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Application of Patient-Customized Cast Type M3 Wax Bolus using a 3D printing for Photon Beam Radiation Therapy in Patients with Scalp Malignant Tumor

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ABSTRACT

Introduction: We investigated the usefulness of patient-customized cast type M3 wax bolus (MWB) in radiation therapy in scalp malignant tumor patients by 3D conformal radiation therapy (3D CRT) and intensity-modulated radiation therapy (IMRT).

Material and Methods: A helmet-type polylactic acid (PLA) hollow model was fabricated using a 3D Printing, and the molten MWB was poured into the mold and allowed to harden. Subsequently, a solid MWB head cast was obtained by removing the PLA. The radiation volume was verified using a metal oxide semiconductor field-effect transistor (MOSFET) dosimeter and EBT3 film.

Results: Radiation dose verification was performed at the anterior, right, and left angles of planning tumor volume. The error rate demonstrated a maximum value of 5.5% and an average of 3.3% using the MOSFET dosimeter, and a maximum value of 7.0% and an average of 5.4% applying the EBT3 film. The homogeneity indices of the treatment plans were obtained as 0.09 and 0.12 using 3D CRT and IMRT, respectively. Moreover, the conformity number of the treatment plans was reported as 0.79 using 3D CRT and 0.81 applying IMRT.

Conclusion: The density of the MWB head cast was 1.05 g/cm^3 which is closer to that of the equivalent tissue than the existing helmet type bolus material. In addition, it reduces the processing time and associated pain during custom manufacturing and has little air gaps. Therefore, it can be considered an effective method for the treatment of patients with scalp malignant tumors.

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Introduction

Radiation therapy is more frequently used in the treatment of patients with carcinoma, such as angiosarcoma, lymphoma, melanoma, mycosis fungoides, and squamous cell carcinoma which consists of different types of scalp malignant tumors, as compared to other methods, such as surgery. The delivery of equal radiation treatment beam and protection of the brain and optic nerve during the treatment of these malignant tumors have high priority; nonetheless, the irregularity of the scalp contour makes the delivery of the beams more difficult [1].

In theory, electron-beam therapy is superior to scalp and skin treatment; however, the delivery of a homogeneous dose on the curvature of the scalp is challenging. Therefore, some methods have been developed for beam delivery using a number of fields [2]. Nevertheless, the use of the electron beam leads to electron scattering which complicates radiation volume and causes inhomogeneous dose. Therefore, the use of a photon beam was attempted to overcome the irregular surface and depth change [3,4].

In general, the treatment of scalp malignant tumors using a photon beam causes inadequate skin dose. To address this problem, several approaches have been adopted. For instance, the use of bolus or immobilizing casts can compensate insufficient skin dose, or alternatively, intensity-modulated radiation therapy (IMRT), volume modulated radiation therapy (VMRT), and helical tomotherapy can be utilized for dose escalation in critical organs [5,6].

To deliver sufficient radiation dose to scalp tumors, a helmet-type bolus is usually used which is fabricated from some materials, such as gel tessuto-equivalente (GTE, Action, USA), paraffin wax (PW, Daejung, Korea), and Vaseline gauze (VG, Junsei, Japan) with densities of 1.03, 0.9, and 0.85 g/cm^3, respectively [7]. GTE, though

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mostly similar to tissue equivalent material, causes serious difficulty in making contact with the scalp; consequently, unwanted air gaps exist which result in dose uncertainty. PW and VG have lower densities, as compared to tissue equivalent material, and the high temperature and prolonged time of custom manufacture can be painful to patients. Customized helmet-type bolus using a 3D Printing has been recently developed to overcome this disadvantage [8]. The main advantage of the helmet-type bolus is that it can provide the patients with the convenience of short procedure time since there is no bolus manufacturing process inside the computed tomography (CT) simulation room. Therefore, it eliminates the complications incurred by them during bolus manufacturing and is not associated with the occurrence of air gaps. However, the helmet-type bolus has the disadvantage of a higher material density of polylactic acid (PLA) of 1.2 g/cm^3, as compared to other tissue equivalent material, which causes difficulties in the prone position of patients wearing the helmet.

In the current study, we custom manufactured a cast type M3 wax bolus (MWB) helmet with a density of 1.05 g/cm^3 equivalent to tissue and softer using a 3D Printing and investigated its effectiveness in the treatment of scalp malignant tumor.

