The Effect of Pattern and Infill Percentage in 3D Printer for Phantom Radiation Applications

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ABSTRACT

3D printing technology was capable of fabricating phantoms to enhance quality assurance in radiation therapy. The ideal phantom has properties equivalent to the real tissue. However, 3D printing has the limits to mimicking the attenuation properties of various tissues because during 3D printing there can be only one type of material. The purpose of this study was to evaluate the effect of infill percentage and infill patterns of 3D printing technology to simulate various types of tissue. This study used 25 samples measuring 5 × 5 × 1 cm³ from PETG material. The 20 samples were printed using variations infill percentages from 5 - 100% and the infill pattern in lines. The five samples were then printed with the infill percentage constant at 50% and used the infill pattern triangles, grid, gyroid, octet, and concentric. We used Computed Tomography (CT) to determine the Hounsfield Unit (HU) value for each sample and evaluated the suitability of each sample for phantom applications in radiation therapy and radiology. However, none of the samples was able to simulate compact bone. As a result, we found that PETG material could simulate the properties of soft tissue, fat, lung, kidney, liver, pancreas, and spongy bone. Thus, the study had shown promising potential for the fabrication of the anthropomorphic phantom of radiation therapy.

Keywords: 3D printing, Hounsfield Unit (HU), PETG, Infill Percentage, Infill Pattern.

INTRODUCTION

3D printing technology has benefited so extensively, especially in the health field. In radiation oncology, 3D printing technology produces bolus for radiotherapy patients in severe curvature areas, like the nose, feet, hands, and ears. As a result, tumor cells close to the skin can receive a maximum radiation dose while reducing the radiation dose to the organs at risk around them (Park et al., 2019). Furthermore, it is possible to create an anthropomorphic phantom with 3D printing technology to create patient-specific anatomy using Digital Imaging and Communications in Medicine (DICOM) Computed Tomography data (Okkalidis, 2018). The phantom is a real mimicking model with properties equivalent to the tissue (White, 1993). In radiodiagnostics, phantoms are important for assessing image quality, optimizing more realistic and controlled imaging systems (Mayer et al., 2015), and developing imaging techniques (Martini et al., 2020). Whereas in radiotherapy, specific anthropomorphic phantoms can improve the accuracy of quality assurance and control in radiation therapy treatment. However, the 3D printing technology has limited applications in quality assurance because 3D printing cannot bring about a variety of human body densities.
replacements that were 3D printed had -794 ± 120 HU and -487 ± 35 HU, respectively (Madamesila et al., 2016). Furthermore, Kairn et al. have also taken a similar approach to Madamesila J. et al. using Acrylonitrile Butadiene Styrene (ABS) materials. The result showed that an infill of 30% for ABS had potential like lung phantoms and infill 90% correlated with tumor, muscle, and other soft tissue density. Therefore, this study will evaluate the density of Polyethylene Terephthalate (PETG) material using various patterns and infill percentages for radiation phantom applications. The choice of PETG material as a phantom radiation material was because this material was easily obtained commercially, had a density of 1.23 g/cm³, and was easier to set up than ABS material. The evaluation process involved evaluating geometric (mass) printing accuracy and tissue equivalence through the Hounsfield Unit (HU) value so that 3D printing techniques can be widely adopted for anthropomorphic phantoms in the future.

**METHODS**

We used PETG filament from Shenzhen eSun Industrial CO., Ltd. with the best print and bed temperature characteristics, 230-250°C and 60-80°C, respectively. We made 25 samples of PETG material in the form of a box measuring 5×5×1 cm³. Sample fabrication used 3D Creality CR 10 MAX (Shenzhen Creality 3D Technology CO. Ltd. China) with a general printing setting shown in Table 1. Printing of 20 samples was carried out by varying percentage infill from 5-100% with increment of 5%, lines pattern. Furthermore, the remaining five samples were printed with variations in inner structure patterns (Grid, Concentric, Gyroid, Octet, and Triangles), the infill percentage kept constant at 50%. All samples were measured for mass using Vernier Analytical Balance Type VAB2104. Then, the percentage difference between the sample printing mass and the estimated mass (obtained from Ultimaker Cura 4.7) can be calculated using equation (1).

\[
\% \text{diff} = \left| \frac{m_a - m_e}{m_e} \right| \times 100\% \quad (1)
\]

where \(m_a\) is the printing mass (g) and \(m_e\) is the estimated mass (g).

