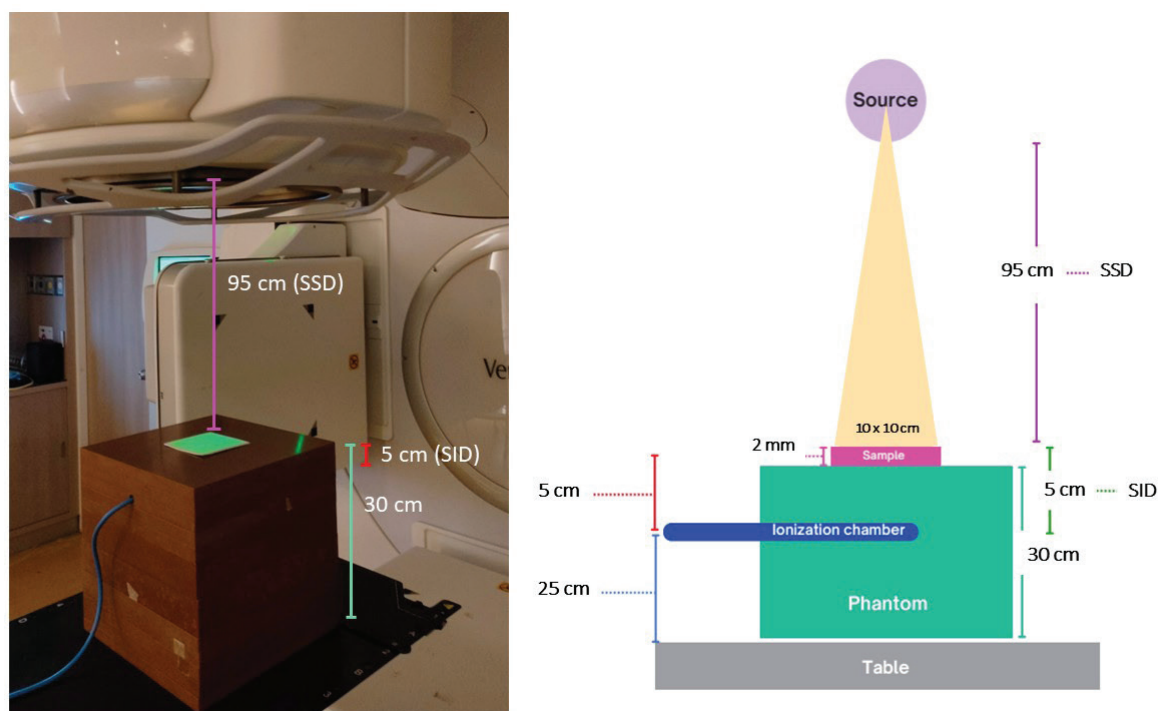


Figure 3. Equipment setup for measuring the radiation transmission.

Result

Fourier transform infrared (FTIR) analysis

FTIR analysis for PLA, PETG, and ASA filaments is given in Figure 4 (A). The FTIR spectra of the 3D printed plastics, recorded in the 4000-400 cm^{-1} wavenumber range, are graphically described.

The characteristic stretching peaks of PLA are the C-O stretching at 1081.83 cm^{-1} , the C-O-C stretching at 1180.49 cm^{-1} , the C-H bending at 1358.90 cm^{-1} and 1452.15 cm^{-1} , the C=O stretching at 1747.47 cm^{-1} . The CH₃ asymmetric and CH₃ symmetric bending frequencies were observed at 2995.13 and 2944.51 cm^{-1} , respectively.

In case of PETG, the characteristic bands of -CH were observed at 724.42 cm^{-1} . The peaks at 1016.47 and 1093.45 cm^{-1} are related with C-H bond vibrations. The peaks at 1407.97 and 1239.95 cm^{-1} are associated with

the -CH₂ deformation band and C-O-O stretching of ester groups, respectively. The peak at 1712.98 cm^{-1} frequency shows C=O ester groups. Asymmetric and symmetrical aliphatic C-H stretching are identified at frequencies of 2855.37 and 2927.41 cm^{-1} , respectively.^{11,12}

For investigation of ASA, the apparent peak at 1732.36 cm^{-1} was the C=O stretching vibration. The appearance of C≡N absorption band at 2236.85 cm^{-1} gave strong supporting evidence that the ASA. The bands with a peak value at around 1601.90, 1493.67, and 1452.67 cm^{-1} were assigned to stretching vibration peak of the benzene ring skeleton. Besides, peaks at 759.16 and 698.42 cm^{-1} represented C-H bending.¹² Figure 4 (B-D) showed the FTIR significant peaks for PLA, PETG, and ASA along with the associated assignments.

