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Dosimetric Characterization of 3D Printed Bolus with Polylactic Acid (PLA) in Breast Cancer External Beam Radiotherapy

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ABSTRACT

Introduction: In this study, 3-Dimention (3D) polylactic acid (PLA) bolus were characterized as human tissue equivalent and specially designed for use in electron radiotherapy of breast cancer.
Material and Methods: This study uses the main material PLA with variations in the infill percentage when printing, which is (20, 40, 60, 80, and 100) %. Dosimetric characterization included measuring the value of Relative Electron Density (RED) and measuring the absorbed dose using LINAC 15 MeV, which was tested using a breast mannequin and compared with a commercial bolus at Andalas University Hospital.
Results: The results showed that the 3D bolus made of PLA provided uniformity in terms of thickness so that every part of the body surface covered by the bolus would get an even dose. 3D bolus made of PLA in all variations in the infill percentage had a RED value equivalent to human tissue. They can help ensure that the bolus does not significantly change the radiation dose distribution, achieving optimal treatment outcomes. However, a bolus with an infill percentage of 20% has a RED value closest to the breast RED, which is 0.99 and can absorb radiation of 1.98 Gy more optimally compared to a commercial bolus that can absorb 1.97 Gy from 2 Gy doses given.
Conclusion: The 3D bolus made of PLA can be an effective alternative for treating breast cancer using electron radiotherapy.

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Introduction

Radiotherapy is one of the most widely used treatments because it effectively reduces metastatic breast cancer and the risk of recurrence by utilizing ionizing radiation [1]. One of the radiotherapy tools with the principle of teletherapy is the Linear Accelerator (LINAC). LINAC utilizes high voltages to accelerate charged particles, such as high-energy electrons, through a linear tube. High-energy electrons between 6 MeV or more used in LINAC can kill cancer cells in the breast [2].

Radiation on radiotherapy using LINAC will produce a beam of electrons and photons that depend on the location and position of the cancer. The choice between photon and electron beams in breast radiotherapy often depends on the target's depth and the organs at risk. Photon beams are typically used for superficial targets and may result in a higher dose to the skin and surrounding normal tissue. However, electron beams have a rapid dose fall-off, which makes them an excellent choice for treating superficial targets with minimal dose to the surrounding tissue [3]. However, in some cases, such as cancer treatment on the skin's surface in the breast, the radiation dose has not provided the maximum surface dose due to the skin-sparing effect. The skin-sparing effect is a condition where the dose received by the skin surface is lower than the dose at a depth below the skin surface. This effect occurs due to the interaction of the radiation with the tissues of the body, resulting in the scattering and absorption of the radiation. As the radiation penetrates deeper into the tissue, it encounters more tissue, which results in a buildup of radiation dose. The skin-sparing effect can also be attributed to air cavities on the skin surface. The air cavities can act as a barrier to the radiation, reducing the dose at the skin surface while increasing the dose at deeper depths. So we need a material that can increase the skin surface dose called a bolus [4].

Bolus is a material that has a density equivalent to human body tissue. Bolus can increase the surface dose, reduce the depth dose, and even out uneven tissue [2]. The bolus is placed on the skin's surface during the irradiation process using LINAC. The bolus used during LINAC treatment should also have a uniform thickness ranging from 0.5 cm to 1.5 cm. The thickness of the bolus did not significantly change the shape of the isodose curve based on dept [2]. Making a bolus should use materials suitable for the tissue [4]. However, making bolus with materials that match the tissue is not accessible several alternative materials

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include paraffin granules, elastomer pads, super labs, thermoplastic sheets, dental wax, polypropylene, plasticine, and rayon cloth [4].

Most bolus forms are in sheets with varying field areas and bolus thickness according to the needs during the radiotherapy process. However, some things could still be improved with this sheet-shaped bolus. The sheet bolus cannot wholly cover uneven body parts such as ears, nose, scalp, and breasts. This results in a gap between the bolus and the skin surface [2].