Table 1. General setting for 3D printing Fused Deposition Method (FDM)

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer Height</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Initial Layer Height</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Infill Density</td>
<td>5 - 100%</td>
</tr>
<tr>
<td>Infill Pattern</td>
<td>Lines</td>
</tr>
<tr>
<td>Printing Temperature</td>
<td>235 °C (PETG)</td>
</tr>
<tr>
<td>Build plate Temperature</td>
<td>60 °C (PETG)</td>
</tr>
</tbody>
</table>

A total of 25 samples were scanned using a CT Scanner under a set of 120 kV, 480 mA, 1 mm thickness. Figure 1. Shown the results of photographic images and topogram images from 25 PETG samples. Hounsfield Unit (HU) is the value that contains the grey level of the CT image and can be calculated through the linear attenuation coefficient value as follows (Khan & Gibbons (Jr.), 2014):

![Figure 1. (A) Photographic image of samples from 5 – 100% infill, a) Concentric, b) Grid, c) Gyroid, d) Octet, e) Triangles. (B) Topogram image of the samples from 5 - 100% infill, ) Concentric, b) Grid, c) Gyroid, d) Octet, e) Triangles obtained from CT-Scan.](image)
Table 2. Percentage of difference in printing mass to the estimated mass by Ultimaker Cura

<table>
<thead>
<tr>
<th>Infill Density (%)</th>
<th>Printing Mass (g)</th>
<th>Estimated Mass (g)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5.709</td>
<td>5.7</td>
<td>0.158</td>
</tr>
<tr>
<td>10</td>
<td>7.071</td>
<td>7.1</td>
<td>0.408</td>
</tr>
<tr>
<td>15</td>
<td>8.471</td>
<td>8.4</td>
<td>0.845</td>
</tr>
<tr>
<td>20</td>
<td>9.839</td>
<td>9.8</td>
<td>0.398</td>
</tr>
<tr>
<td>25</td>
<td>11.292</td>
<td>11.1</td>
<td>1.730</td>
</tr>
<tr>
<td>30</td>
<td>12.621</td>
<td>12.5</td>
<td>0.968</td>
</tr>
<tr>
<td>35</td>
<td>14.101</td>
<td>13.8</td>
<td>2.181</td>
</tr>
<tr>
<td>40</td>
<td>15.831</td>
<td>15.2</td>
<td>4.151</td>
</tr>
<tr>
<td>45</td>
<td>17.172</td>
<td>16.8</td>
<td>2.214</td>
</tr>
<tr>
<td>50</td>
<td>17.765</td>
<td>17.9</td>
<td>0.754</td>
</tr>
<tr>
<td>55</td>
<td>19.815</td>
<td>19.2</td>
<td>3.203</td>
</tr>
<tr>
<td>60</td>
<td>21.538</td>
<td>20.6</td>
<td>4.553</td>
</tr>
<tr>
<td>65</td>
<td>22.747</td>
<td>21.9</td>
<td>3.868</td>
</tr>
<tr>
<td>70</td>
<td>24.071</td>
<td>23.3</td>
<td>3.309</td>
</tr>
<tr>
<td>75</td>
<td>25.211</td>
<td>24.6</td>
<td>2.484</td>
</tr>
<tr>
<td>80</td>
<td>26.341</td>
<td>26</td>
<td>1.312</td>
</tr>
<tr>
<td>85</td>
<td>27.101</td>
<td>27.3</td>
<td>0.729</td>
</tr>
<tr>
<td>90</td>
<td>28.535</td>
<td>28.7</td>
<td>0.575</td>
</tr>
<tr>
<td>95</td>
<td>29.709</td>
<td>29.8</td>
<td>0.305</td>
</tr>
<tr>
<td>100</td>
<td>30.132</td>
<td>31.1</td>
<td>3.113</td>
</tr>
<tr>
<td>50 (triangular)</td>
<td>17.698</td>
<td>17.9</td>
<td>1.128</td>
</tr>
<tr>
<td>50 (octec)</td>
<td>17.77</td>
<td>17.9</td>
<td>0.726</td>
</tr>
<tr>
<td>50 (gyround)</td>
<td>17.852</td>
<td>17.6</td>
<td>1.432</td>
</tr>
<tr>
<td>50 (Concentric)</td>
<td>17.519</td>
<td>17.5</td>
<td>0.109</td>
</tr>
<tr>
<td>50 (grid)</td>
<td>17.861</td>
<td>17.9</td>
<td>0.218</td>
</tr>
</tbody>
</table>