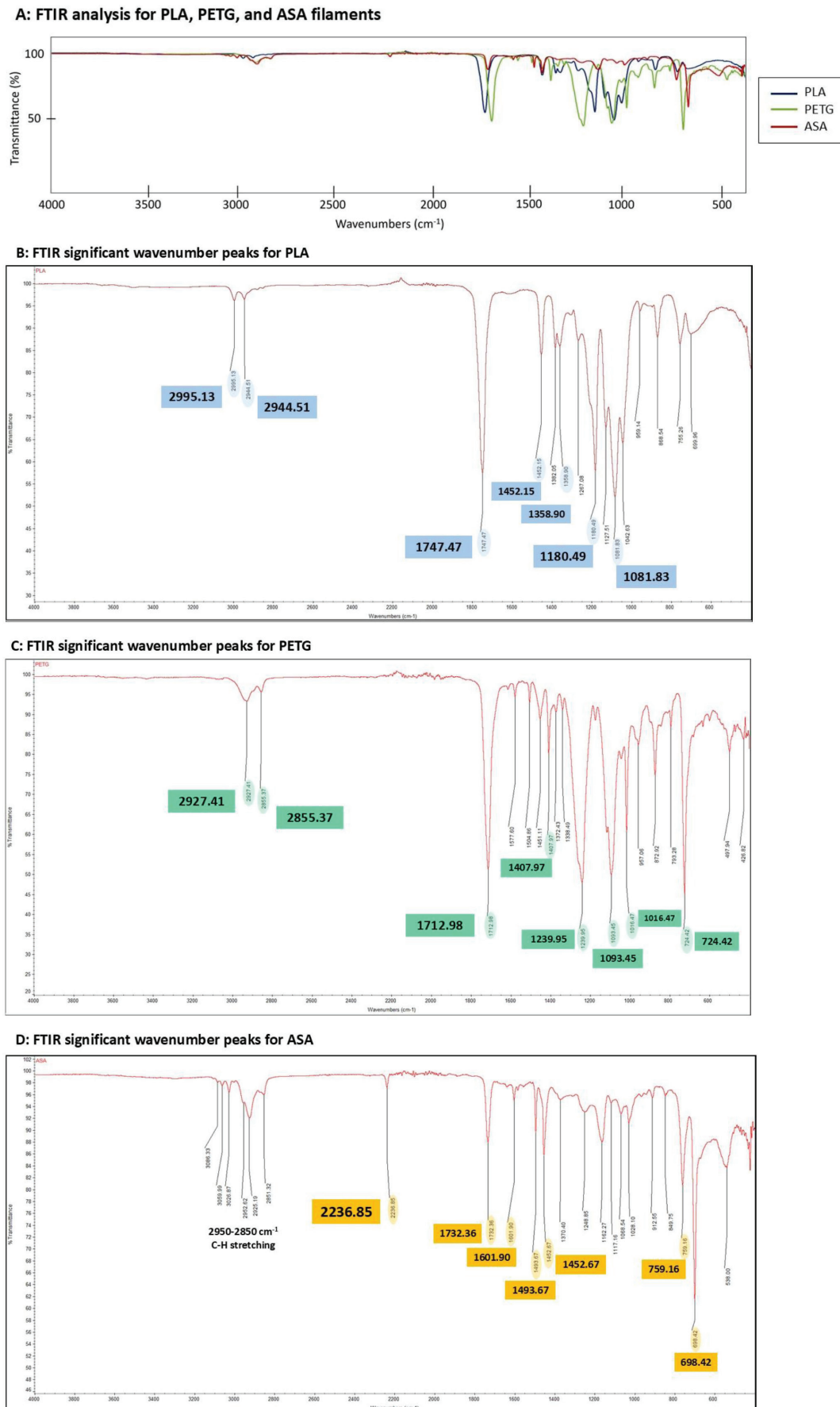


Figure 4. FTIR analysis of 3D printed specimens. A: FTIR analysis for PLA, PETG, and ASA filaments, B: FTIR significant wavenumber peaks for PLA, C: FTIR significant wavenumber peaks for PETG, D: FTIR significant wavenumber peaks for ASA.

Mechanical testing

Simulation-based testing using Autodesk Fusion 360

The mechanical characteristics were evaluated using numerical simulation. The outcomes of the mechanical test are presented in Table 2. All testing was performed utilizing Autodesk Fusion 360 in simulation mode. The stress testing, which evaluates the object's capacity to withstand external forces and its flexibility, revealed that

the PLA plastic sample featuring a honeycomb design had the highest strength at 41.46 MPa and a flexibility of 1.46 mm in the triangular infill pattern. In strain testing, which measures the force inducing deformation in an item, the ASA-honeycomb sample demonstrated a maximum value of 0.037 MPa. Figure 5 demonstrates the normalized physical properties of the material manufactured by the 3D printer.

Table 2. Mechanical properties test

Plastic type	Infill pattern	Stress	Strain	Flexibility
		Maximum (MPa)	Maximum (MPa)	Maximum (mm)
PLA	Triangle	20.82	0.02	1.46
	Honeycomb	41.46	0.04	0.39
	Honeycomb-gyroid	0.33	0.00*	0.01
	Gyroid	0.44	0.00*	0.07
PETG	Triangle	16.84	0.02	0.54
	Honeycomb	30.07	0.04	0.54
	Honeycomb-gyroid	0.33	0.00*	0.02
	Gyroid	0.40	0.00*	0.10
ASA	Triangle	20.81	0.02	0.42
	Honeycomb	39.56	0.04	0.42
	Honeycomb-gyroid	0.32	0.00*	0.01
	Gyroid	0.43	0.00*	0.01

Note: *values less than 0.01.