Materials and Methods

Bolus property comparison

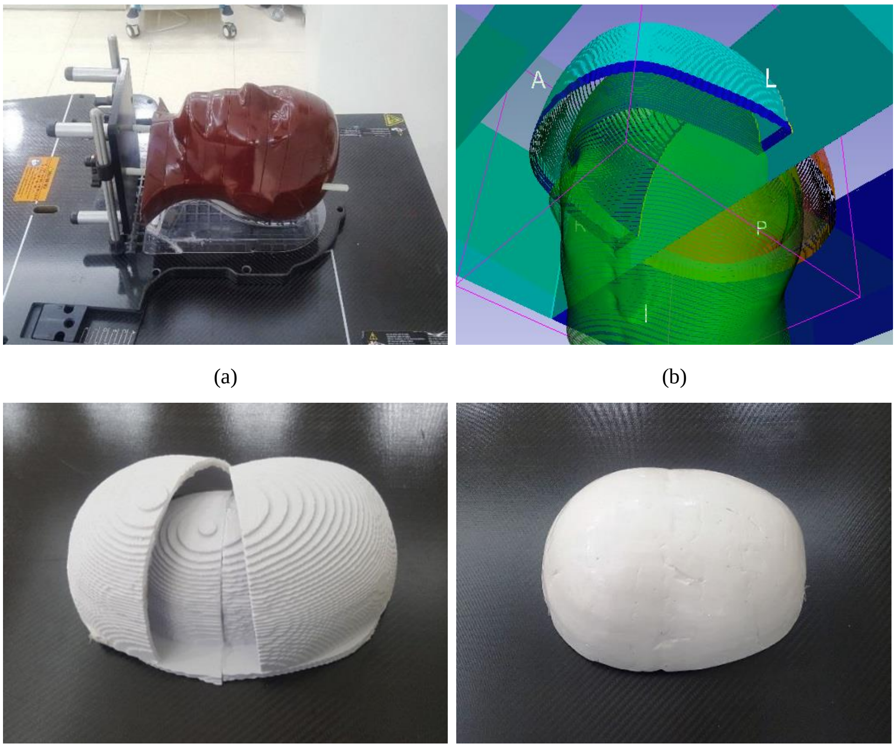
The Hounsfield unit (HU) and standard deviation of five materials (MWB, GTE, PW, VG, and PLA) that can be used as a bolus were measured using CT scan (Light speed RT16, General Electric, USA). The CT filming conditions were as follows: 120 kVp, 200 mA, large filter, 2.5 mm slice thickness, and 40 mm^2 measurement area.

Helmet-type M3 wax bolus manufacturing

To model the helmet-type MWB, CT examinations were performed on an Alderson radiation therapy (ART) head and neck phantom (Head Rando Phantom: ART-310X, Radiology support devices INC., USA), and the respective images were converted to digital imaging and communication in medicine files.

Table 1. Volume and ratio of M3 wax bolus used in the experiment

	Density(g/cm^3)	Mass(g)	Composition ratio(%)
Paraffin wax(Daejung, Korea)	0.90	1538.6	76.93
Magnesium oxide(Junsei, Japan)	3.58	447.0	22.35
Calcium carbonate(Daejung, korea)	2.71	14.4	0.72
M3 wax	1.05	2000.0	100.00



(a) (b) (c) (d)

Figure 1. a) Head rando phantom image acquisition, b) Body contour and polylactic acid bolus contour acquisition, c) Polylactic acid casting printed by a 3D Printing, d) M3 wax bolus manufactured with polylactic acid

To produce the volume of the helmet, the CT images were sent to a treatment planning system (TPS: eclipse 8.6, Varian Medical system, USA). After the production of the virtual mock-up images of the helmet (inner thickness=0.5 cm; outer thickness=0.5 cm; MWB insertion space=2.0 cm), a casting made of PLA was fashioned using a 3D printer (3DP-310F, CUBICON, Korea). The MWB, which was melted in the mixing ratio displayed in Table 1 [9], was poured into the casting. A bolus was obtained after the MWB liquid solidified and the PLA was removed from the hardened MWB (Figure 1).

Treatment Planning

The manufactured MWB was placed on the head of the phantom, and a CT image was acquired and transferred to the Treatment Planning System (TPS). Clinical tumor volume (CTV) was drawn on the transferred file, and the two treatment plans of coplanar 7 portal 3D conformal radiation therapy (3D CRT) and Intensity-modulated radiation therapy (IMRT) were established at the same angle under the conditions of 0.5 cm margin of planning tumor volume (PTV) and 0.5 cm margin of the multi-leaf collimator(MLC). A total dose of 5000 cGy was delivered with 25 fractional doses each of 200 cGy calculated by analytical anisotropic algorithm (AAA) of the TPS. The prescribed dose was 100% of 5,000 cGy.