\[
H_U = \frac{\mu_{\text{material}} - \mu_{\text{water}}}{\mu_{\text{water}}} \times 1000 \tag{2}
\]

where \(\mu_{\text{material}}\) is the linear attenuation coefficient for specific materials and \(\mu_{\text{water}}\) is the linear attenuation coefficient of water. Air has a HU value equal to -1000 because the linear attenuation coefficient of air is 0, and water has a HU value equal to 0. In this study, we created a region of interest (ROI) derived from the appearance of the axial CT image to evaluate the HU value for each sample. The average value of HU obtained from PETG material with an infill percentage of 5-100% was presented in a graph where the x-axis was the infill percentage, and the y-axis was the average value of HU. Furthermore, the graph was analyzed by the fitting method using the linear equation below:

\[
H_U = a \cdot \text{infill density} + b \tag{3}
\]

Moreover, the mean value of HU was also obtained from PETG with variations in the internal structure filling pattern shown in Table 4 for us to compare.

RESULTS AND DISCUSSION
As shown in Table 2, the percentage difference between the printing mass and the estimated was calculated using equation (1). Generally, the printing mass of PETG material had a slightly larger value than the estimated Ultimaker Cura. The percentage difference between the printing mass over the estimated mass was between <5%, and the variation in printing mass was still within the acceptable range. The average value of HU overall was obtained at 1.635%.

Table 3. Fitting parameter values and R-squared values for curves of PETG material

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter</th>
<th>R-squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETG</td>
<td>-1016.23</td>
<td>11.45</td>
</tr>
</tbody>
</table>

PETG: Polyethylene Terephthalate shows the correlation of the average HU value to the infill value of the Polyethylene Terephthalate (PETG) material. The average HU value of Polyethylene Terephthalate (PETG) material from 5 - 100% infill variation was -961.17 ± 42.97 to 140.3 ± 10.22.
Effect of Pattern and Infill Percentage

… (Hariyanto, et al)

Figure 2. The correlation between the Hounsfield Unit (HU) value and the percentage infill value of Polyethylene Terephthalate (PETG) material were plotted with a blue dash line. The linear fitting curve for PETG was plotted with a solid line in red.

Table 4. Effect of 3D printing infill pattern on HU value

<table>
<thead>
<tr>
<th>Infill (%)</th>
<th>Pattern</th>
<th>HU Value</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lines</td>
<td>-452.45</td>
<td>7.94</td>
</tr>
<tr>
<td></td>
<td>Triangles</td>
<td>-463.17</td>
<td>84.20</td>
</tr>
<tr>
<td></td>
<td>Octet</td>
<td>-451.14</td>
<td>187.14</td>
</tr>
<tr>
<td></td>
<td>Gyroid</td>
<td>-425.27</td>
<td>6.48</td>
</tr>
<tr>
<td></td>
<td>Concentric</td>
<td>-460.57</td>
<td>3.03</td>
</tr>
<tr>
<td></td>
<td>Grid</td>
<td>-443.38</td>
<td>25.80</td>
</tr>
</tbody>
</table>

SD: Standard of Deviation, Min: Minimum, Max: Maximum

Table 5. The typical value of the Hounsfield Unit (HU) for human tissue (Kalender, 2011)