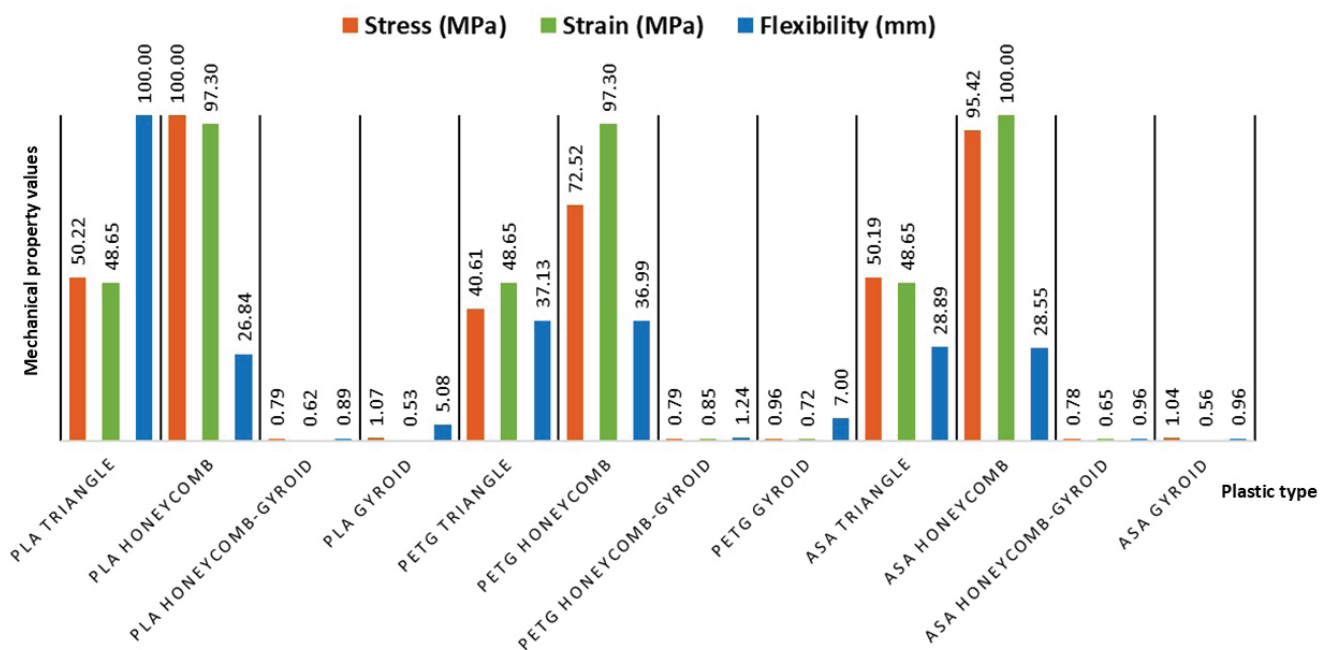


Figure 5. The mechanical properties, including stress, strain, and flexibility, of each plastic material and infill pattern.

Strength and flexibility testing using universal testing machine (UTM)

Testing was performed utilizing the Lloyd Instruments LS 2.5 Universal Testing Machine. PLA exhibited the highest ultimate tensile strength with the gyroid pattern (8.59 ± 1.67 MPa) and Young's modulus (461 ± 19 MPa); however, the triangle pattern displayed superior flexibility, achieving maximum strain at failure ($3.36 \pm 0.67\%$). The gyroid pattern for PETG had the highest ultimate tensile strength (10.88 ± 1.55 MPa), but the honeycomb pattern displayed enhanced flexibility with a maximum strain at

failure of $7.36 \pm 1.87\%$. Furthermore, the gyroid pattern demonstrated superior stiffness with a Young's modulus of 258 ± 41 MPa, significantly outperforming other patterns. For ASA, The gyroid pattern demonstrated superior stiffness (415 ± 15 MPa Young's modulus) and high tensile strength (9.38 ± 0.40 MPa), whereas the triangle pattern showed exceptional flexibility ($5.09 \pm 0.17\%$ strain at maximum load). The values of strength and flexibility obtained using the universal testing machine (UTM) are presented in Table 3 and Figure 6.

Table 3. The mechanical performance of each 3D-printed specimen with four different infill patterns.

Plastic type	Infill pattern	Ultimate Tensile Strength (MPa) $\pm$ SD	Strain at Max load (%) $\pm$ SD	Young's Modulus (MPa) $\pm$ SD	Elongation (mm)
PLA	Triangle	7.79 ± 1.35	3.36 ± 0.67	292 ± 24	1.16
	Honeycomb	8.26 ± 0.21	2.96 ± 0.53	336 ± 47	1.07
	Honeycomb-gyroid	2.63 ± 0.53	2.48 ± 0.95	160 ± 11	1.05
	Gyroid	8.59 ± 1.67	2.48 ± 0.27	461 ± 9	0.85
PETG	Triangle	6.67 ± 0.51	4.13 ± 0.27	192 ± 8	1.34
	Honeycomb	9.40 ± 1.49	7.36 ± 1.87	214 ± 7	2.81
	Honeycomb-gyroid	5.37 ± 0.45	6.76 ± 1.50	175 ± 10	2.35
	Gyroid	10.88 ± 1.55	5.86 ± 0.23	258 ± 41	1.81
ASA	Triangle	4.62 ± 0.26	5.09 ± 0.17	151 ± 8	1.58
	Honeycomb	8.93 ± 0.75	3.76 ± 0.56	278 ± 10	1.24
	Honeycomb-gyroid	4.00 ± 0.14	4.10 ± 0.41	164 ± 7	1.32
	Gyroid	9.38 ± 0.40	2.89 ± 0.20	415 ± 15	0.94