Wang et al. [5] reported that patients treated with a three-dimensional bolus showed significantly lower complications than patients treated with a standard sheet bolus in radiation therapy. 3 Dimentional printed bolus usually comprises thermoplastic sheets such as Polylactic acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). PLA performs better because it has a Relative Electron Density (RED) value equivalent to the human body tissue [6]. Similar studies have also shown that 3D-printed bolus with PLA material can be used efficiently. Fan et al. [7] made a 3D bolus with PLA material which was tested using patients with cancer around the ear. Park et al. [8] made a 3D bolus with PLA material, which was tested using breast cancer patients.

Previous studies have shown that 3D printed bolus with PLA materials can improve dosimetry properties on uneven skin surfaces by reducing air gaps. However, most of these studies used only a single variation in the percentage of ingredient content, typically 100%, during 3D bolus printing. It is important to note that 3D printing technology can modify the density of the printed object by varying the fill percentage. Thus, differences in the percentage of infill may affect the suitability of the bolus for the needs of a particular patient. This is the background to overcome this problem, further research is needed to investigate the effect of infill percentage on the dosimetric properties of 3D bolus made of PLA, especially for the treatment of breast cancer. By identifying the optimal filling percentage for 3D printed bolus, it can potentially increase the effectiveness of radiotherapy treatment and improve patient outcomes.

Materials and Methods

Mannequin image capture

An image of a breast mannequin is taken using a CT-Simulator, making it easier to design a 3D bolus shape according to the observed object. The mannequin image is a gray image consisting of 125 slices. Mannequin images are processed into 3D shapes by designing them using software called a 3D Slicer 4.10. The 3D Slicer tool helps segment each image slice to form an image.

Bolus fabricating

A 3D bolus made of PLA material was created using a 3D printer Creality 10 5S and started by designing a flat bolus using a 3D design application called TinckerCAD. The bolus is designed with a size of (80×80) mm^2 and a thickness of 10 mm [9] . A typical range of bolus thickness in radiotherapy is between 5 mm to 15 mm. The choice of thickness depends on various factors, such as the treatment area's depth, the radiation beam's energy, and the type of tissue being treated. A thickness of 10 mm is commonly used to treat superficial tumors, such as breast cancer. The bolus samples that were successfully designed were mannequin breast bolus and flat bolus; then, the settings were made on a 3D printer. The 3D printer settings can be seen in Table 1. Then the object position, density level, and 3D printer speed are set, the 3D printer connectivity with the computer is established, and the last step is to print the object.

Dosimetry characterization of bolus samples

The 3D bolus made of PLA was scanned using a Computed Tomography simulator to obtain tomographic images in the axial and coronal directions. Then a region of interest (ROI) is created on the bolus image so that the CT-Number value of each bolus is obtained. The making of this ROI consists of 5 circular fields with a diameter of 37.1 mm; then, the ROI values are averaged. The CT Number obtained will be used to calculate the RED value. RED is an important parameter used in radiotherapy treatment planning as it is used to convert CT numbers to physical density for dose calculation. The calculation of RED involves using a reference material with a known physical density and RED value. This study used solid water as reference material, a shadow material commonly used in radiation therapy. The method used to calculate RED involves the following steps:

a. Obtain CT-Number values for the 3D bolus and solid water reference material using the same CT simulator and imaging protocol.

b. Calculate the Hounsfield unit (HU) value of the two materials using the formula HU = (CT Number - CT Water Number) / Water CT Number, where the CT Water Number is the CT number of water at the same energy level.

c. Calculate the 3D RED bolus using equations 1 and 2 [4].

$$\rho_a = 1{,}052 + 0.00048 N_{CT} \quad (1)$$
$$\rho_b = 1{,}000 + 0.001 N_{CT} \quad (2)$$

N_{CT} is the value of CT-Number ρ_a is RED value with CT-Number value greater than 100, and ρ_b is RED value with CT-Number value less than 100.

This method has previously been described in the literature and is an accurate and reliable way of calculating the RED values of various materials used in the radiation therapy [10].