<table>
<thead>
<tr>
<th>Tissues</th>
<th>HU Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>-1005 to -995</td>
</tr>
<tr>
<td>Lung</td>
<td>-950 to -550</td>
</tr>
<tr>
<td>Fat</td>
<td>-100 to -80</td>
</tr>
<tr>
<td>Water</td>
<td>-4 to 4</td>
</tr>
<tr>
<td>Kidney</td>
<td>20 to 40</td>
</tr>
<tr>
<td>Pancreas</td>
<td>30 to 50</td>
</tr>
<tr>
<td>Blood</td>
<td>50 to 60</td>
</tr>
<tr>
<td>Liver</td>
<td>50 to 70</td>
</tr>
<tr>
<td>Muscle, Soft Tissue</td>
<td>20 to 100</td>
</tr>
<tr>
<td>Adipose Tissue</td>
<td>-200 to -20</td>
</tr>
<tr>
<td>Spongious Bone</td>
<td>50 to 300</td>
</tr>
<tr>
<td>Compact Bone (Cortical)</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

Next, for the fitting curve, followed equation (3). The result of fitting using a linear equation for PETG material was shown in Table 3. fitting with the linear equation had been successful. This result was following the study conducted by Yea et al., who obtained an R-squared linear fitting of 0.99 for the PLA (Oh et al., 2017), also obtained an R-squared linear fitting of 0.99 for PLA and 0.97 for HIPS materials (Park et al., 2019). Furthermore, the effect of the pattern on the HU values is shown in Table 4.
Based on the research of (Madamesila et al., 2016) the effect of the filling pattern could affect the size of the air gap and the value of HU. The size of air gap and HU value played an important role in achieving equivalent tissue and image quality. Table 4 showed the effect of filling patterns on the HU values of the samples using line, triangle, octet, gyroid, concentric, and grid filling patterns because these patterns were available in the Ultimaker Cura 4 software. The calculation of the average HU value showed a relatively small difference, except for the gyroid infill pattern. It indicated that the gyroid infill pattern’s air gap was larger than other infill patterns.

The HU value obtained and associated with the tissue HU value summarized by Kalender, 2011 is shown in Table 5. Based on Table 5, we had succeeded in simulating lung tissue using PETG material with an infill percentage of 10 - 45% (Kalender, 2011) and a high-density lung using a 50 - 55% and also infill pattern of lines, triangles, octet, gyroid, concentric, grid with constant infill at 50% (Kairn et al., 2015). The PETG material with an infill percentage of 75 - 85% could represent adipose tissue. PETG material with an infill percentage of 90 - 95% could represent soft tissue, liver, blood, kidneys, and pancreas. Meanwhile, PETG with infill 100% represented spongy bone with a HU value of 140.3 ± 10.22 (Kalender, 2011). Furthermore, we evaluated the potential of PETG material to be used as a reference as a material to simulate the thorax body parts for quality assurance and control in radiotherapy. Based on Craft and Howell’s research, to simulate the heart, breast, and lungs, can use PETG material with the percentage of line pattern filling, 95 - 100%, 80 - 85%, and 15 - 30%, respectively (Craft & Howell, 2017). In addition, to make lung tumor tissue mimicking, PETG material can be used with a line pattern filling percentage of 80-90% (Hazelaar et al., 2018).

Our study’s PETG material successfully simulated soft and low-density tissues based on the analysis. However, they could not represent the high-density tissue such as compact bone. It was a challenge for the researcher to cover the limitations of high-density 3D printing technology. On the other hand, our study had successfully confirmed the feasibility of 3D printing the PETG material as a radiation phantom material that could represent soft tissue, adipose, lung, and spongy bone by varying the infill density and infill pattern. Moreover, there was a need to develop methods or materials for simulating high-density tissue like conducting combined 3D printing and casting methods or developing high-density 3D printing materials. Thus, the heterogeneous anthropomorphic phantoms can be achieved excellent, thereby improving the quality assurance process in radiation therapy.

CONCLUSION

The value of PETG material had successfully represented soft tissue and low-density organs by varying the infill percentage and infill pattern on 3D printed. The result indicated that 3D printing technology could help improve quality assurance in radiation therapy by producing a specific anthropomorphic phantom. On the other hand, we still need to develop methods or materials to represent high-density tissues.

ACKNOWLEDGEMENTS

This work was supported by the Institut Teknologi Sepuluh Nopember (ITS), RISTEKBRIN under Penelitian Dasar Unggulan Perguruan Tinggi (PDUPT) (No. 966/PKS/ITS/2021).

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