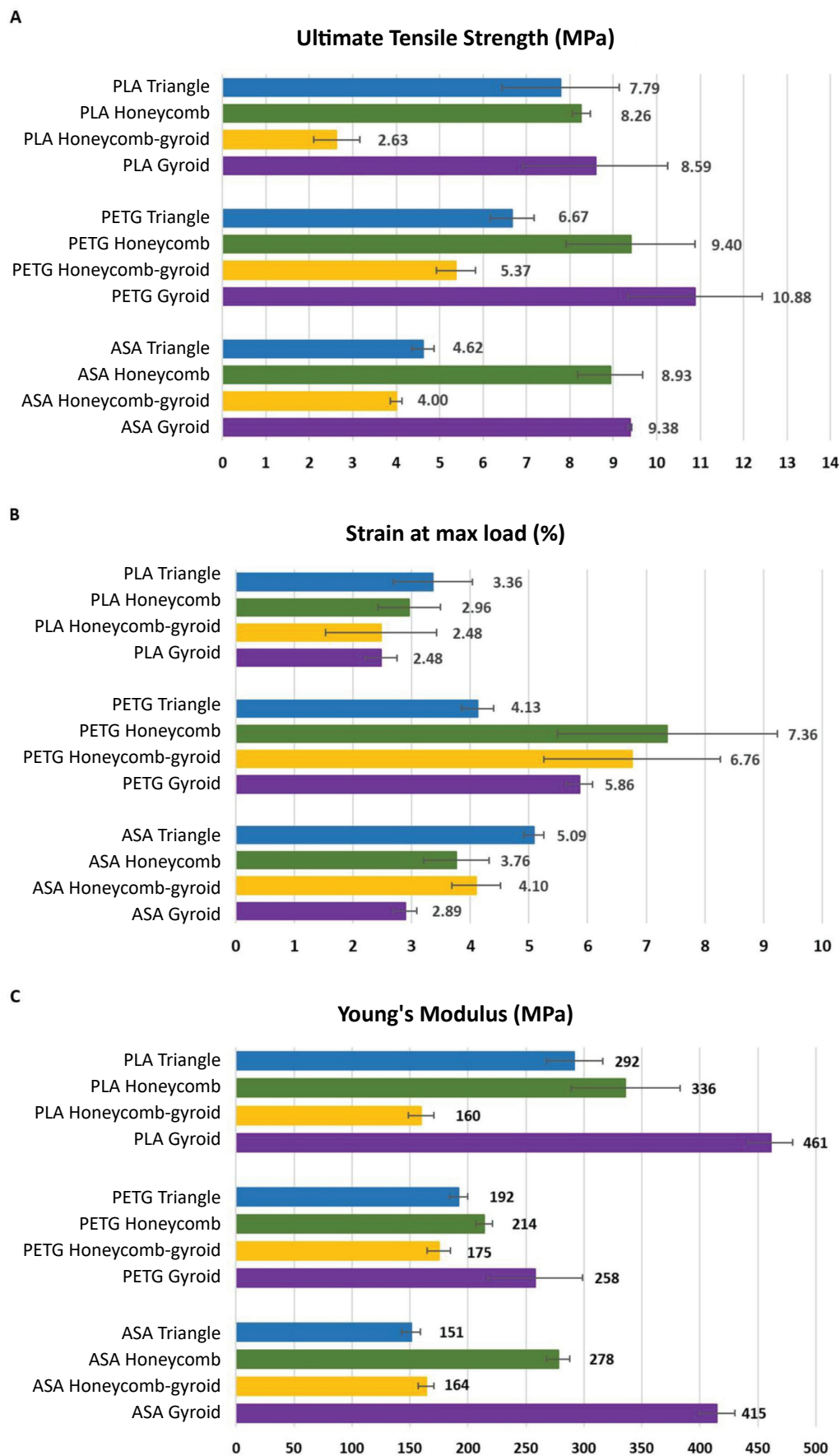


Figure 6. The mechanical properties of UTM of each plastic material and infill pattern.
A: ultimate tensile strength, B: strain at max Load, C: Young's Modulus (stiffness).

Uniformity and Hounsfield unit (HU) Testing

The uniformity assessment of the objects was performed by radiography each sample and evaluating the resultant images for uniformity utilizing the Image J software. The region of interest (ROI) was delineated at five spots on the pictures, and the homogeneity of each sample together with the thermoplastic mask was evaluated. The homogeneity of each plastic type—PLA, PETG, and ASA—exhibits the following ranges of mean and

standard deviation: 80.31-89.13 (5.27-10.33), 79.81-89.76 (5.44-8.98), and 79.99-88.66 (4.05-8.18), respectively. The previous values are presented in Table 4. The density of the 3D-printed plastic plates, measured in Hounsfield units (HU), was evaluated using the Synapse® PACS (Fujifilm Medical System, Japan), as shown in Table 4. The HU ranges for PLA, PETG, and ASA are -774.88 to -677.6, -730.27 to -649.24, and -757.7 to -620.21, respectively.

Table 4. Uniformity and Hounsfield unit of 3D-printed samples and standard thermoplastic mask

Plastic type	Infill pattern	Uniformity (gray values) Mean±SD	Hounsfield unit (HU) Mean±SD
Uni-frame® Thermoplastic mask		79.00±7.37	-567.53±40.09
Type-S™ Thermoplastic mask		79.90±7.44	-559.17±42.0
PLA	Triangle	80.31±10.33	-774.88±12.09
	Honeycomb	84.09±6.68	-699.43±22.23
	Honeycomb-gyroid	89.13±8.23	-722.48±25.29
	Gyroid	85.67±5.27	-677.6±23.27
PETG	Triangle	79.81±6.59	-730.27±36.36
	Honeycomb	83.98±6.47	-724.29± 20.61
	Honeycomb-gyroid	89.76±8.98	-711.25±34.87
	Gyroid	86.55±5.44	-649.24±29.10
ASA	Triangle	79.99±8.18	-757.7±34.02
	Honeycomb	84.22±6.76	-699.5±28.32
	Honeycomb-gyroid	88.66±4.05	-702.59±26.68
	Gyroid	86.58±4.73	-620.21±27.70

Dosimetric properties

As illustrated in Table 5, the percentages of dose differences and transmitted radiation are presented. The dose difference was determined by reducing the initial radiation dose from the dose that passed through the

sample. A standard immobilization thermoplastic mask (CIVCO Medical Solutions, Iowa, USA) approximately 2.4 mm thick, was irradiated to determine a term of comparison.

Table 5. Radiation transmission in different plastic type plates and infill pattern.

Plastic type	Infill pattern	% Dose difference	% Transmitted dose
No mask (control)		-	-
Uni-frame® Thermoplastic mask		0.4391	99.56
Type-S™ Thermoplastic mask		0.3585	99.64
PLA	Triangle	0.0896	99.91
	Honeycomb	0.1344	99.87
	Honeycomb-gyroid	0.4584	99.54
	Gyroid	0.1165	99.88
PETG	Triangle	0.5992	99.40
	Honeycomb	0.5834	99.42
	Honeycomb-gyroid	0.5318	99.47
	Gyroid	0.6994	99.30
ASA	Triangle	0.4693	99.53
	Honeycomb	0.5229	99.48
	Honeycomb-gyroid	0.5229	99.48
	Gyroid	0.5854	99.41

Comparable results were seen when the differences in transmission between each plate and the conventional mask were below 0.7%. PLA with triangular infill demonstrated superior performance compared to other materials for 6 MV photon energy, exhibiting a lower attenuation of 0.09% versus 0.4% for the typical thermoplastic mask.

The analysis of radiation dose transmission through 3D-printed masks made from PLA plastic (triangle, gyroid, honeycomb) reveals a transmission percentage ranging from 99.87% to 99.91%. This percentage is notably higher than the standard thermoplastic mask, which transmits between 99.56% and 99.64%, as illustrated in Figure 7.