After determining the value of RED, the value of the absorbed bolus dose can be determined. The dose given when irradiating LINAC is 2 Gy with Source-to-Surface Distance (SSD) set at 100 cm and energy 6 MeV; the bolus is placed on the phantom slab at the maximum depth so that the material used is expected to have a value close to the given dose. The results of the absorbed dose measurement can be read directly on the electrometer, which is connected to the parallel chamber plan detector, which is placed on the phantom slab with three repetitions. After determining the RED value, the value of the bolus dose absorbed can be determined. The dose given when irradiating using LINAC is 2 Gy with the Source-to-Surface Distance (SSD) set at 100 cm and an energy of 6 MeV. The bolus is placed on the phantom slab at maximum depth so that the material used is expected to have a value close to the dose given. The results of the absorbed dose measurement can be read directly on the electrometer connected to the parallel chamber plan detector placed on the phantom slab with three repetitions. But in this study, modified similar plate space with built-in 3D bolus material. The practical point of the room is considered during our measurements. We place the vessel at a depth of 10 cm in a solid water phantom and ensure that the obvious point of the vessel lies at the same depth. We also verified the chamber response using a 6 MV photon beam and found that the answer was consistent with the manufacturer's specifications.

Evaluation of 3D bolus made of PLA on mannequin breast

The 3D bolus made of PLA used during this evaluation was a dosimetrically characterized bolus that best suited the characteristics of the breast tissue. After finding the bolus with the correct infill percentage, the bolus was designed according to the printed mannequin breast. The breast mannequin has a thickness of 4.2 cm. Based on the recommendation of giving energy during treatment using LINAC, a depth of 4.2 cm can be reached by the energy of 15 MeV. The recommendation for using 15 MeV energy to get a depth of 4.2 cm in breast tissue during radiotherapy comes from various studies and guidelines in the field of medical physics.

One such reference is the report of the American Association of Physicists in Medicine Task Group 105, which recommends a range of electron energies for clinical use in superficial radiotherapy. The report states that 15 MeV is suitable for treating depths up to 4.5 cm in water, which is a close approximation to the average density of breast tissue.

Another reference is the European Society for Radiotherapy & Oncologi booklet on electron and photon selection for radiotherapy, which provides recommendations for selecting the appropriate energy for a given target depth and tissue type. The booklet suggests using electron energies in the range of 6-18 MeV for breast tissue, with 15 MeV being a common choice for treating depths up to 5 cm [11].

The evaluation of using a 3D bolus made of PLA was determined based on the absorbed dose of the bolus and compared with the absorption dose of a commercial bolus made of plasticine and the condition when the mannequin breast was not coated with the bolus. A good bolus increases the surface dose. So, based on this measurement of the absorbed dose, it can be evaluated which bolus is best used for the breast during treatment using LINAC. During this evaluation, the size of the absorbed dose used the same method when characterizing dosimetry. The only difference is that the phantom used is replaced with a mannequin breast.

Table 1. 3-Dimention printer settings or settings [12]

Parameter	Size
Diameter Nozzle	0.4 mm
PLA thickness	2.85 mm
Bed temperature	70^{0}C
Bed type	Glass
Nozzle temperature	190^{0}C
Initial layer height	0.5 mm
Layer height	0.3 mm
line width	0.35 mm
Shells	1
Infill (%)	20, 40, 60, 80, and 100
Print speed	50 mm/s
initial layer speed	25 mm/s

Results

3D bolus fabrication results made from PLA

The results of the 3D bolus fabrication made from PLA in Figure 1 show good performance to be used as a bolus for the breast because there was no gap between the bolus and the skin surface.