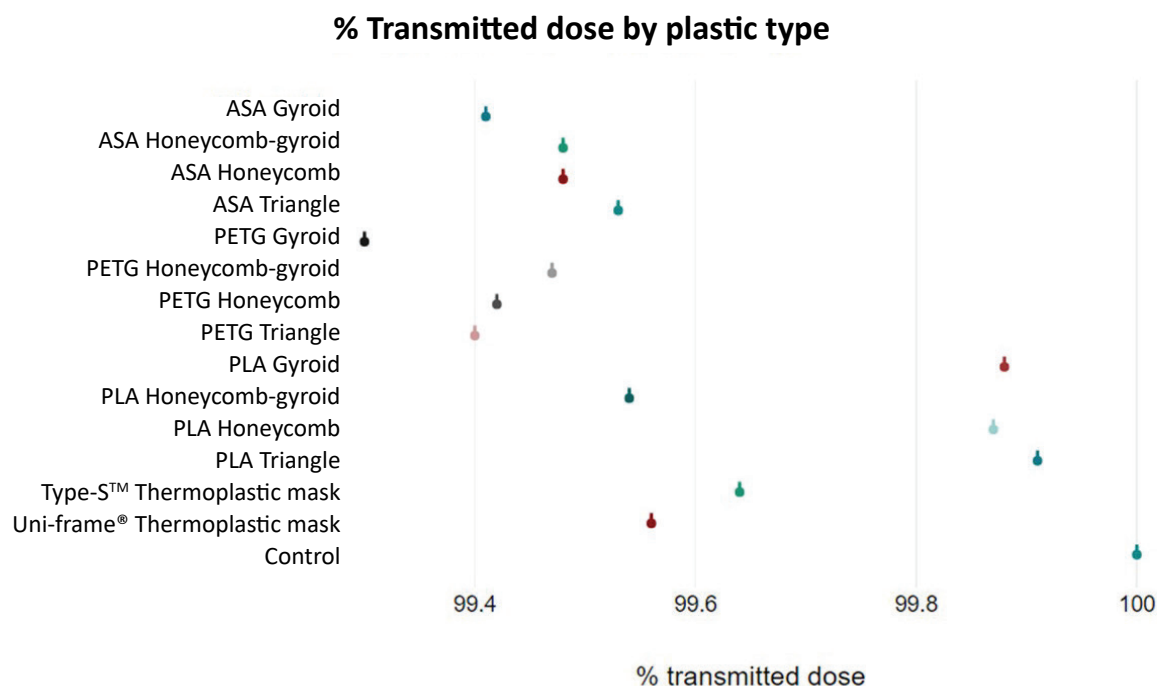


Figure 7. Variation of the transmitted radiation in percentage for different plastic type plates and infill pattern. (Graph plotted by DATAtab.net, Graz, Austria)

Discussion

Surgery, radiotherapy, and chemotherapy are widely utilized approaches in the treatment of cancer. A significant majority of patients with cancer receive treatment through radiotherapy. The primary objective in radiotherapy is to achieve optimal dose delivery to the tumor while reducing the side effects associated with the treatment. Therefore, it is crucial to carefully execute the radiation treatment design. While the introduction of advanced radiotherapy technologies has minimized errors associated with reconstructing the patient's geometry, certain inaccuracies remain in the production of accessories. The application of medical devices is not appropriate for every patient. Currently, 3D printing technology is regarded as a promising approach that can efficiently adapt to the treatment of individuals on a personalized basis. Consequently, there is significant interest in the utilization of 3D printing technology within the radiotherapy process.¹³

A variety of materials have been utilized to create the intended 3D object using the 3D printer, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG), thermoplastic elastomers (TPE), polyamide (PA, commonly referred to as nylon), thermoplastic polyurethane (TPU), and polyvinyl acetate, all of which have been assessed for their application in radiation therapy.^{14,15}

FTIR analysis was used to examine the chemical characteristics of three different types of filaments that were produced for 3D-printed sheets. The transmittance bands from 2996–2944 cm^{-1} correspond to the symmetric and asymmetric stretching of the CH_3 group. The band approximately of 1750 cm^{-1} (range of 1745–1758 cm^{-1}) corresponds to the vibration of the $\text{C}=\text{O}$ bond of PLA because of the presence of the ester. This peak was intense due to the concentration of PLA and ester in the formulation. The band at 1267 cm^{-1} is associated with the $\text{C}=\text{O}$ bending vibration, while the bands at 1180 and 1130 cm^{-1} correspond to the $\text{C}-\text{O}-\text{C}$ stretching vibration of the ester groups in PLA polymer.¹⁶

The % transmittance at around 1717 cm^{-1} indicates a significant peak of PETG associated with the $\text{C}=\text{O}$ stretching vibration in the ester group, contrasting with PLA, which exhibits a band at 1750 cm^{-1} . The PETG spectrum has peaks at around 1505, 875, and 730 cm^{-1} , indicative of aromatic bond vibrations that are absent in the PLA spectra.¹⁷

The $\text{C}\equiv\text{N}$ stretching band (2236–2238 cm^{-1}) is the most significant and characteristic peak of ASA, indicating the vibration of the $\text{C}\equiv\text{N}$ bond in the nitrile group of the acrylonitrile unit. The $\text{C}=\text{O}$ stretching seen at around 1733–1735 cm^{-1} indicates the vibration of the $\text{C}=\text{O}$ bond within the ester group of the acrylate component in ASA. The aromatic $\text{C}=\text{C}$ stretching peaks are observed at roughly 1602 and 1493 cm^{-1} , signifying the vibration of the

C=C bond within the benzene ring, a hallmark of the aromatic structure in the styrene component. This verifies that ASA is a terpolymer consisting of three primary constituents: acrylonitrile, styrene, and acrylate.¹²

FTIR analysis in this experiment revealed that PLA corresponded with polylactide at 95.65%; PETG aligned with poly (ethylene terephthalate) at 95.11%; and ASA matched with copier toner (ether extract) styrene acrylate copolymer at 87.40% and poly (styrene: acrylonitrile: methyl acrylate) at 83.91%. The matching was conducted with the reference spectrum from the OMNIC software library.

Different materials and filling patterns will yield varying outcomes based on mechanical test analysis. In Autodesk Fusion 360 simulation testing, the strength testing showed that honeycomb patterns are the strongest, supporting the results of previous study³, which found that hexagons have better stress and strain scores than other shapes. Flexural testing indicates that PLA with a triangle infill pattern exhibits the greatest flexibility, followed by PETG and ASA materials. Most types of thermoplastic masks allow deviations of 2 to 5 mm.¹⁸ In all plastic plates, the displacement (in mm) was less than 1.46 mm. This was below the previously reported range of 2 to 5 mm and proved to be an excellent result.

While, in universal tensile machine (UTM) testing, the gyroid infill pattern revealed the highest ultimate tensile strength, closely followed by honeycomb across all plastic types. These findings correspond with recent studies indicating that complex 3D infill patterns, such as gyroid, offer enhanced strength-to-weight ratios owing to their isotropic load distribution properties.^{19,20}

Our results demonstrate that material-infill pattern interactions significantly influence mechanical performance. The gyroid infill pattern emerged as the optimal choice across all three materials for applications requiring high stiffness and strength^{21,22}, which demonstrate gyroid's superior mechanical resistance compared to conventional patterns.

For Flexibility, the triangle infill pattern consistently provided superior flexibility across PLA and ASA materials, achieving strain values of 3.36% (PLA) and 5.09% (ASA) at maximum load. This aligns with recent literature indicating triangular patterns' exceptional energy absorption and impact resistance capabilities.²³

While honeycomb patterns showed high theoretical strength potential, our analysis revealed significant manufacturing consistency challenges, 3D-printed plastics sheet with honeycomb has strength less than gyroid pattern. This contrasts with some literature suggesting honeycomb as the universally strongest pattern²⁴, highlighting the importance of material-specific optimization and quality control in FDM processing.

On material-specific performance characteristics, PLA demonstrated exceptional stiffness characteristics, achieving the highest Young's modulus values (up to 461 MPa with gyroid infill pattern), consistent with literature reporting PLA's superior mechanical properties in controlled environments. However, our findings confirm PLA's brittleness

limitations, with relatively low strain values and reduced performance under environmental stress conditions, supporting recent weathering studies.^{25,26}

PETG emerged as the most balanced performer, achieving the highest ultimate tensile strength (10.88 MPa with gyroid) while maintaining excellent flexibility (7.36% strain with honeycomb).²⁵ The material's consistent performance across all infill patterns supports its growing adoption for functional applications requiring both strength and durability.²⁷

ASA showed competitive mechanical properties with exceptional environmental resistance capabilities, achieving high stiffness (415 MPa) comparable to PLA while maintaining better flexibility characteristics. However, manufacturing inconsistencies, particularly with complex infill patterns, highlight processing optimization needs.²⁷

Nonetheless, various factors can affect the analysis of the mechanical properties of plastic plates: infill density, extrusion temperature, infill orientation, layer thickness, and even filament color. Consequently, it is essential for the printed mask to undergo mechanical testing with standard material dimension size to ensure a more accurate assessment of its properties and to determine the actual displacement.²⁸

The plastic plates produced by the 3D printer demonstrate consistent quality, as analyzed through the ImageJ program, with an average standard deviation between 5.93 and 7.63. The thermoplastic mask illustrates a value of 7.4, suggesting that the 3D printer has the capability of consistently producing each piece.

The analysis of sample density through Hounsfield unit (HU) revealed that the ASA featuring a gyroid structure has a HU of -620.21, which is nearest to the Uni-frame® and Type-S™ Thermoplastic mask. The HU values for all 3D-printed samples range from -774.88 to -620.21, indicating a very low radiological density—comparable to lung density (-950 to -550)²⁹, which is advantageous for radiotherapy applications as it minimizes beam attenuation.^{1,30} The filling pattern may influence the size of the air gap and the value of HU. The dimensions of the air gap and the HU value were significant factors in getting equivalent tissue.

The radiological properties of 3D-printed materials, particularly their Hounsfield unit (HU) values, have been the subject of extensive research by numerous research groups. These studies have revealed substantial variations that are dependent on the material composition, infill density, and printing parameters. Across various research groups, PLA material exhibits the most extensively investigated HU characteristics. Fundamental baseline values were reported in the previous study, which demonstrated a strong infill density dependence with HU values ranging from -904 at 10% infill to +61 at 100% infill. At the 60% infill density that is frequently employed, PLA demonstrated HU values of -530±25, which places it within the lung-to-soft tissue equivalent range.³⁰ In the fabrication of the anthropomorphic phantom or thermoplastic mask of radiation therapy, the infill density of 45-55% is equivalent to the HU of lung tissue when

constructed from other materials, such as PETG, ASA, and ABS.^{31,32} This is in accordance with this research that was printed with a 40% infill density, and the Hounsfield units (HU) of the three varieties of plastic are near the density of lung tissue.

The triangle structure in PLA allows the highest radiation transmission at 99.91%, displaying a minimal dose difference of 0.09%. By contrast, the PLA gyroid structure attains a 99.88% transmission rate with a 0.12% dose difference. The honeycomb-gyroid structure made from PETG demonstrates the lowest radiation transmission at 99.30%, showing a dose difference of 0.70%. The results show that all three types of plastic plates radiation similarly to the thermoplastic mask samples, which have transmission rates of 99.56% and 99.64%, with dose differences of 0.44% and 0.36%. The increased thickness in plate manufacture may affect radiation attenuation.

Limitations

The strength and flexibility values tested through Autodesk Fusion 360 in simulation mode using a compressive force of 10 Newtons (equivalent to 1.02 kilograms) are only predicted values from the program. In simulation mode does not fully support the analysis of the strength and flexibility of internal structures like gyroid and honeycomb-gyroid as comprehensively as other internal structures. Therefore, the strength and flexibility values for gyroid and honeycomb-gyroid internal structures may deviate from their actual values.