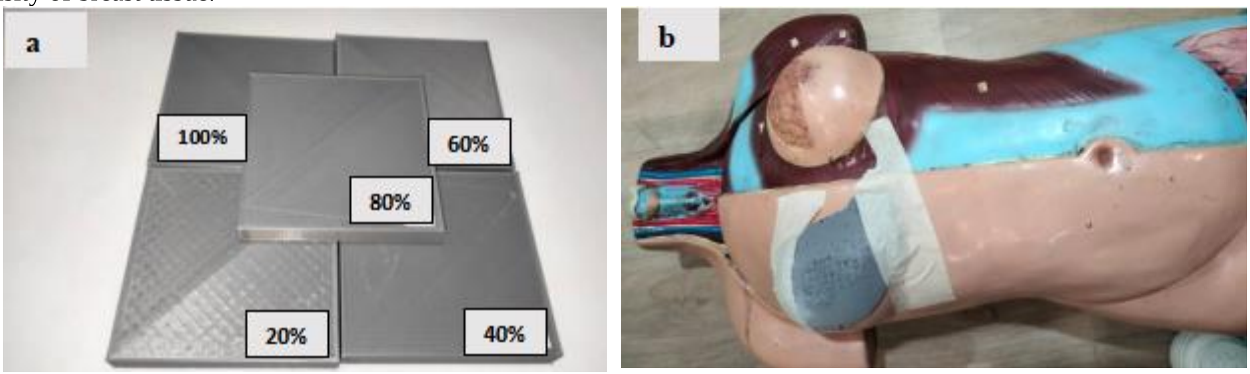

Figure 1. Results of 3D Bolus Fabrication made from PLA. (a) Flat bolus, (b) 3D bolus of breast

Results of 3D bolus dosimetry characterization made from polylactic acid

The results of the calculation of the RED value are based on the creation of the ROI to obtain the CT Number value, and the results of the CT Number observations and the analysis of the RED bolus can be seen in Table no 2.

Table 2. CT Number and RED 3D bolus values made from Polylactic Acid

No.	Infill (%)	CT-Number value (HU)	RED
1.	20	-825.387 ± 0.026	0.9991
2.	40	-650.365 ± 0.013	0.9993
3.	60	-453.983 ± 0.014	0.9995
4.	80	-260.890 ± 0.051	0.9997
5.	100	21.667 ± 0.023	1.0228

CT Number of 3D bolus made from PLA ranges from (-825.387 ± 0.026) HU to 21.667 ± 0.023 HU. A negative value in the CT Number indicates the level of bolus density. The infill percentage is varied during printing to change the thickness of a 3D bolus made of PLA. Infill percentage refers to the amount of internal structure present in a 3D-printed object. This determines how dense or hollow the bolus is. The bolus with the lowest infill percentage of 20% has the most negative CT number value, indicating the lowest density.

Conversely, a higher content percentage bolus has a positive CT number value, meaning a higher density [13] . This is following the data obtained that the bolus with the lowest infill percentage, which is 20%, has the most negative CT Number value, which is -825.38 HU. A Bolus with an infill percentage of 100% has a positive CT Number value, indicating that the bolus has a higher density.

The RED of a 3D bolus made of PLA ranges from 0.9991 to 1.022, based on Figure 2. This 3D bolus of PLA shows a range of RED values in the RED range of soft tissue, muscle, breast, and solid tissue, namely solid bone. This is important because the RED value determines the dose given during radiotherapy treatment. The bolus RED value is expected to be equivalent to the tissue to be treated [14] .

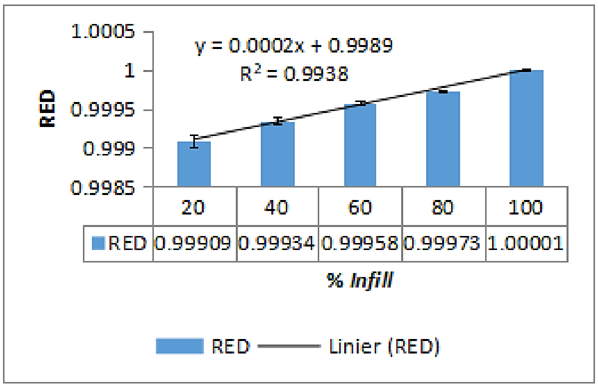

Figure 2. Infill percentage relationship with RED Value

The results of the absorbed dose measurement can be read directly on the electrometer connected to the parallel chamber plan detector with three repetitions. The results of the average absorbed dose can be seen in Figure 3.

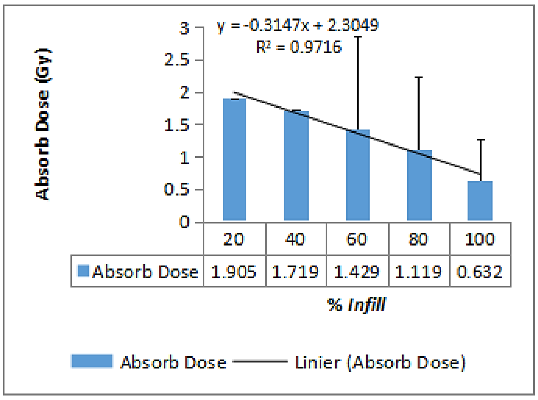

Figure 3. Infill percentage relationship with absorbed dose (Gy)

When the solid phantom was coated with a bolus made of PLA, the dose received by the solid phantom ranged from 0.632 Gy to 1.905 Gy. A 3D bolus made of PLA with an infill percentage of 20% showed a good absorption of the dose, namely 1.905 Gy from the 2 Gy given dose, while a bolus with an infill percentage of 100% showed a low dose absorption of 0.632 Gy.

Evaluation results of 3d bolus made of PLA on mannequin breasts.

A bolus with an infill percentage of 20% is recommended for bolus radiotherapy to the breast. However, to determine the effectiveness of this bolus with an infill percentage of 20%, further research needs to be done by creating a 3D bolus that is adjusted to the results of the image of the breast mannequin. The results of the measurement of the average bolus absorbed dose on the mannequin can be seen in Table no 3.

Table 3. The results measurement of the average absorbed dose of breast mannequin

No.	Treatment on mannequins	Absorbed dose (Gy)
1.	Without Bolus	1.950 ± 0.056
2.	With 3D bolus made of PLA	1.983 ± 0.029
3.	With commercial bolus	1.972 ± 0.073

Based on the measurement results of the average absorbed dose for breast mannequins in Table 3, it can be seen that the mannequins given a dose of 2 Gy after being given several treatments obtained a different average absorption dose. The non-bolus-coated mentioned breast had an absorbed dose of 1.950 Gy. Then after being given a 3D bolus made from PLA, the absorption dose increased to 1.983 Gy. This is under the purpose of using a bolus to increase the surface dose to treat cancers in the skin's surface area (15) when compared with a commercial bolus made of plasticine with an absorption dose of 1.972 Gy, which is also able to increase the surface dose but has a lower value than a bolus made of PLA.

Discussion

A bolus is a material that has a density equivalent to that of human body tissue and is able to increase surface dose, reduce depth dose and flatten uneven body tissue such as the breast. Based on this research, 3D bolus made of PLA are able to provide uniformity in terms of thickness and infill percentage when printed using a 3D printer. This causes the body surface area covered by the bolus to receive an even dose when compared to commercial bolus made of plasticine and in the form of sheets (Figure 1). This statement is in accordance with research conducted by Diaz-Merchan et al. [16] that bolus in the form of sheets are unable to completely cover uneven body parts such as the ears, nose, scalp, breasts and result in gaps between the bolus and the skin surface. The gap that is formed can affect the distribution of doses on the target volume (PTV) and allows healthy organs around the cancer to get higher doses [8] . Lobo et al. [7] also analyzed the effect of the air gap on the sheet bolus. The results of the analysis show that the surface dose has decreased from 14.8% to 3.2%, 14.9% to 1.1% and 12.6% to 0.7% when there is an air gap (1-3) cm. This study succeeded in showing that 3D bolus made from PLA had better performance in reducing the air gap between the bolus and the skin surface.

This study also explains that 3D bolus made from PLA are very suitable for use as bolus because they have a RED value equivalent to human tissue (Table 2). PLA material was chosen because it has the appropriate characteristics as a bolus material in radiotherapy treatment. This is in accordance with what was described by Ying Lu et al. (17) that PLA has radiotherapy adjuvant performance as well as several other compound properties, including tissue equivalence, biocompatibility, antibacterial activity, and antiphlogosis. Y Zhan et al. (18) compared the dosimetry characteristics of 3D printing and commercial bolus in post-mastectomy radiotherapy. It was found that the 3D printed bolus had a more uniform surface dose and better dose conformity than the commercial bolus.

In terms of the RED value which is a benchmark for the compatibility of bolus materials with body tissues, this study found that 3D bolus made of PLA with a content percentage of 20% had a RED value close to the RED value of the breast. This follows the research of Haryanto et al. [19] showed that the RED values of the various materials used for bolus preparation approached the RED values of water, with some variations depending on the ingredients and the percentage of filler. Therefore, the findings in this study are in accordance with previous studies which concluded that PLA material is very suitable for use as a 3D bolus material.