The mechanical testing conducted through simulation in Autodesk Fusion 360 provides valuable preliminary information. The test plastics utilized were flat sheets, inadequate to resemble the curvature required for actual anatomical patient application. Additional investigations will be conducted using 3D models to align with realistic patients.

The mechanical testing conducted by UTM has been limited by factors such as the dimensions of plastic sheets, the size of specimens for cross-sectional area assessments, the restriction to a single environmental testing setting, and the limited number of samples for certain material-pattern combinations.

Recommendations

Strength and flexibility tests of the plastic sheets should be conducted using a compressive testing machine alongside Autodesk Fusion 360 to increase the accuracy of the strength and flexibility values obtained.

Perform experiments focused on the production of larger components and their fabrication using 3D patient models, which are obtained from techniques like computed tomography (CT) or magnetic resonance imaging (MRI), combined with sophisticated computer-aided design (CAD), 3D scanning, and virtual planning software.

Subsequent research should address these shortcomings by implementing expanded testing matrices and consistent specimen preparation techniques for tensile testing and comparative investigation in different material filament brands.

Conclusion

This pilot study examines Fused Deposition Modeling (FDM) technology in 3D printing using the four different infill patterns of Polylactic Acid (PLA), Polyethylene Terephthalate Glycol-Modified (PETG), and Acrylonitrile Styrene Acrylate (ASA) for the fabrication of radiation immobilization devices. Based on comprehensive property testing, all three types of plastic have proven to be appropriate alternative materials for the integration of an immobilization mask. As a result, PLA plates displayed advantageous results in terms of radiation transmission, while PETG emerged as the most balanced performer in terms of mechanical properties, showing high strength and flexibility. ASA, a polymer containing a benzene ring, demonstrated that it is more resistant to radiation. Additionally, the Hounsfield unit (HU) value that is related to each soft tissue could be varied according to the characteristics and % infill pattern density.

Funding

The authors gratefully acknowledge the financial support provided by the Faculty of Allied Health Sciences Research Fund, Contract No. AHSNS1/2565

Conflict of interest

The authors declare that they have no conflicts of interest.

CRediT authorship contribution statement

Kochakorn Phantawong: conceptualization, methodology, validation, formal analysis, data curation, writing: original draft, review and editing, project administration and funding acquisition; **Nongnat Singthuan:** data collection, analysis, interpretation of results and writing: original draft; **Kanjana Pinichsai:** data collection, analysis, interpretation of results and writing: original draft; **Somchat Taertulakarn:** supervision and funding acquisition

Acknowledgements

The authors would like to thank the staff of the Radiation Oncology Center at Thammasat University hospital for their assistance and use of their facilities during this research.

References

- [1] Duarte J, Loja MAR, Portal R, Vieira L. 3D printing of abdominal immobilization masks for therapeutics: dosimetric, mechanical and financial analysis. *Bioengineering (Basel)*. 2022; 9(2): 55. doi: 10.3390/bioengineering9020055.
- [2] Mattke M, Rath D, Häfner M, Unterhinninghofen R, Sterzing F, Debus J, et al. Individual 3D-printed fixation masks for radiotherapy: first clinical experiences. *Int J Comput Assist Radiol Surg*. 2021; 16(6): 1043-9. doi: 10.1007/s11548-021-02393-2.
- [3] Sa'ude N, Ab Latib NAN. A study on the mechanical properties of PLA, ABS and PETG filament printed by various type of infill design using 3D printing