A 3D bolus made from PLA with an infill percentage of 20% also showed good dose absorption of 1.983 Gy from a given 2 Gy dose, while a bolus with a 100% infill percentage showed a lower dose absorption of 0.632 Gy. This is because 3D bolus made from PLA with a 100% infill percentage have a high density so that the dose given is inhibited and few can hit the phantom, in accordance with the theory which states that bolus with high density absorb more doses (14). Commercial bolus made from plasticine also have a good dose absorption capacity of 1.972, but lower than 3D bolus made from PLA. Therefore, 3D bolus made from PLA with an infill percentage of 20% are recommended for use because they have a better ability to absorb radiation. The results of this study are consistent with the findings of Poon et al. [20] who investigated the effect of 3D printed bolus on surface dose and dose distribution in head and neck radiotherapy. It was found that 3D printed bolus have higher and better surface dose elevating ability than conventional bolus. Then Yang et al. [21] evaluated the dosimetry properties of 3D printed bolus for chest wall radiotherapy. It was reported that 3D printed bolus provided a more homogeneous dose distribution and better dose coverage than commercial bolus. Kim et al. [22] also found that customized 3D printed bolus could improve dose homogeneity and reduce air gaps. Hossei et al, [23] also conducted a study by placing a bolus on the lateral and medial skin, especially the breast area. The results show that the bolus can increase the surface dose by approximately 80% and 92% in a trial of 20 patients, respectively. This shows a favorable performance in dose calculations when using bolus. This finding is consistent with the study by Sasaki et al. [24] who also demonstrated that using 3D printing for bolus production could improve dose uniformity.

Overall, this study provides valuable insight into the practical use of 3D boluse of PLA with varying infill percentage in radiotherapy and contributes to the increase in the literature on this topic.

Conclusion

PLA-based bolus has a better ability to increase the surface dose compared to commercial plasticine-based bolus. This is because the commercial bolus made of plasticine is still in the form of a sheet that allows a gap between the bolus and the patient's skin surface. In contrast, the 3D bolus made of PLA has a shape that is adjusted to the shape of the mannequin's breast so that the possibility of gaps can be minimized. The higher absorption dose can prove the low gap in the 3D bolus made from PLA compared to the commercial bolus.

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References

1. da Luz FAC, da Costa Marinho E, Nascimento CP, de Andrade Marques L, Duarte MBO, Delfino PFR,

et al. The effectiveness of radiotherapy in preventing disease recurrence after breast cancer surgery. Surg Oncol. 2022;41:101709. Available from: https://doi.org/10.1016/j.suronc.2022.101709.

2. Sutanto H, Eko H, Gede JW, Santi. AY, Suparman Suppa Astri SS. Bolus Berbahan Silicone dan Natural Rubber. Semarang: Undip Press. 2018. Available from: https://clinicsofsurgery.com/uploads/IMG_936135.pdf
3. Rumgay H, Shield K, Charvat H, Ferrari P, Sornpaisarn B, Obot I, et al. Global burden of cancer in 2020 attributable to alcohol consumption: a population-based study. Lancet Oncol. 2021;22(8):1071–80.
4. Podgorsak EB. Radiation Oncology Physics: A Handbook for Teachers and Students, [Internet]. Vienna: IAEA; 2019. Available from: https://ecommons.aku.edu/pakistan_fhs_mc_radiat_oncol/16
5. Wang KM, Rickards AJ, Bingham T, Tward JD, Price RG. Technical note: Evaluation of a silicone-based custom bolus for radiation therapy of a superficial pelvic tumor. J Appl Clin Med Phys [Internet]. 2022;(January 2021):1–8. Available from: https://doi.org/10.1002/acm2.13538
6. Fan J, Xu G, Yang D, Chen W, Zhang D, Wang M, et al. Fabrication and Application of 3D Printed Bolus for Optimizing Radiotherapy in Superficial Tumor. Clin Surg [Internet]. 2021;06(12). Available from: https://clinicsofsurgery.com/uploads/IMG_936135.pdf
7. Lobo D, Banerjee S, Srinivas C, Ravichandran R, Putha SK, Saxena PP, et al. Influence of air gap under bolus in the dosimetry of a clinical 6 MV photon beam. Journal of Medical Physics. 2020 Jul 1;45(3):175-81. Available from: https://doi.org/10.4103/jmp.JMP_53_20.
8. Park SY, Choi CH, Park JM, Chun M, Han JH, Kim JI. A patient-specific polylactic acid bolus made by a 3D printer for breast cancer radiation therapy. PloS one. 2016 Dec 8;11(12):e0168063. Available from: https://doi.org/ 10.1371/journal.pone.0168063
9. Lizondo M, Latorre-Musoll A, Ribas M, Carrasco P, Espinosa N, Coral A, et al. Pseudo skin flash on VMAT in breast radiotherapy: optimization of virtual bolus thickness and HU values. Physica Medica. 2019 Jul 1;63:56-62.
10. Schneider U, Pedroni E, Lomax A. The calibration of CT Hounsfield units for radiotherapy treatment planning. Physics in Medicine & Biology. 1996;41(1):111.
11. Li JS, Pawlicki T, Deng J, Jiang SB, Mok E, Ma CM. Validation of a Monte Carlo dose calculation tool for radiotherapy treatment planning. Physics in Medicine & Biology. 2000 Oct 1;45(10):2969.
12. Ricotti R, Ciardo D, Pansini F, Bazani A, Comi S, Spoto R, et al. Dosimetric characterization of 3D printed bolus at different infill percentage for external photon beam radiotherapy. Phys Medica. 2017;39:25–32. Available from: https://doi.org/10.1016/j.ejmp.2017.06.004.
13. Chantika L. Perbandingan Dosis Serap Bolus Berbahan Plastisin Dengan Bolus Berbahan Silicone Rubber. 2021.
14. Endarko E, Aisyah S, Carina CC, Nazara T, Sekartaji G, Nainggolan A. Evaluation of dosimetric properties of handmade bolus for megavoltage electron and photon radiation therapy. Journal of Biomedical Physics & Engineering. 2021 Dec;11(6):735.
15. Hellstrom, Kristina, Atila, Dan Lucian. A Broad Literature Review of Density Measurements of Liquid Cast Iron. Metals (Basel). 2017;7:165–85.
16. Diaz-Merchan JA, Martinez-Ovalle SA, Vega-Carrillo HR. Characterization of a novel material to be used as bolus in radiotherapy with electrons. Appl Radiat Isot [Internet]. 2022;183:110154. Available from: https://doi.org/10.1016/j.apradiso.2022.110154
17. Lu Y, Song J, Yao X, An M, Shi Q, Huang X. 3D Printing Polymer-based Bolus Used for Radiotherapy. Int J Bioprinting. 2021;7(4):27–42.
18. Ren L, Wang Y, Xie Y, Chen Y, Zhou Z, Liu D. Dosimetric characteristics of 3D-printed bolus for postmastectomy radiotherapy. ournal Radiother Pract. 2019;18(2):184–90.
19. Hariyanto AP, Fachrina UM, Levina A, Endarko E, dan Bambang HS. Fabrication and characterization of bolus material using propylene glycol for radiation therapy. Iran J Med Phys. 2020;70(3):161–9. Available from: http://eprints.mums.ac.ir/18713/
20. Poon I, Fung KW, Lam KO, Cheung FW, Yu PK, Tung SY. Dosimetric impact of 3D-printed bolus in postmastectomy radiotherapy. Technol Cancer Res Treat. 2017;16(4):425–32.
21. Yang J, Xu S, Zhu T, Ding X, Chen J. Dosimetric evaluation of 3D-printed bolus for chest wall radiotherapy. J Appl Clin Med Phys. 2017;18(3):44–51.
22. Zou W, Fisher T, Zhang M, Kim L, Chen T, Narra V, et al. Potential of 3D printing technologies for fabrication of electron bolus and proton compensators. J Appl Clin Med Phys. 2015;16(3):90–8. Available from: https://doi.org/10.1093/jrr/rrac013.
23. Hosseini FS, Baghani HR, Robatjazi M, Mowlavi AA, Porouhan P. Performance evaluation of buildup bolus during external radiotherapy of mastectomy patients: treatment planning and film dosimetry. Medical & Biological Engineering & Computing. 2023 Feb;61(2):435-44.
24. Sasaki T, Kohno R, Shimizu Y. Development of a patient-specific bolus using 3D printing for intensity-modulated radiation therapy. J Radiat Res. 2016;57(6):712–7.