- machine. RPMME. 2023; 4(2): 162-7. [cited 2025 May 11]. Available from: <https://publisher.uthm.edu.my/periodicals/index.php/rpmme/article/view/11492>.
- [4] Asfia A, Novak JI, Mohammed MI, Rolfe B, Kron T. A review of 3D printed patient specific immobilisation devices in radiotherapy. *Phys Imaging Radiat Oncol*. 2020; 13: 30-5. doi: 10.1016/j.phro.2020.03.003.
 - [5] Farah S, Anderson DG, Langer R. Physical and mechanical properties of PLA, and their functions in widespread applications—A comprehensive review. *Adv Drug Deliv Rev*. 2016; 107: 367-92. doi: 10.1016/j.addr.2016.06.012.
 - [6] Van der Walt M, Crabtree T, Albantow C. PLA as a suitable 3D printing thermoplastic for use in external beam radiotherapy. *Australas Phys Eng Sci Med*. 2019; 42: 1165-76. doi: 10.1007/s13246-019-00818-6.
 - [7] Ramírez-Revilla S, Camacho-Valencia D, Gonzales-Condori EG, Márquez G. Evaluation and comparison of the degradability and compressive and tensile properties of 3D printing polymeric materials: PLA, PETG, PC, and ASA. *MRS Commun*. 2023; 13(1): 55-62. doi: 10.1557/s43579-022-00311-4.
 - [8] Robar JL, Kammerzell B, Hulick K, Kaiser P, Young C, Verzwylt V, et al. Novel multi jet fusion 3D-printed patient immobilization for radiation therapy. *J Appl Clin Med Phys*. 2022; 23(11): e13773. doi: 10.1002/acm2.13773.
 - [9] Novak JI, Liu MZ-E, Loy J. Designing thin 2.5 D parts optimized for fused deposition modeling. *Additive Manufacturing Technologies From an Optimization Perspective*. Hershey, PA: IGI Global; 2019: pp 134-64. doi: 10.4018/978-1-5225-9167-2.
 - [10] Kim T-H, Cho M-S, Shin D-S, Shin DH, Kim S. Development of a real-time thermoplastic mask compression force monitoring system using capacitive force sensor. *Front Robot AI*. 2022; 9: 778594. doi: 10.3389/frobt.2022.778594.
 - [11] Demir E, Duygun İK, Bedeloğlu A. The mechanical properties of 3D-printed polylactic acid/polyethylene terephthalate glycol multi-material structures manufactured by material extrusion. *3D Print Addit Manuf*. 2024; 11(1): 197-206. doi: 10.1089/3dp.2021.0321.
 - [12] Zhang Y, Zhang X, Cao Y, Feng J, Yang W. Acrylonitrile-styrene-acrylate particles with different microstructure for improving the toughness of poly (styrene-co-acrylonitrile) resin. *Adv Polym Technol*. 2021; 2021(1): 3004824. doi: 10.1155/2021/3004824.
 - [13] Moghaddam SHZ. Applications of Three-Dimensional Printing Technology in Radiotherapy: Advances in 3D Printing. London: IntechOpen; 2023. doi: 10.5772/intechopen.109398.
 - [14] Alssabbagh M, Abdulmanap M, Zainon R. Evaluation of 3D printing materials for fabrication of a novel multi-functional 3D thyroid phantom for medical dosimetry and image quality. *Radiat Phys Chem*. 2017; 135: 106-12. doi: 10.1016/j.radphyschem.2017.02.009.
 - [15] Zhao Y, Moran K, Yewondwossen M, Allan J, Clarke S, Rajaraman M, et al. Clinical applications of 3-dimensional printing in radiation therapy. *Med Dosim*. 2017; 42(2): 150-5. doi: 10.1016/j.meddos.2017.03.001.
 - [16] Moldovan A, Cuc S, Prodan D, Rusu M, Popa D, Taut AC, et al. Development and characterization of polylactic acid (PLA)-based nanocomposites used for food packaging. *Polymers (Basel)*. 2023; 15(13): 2855. doi: 10.3390/polym15132855.
 - [17] Talataisong W, Ismaeel R, Marques TH, Abokhamis Mousavi S, Beresna M, Gouveia M, et al. Mid-IR Hollow-core microstructured fiber drawn from a 3D printed PETG preform. *Sci Rep*. 2018; 8(1): 8113. doi: 10.1038/s41598-018-26561-8.
 - [18] Haefner M, Giesel F, Mattke M. 3D-Printed masks as a new approach for immobilization in radiotherapy—A study of positioning accuracy. *Oncotarget*. 2018; 9(5): 6490-8. doi: 10.18632/oncotarget.24032.
 - [19] Aboelella MG, Ebeid SJ, Sayed MM. Layer combination of similar infill patterns on the tensile and compression behavior of 3D printed PLA. *Sci Rep*. 2025; 15(1): 11759. doi: 10.1038/s41598-025-94446-8.
 - [20] Dawood LL, AlAmeen ES. Influence of infill patterns and densities on the fatigue performance and fracture behavior of 3D-printed carbon fiber-reinforced PLA composites. *AIMS Mater Sci*. 2024; 11(5): 833–57. doi: 10.3934/matricsci.2024041.
 - [21] Pandžić A, Hodžić D, Milovanović A, editors. Effect of infill type and density on tensile properties of PLA material for FDM process. *Proceedings of the 30th DAAAM international symposium*; 2019: 0545-0554. doi: 10.2507/30th.daaam.proceedings.074.
 - [22] Pandzic A, Hodzic D, editors. Mechanical properties comparison of PLA, tough PLA and PC 3D printed materials with infill structure—Influence of infill pattern on tensile mechanical properties. *IOP Conf Ser Mater Sci Eng*. 2021; 1208 (1): 012019. doi: 10.1088/1757-899X/1208/1/012019.
 - [23] Amador AMG, Avendano RAV, González AQ, Fernández LP. Mechanical characterization and testing of multi-polymer combinations in 3D printing. *Heliyon*. 2025; 11(3): e42420. doi: 10.1016/j.heliyon.2025.e42420.
 - [24] Eryildiz M. The effects of infill patterns on the mechanical properties of 3D printed PLA parts fabricated by FDM. *Ukr. J Mech Eng Mater Sci*. 2021; 7(1-2): 1-8. doi: 10.23939/ujmms2021.01-02.001.
 - [25] Sedlak J, Joska Z, Jansky J, Zouhar J, Kolomy S, Slany M, et al. Analysis of the mechanical properties of 3D-printed plastic samples subjected to selected degradation effects. *Materials (Basel)*. 2023; 16(8): 3268. doi: 10.3390/ma16083268.
 - [26] Cressall S, Phillips CO, Al-Shatty W, Deganello D. The effect of high-intensity gamma radiation on PETG and ASA polymer-based fused deposition modelled 3D printed parts. *J Mater Sci*. 2024; 59(4): 1768-82. doi: 10.1007/s10853-023-09309-2.
 - [27] Iacob DV, Zisopol DG, Minescu M. Technical-economical study on the optimization of FDM

- parameters for the manufacture of PETG and ASA parts. *Polymers (Basel)*. 2024; 16(16): 2260. doi: 10.3390/polym16162260.
- [28] Asfia A, Deepak B, Novak JI, Rolfe B, Kron T. Multi-jet fusion for additive manufacturing of radiotherapy immobilization devices: Effects of color, thickness, and orientation on surface dose and tensile strength. *J Appl Clin Med Phys*. 2022; 23(4): e13548. doi: 10.1002/acm2.13548.
- [29] Kalender WA. *Computed tomography: fundamentals, system technology, image quality, applications*: 3rd Edition. Germany: John Wiley & Sons; 2011.
- [30] Park S-Y, Choi N, Choi BG, Lee DM, Jang NY. Radiological characteristics of materials used in 3-dimensional printing with various infill densities. *Prog Med Phys*. 2019; 30(4): 155-9. doi: 10.14316/pmp.2019.30.4.155.
- [31] Hariyanto AP, Christiani KH, Rubiyanto A, Nasori N, Haekal M, Endarko E. The effect of pattern and infill percentage in 3D Printer for phantom radiation applications. *JID*. 2022; 23(2): 87-92. doi: 10.19184/jid.v23i2.27256.
- [32] Bustillo JPO, Mata JL, Posadas JRD, Inocencio ET, Rosenfeld AB, Lerch ML. Characterization and evaluation methods of fused deposition modeling and stereolithography additive manufacturing for clinical linear accelerator photon and electron radiotherapy applications. *Phys Med*. 2025; 130: 104904. doi: 10.1016/j.ejmp.2025.104904.