To compare the homogeneity and conformity of the treatment plan, the homogeneity index (HI, equation 1) and the conformity number (CN, equation 2) were calculated using the following equation [10,11].

$$HI=\frac{D_2\%-D_{98}\%}{PTV_{mean}} \tag{1}$$

$D_2\%$=2% dose of the PTV
$D_{98}\%$=98% dose of the PTV
PTV_{mean}=Mean dose of the PTV

$$CN=\frac{TV_{RI}}{TV}\times\frac{TV_{RI}}{V_{RI}} \tag{2}$$

TV_{RI}=Target volume covered by the reference isodose
TV=Target volume
V_{RI}=Volume of the reference dose

In order to compare brain dose by the treatment plan, the reduction rate of brain doses of V_{10}, V_{20}, $V_{30,}$ and V_{40} was calculated using the following equation 3:

$$\text{Reduction ratio}=\frac{V_{RI\_IMRT}-V_{RI\_3D\ CRT}}{V_{RI\_IMRT}}\times 100 \tag{3}$$

V_{RI_IMRT}=Brain dose of the reference volume in IMRT
$V_{RI\_3D\ CRT}$=Brain dose of the reference volume in 3D CRT

Dose Verification

The linear accelerator has been calibrated in accordance with TRS-398[12]. Gafchromic EBT3 films (EBT3 film, Ashland, USA), and metal oxide semiconductor field-effect transistor dosimeters (MOSFETs: TN-502RD, T & N, Canada) were calibrated in the following method using linear accelerators. Ten solid water slab phantoms (Slab phantom, Lab, Germany, 30×30×1 cm^3, 1.045 g/cm^3) and a 1.5 cm solid water slab phantom on the top were piled up on a linear accelerator (Clinac ix, Varian, USA) for backscatter measurement.

The dose delivery of a 6 MV photon beam was measure repeated three times starting at 0 cGy by unit of 20 cGy up to a maximum of 240 cGy. [13-15]. The Gafchromic EBT3 film which was exposed (Re 6) to the dose was analyzed using a scanner (Epson Expression 10000XL flatbed scanner, Epson Seiko Corp., Japan) and patient plan verification software (Film QA Pro, Ashland, USA), and an optic density-dose calibration curve was obtained. In the MOSFET dosimeter delivered to the dose, a dose calibration curve was obtained using several doses as indicated in the device (Figure 2).

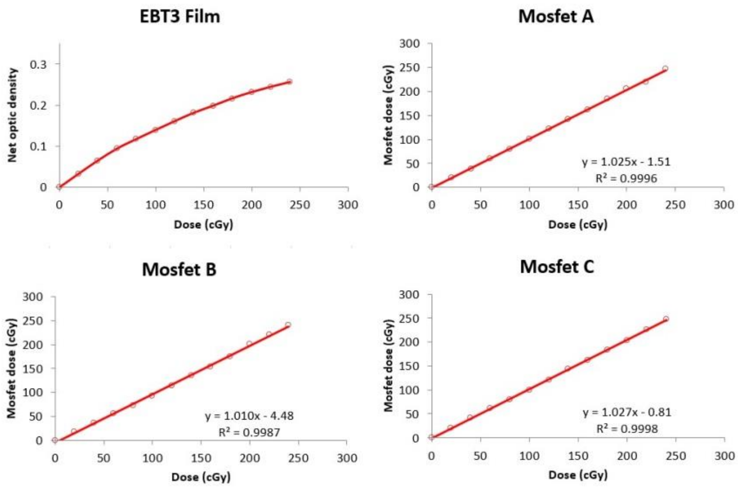


Figure 2. EBT3 film, MOSFET A, B, C calibration curve.

(a) (b)

Figure 3. a) Dose measurement point A (Anterior), B (Right) and C (Left) Point, b) Dose measurement using EBT3 film and MOSFET dosimeter

For dose measurements, a Rando head phantom was reproduced in the radiation therapy room under conditions similar to those of the CT simulation room. The EBT3 film and MOSFET confirmed that the dose of the 3D CRT and IMRT plan was delivered to the ART phantom using a linear accelerator. Three different points on scalp surface (anterior, right, left) of PTV were measured three times using the Gafchromic EBT3 film and MOSFET dosimeter (Figure 3). The error rate was calculated by the following equation:

$$\text{Error ratio} = \frac{D_M - D_P}{D_M} \times 100 \quad (4)$$

D_M=Measurement dose in the 3D CRT or IMRT plans
D_P= Treatment planning system dose

Results

Hounsfield unit in computed-tomography image evaluation

HU in CT after attaching the MWB on Rando head phantom was calculated at 53.2±35.4. The HU of comparison targets was -47.1±11.6 on GTE, –116.5±64.1 on PW, –165.3±38.8 on VG, and 108.6±21.1 on PLA (Table 2).

Treatment Planning System Evaluation

Dose distribution of the 3D CRT plan, with the total dose of 5,000 cGy, was obtained as 5,025 cGy, 4,345 cGy, and 4,810 cGy for each maximum, minimum, and average dose on CTV, respectively. On the other hand, the respective values were measured at 5,140 cGy, 4,230 cGy, and 4,830 cGy on IMRT. In addition, the dose distribution of the 3D CRT plan was 5,100 cGy, 4,185 cGy, and 4,790 cGy for each maximum, minimum, and average dose on PTV, respectively, while the respective values were obtained as 5,400 cGy, 3,930 cGy, and 4,775 cGy on IMRT.

Table 2. Hounsfield unit measurement for each bolus type

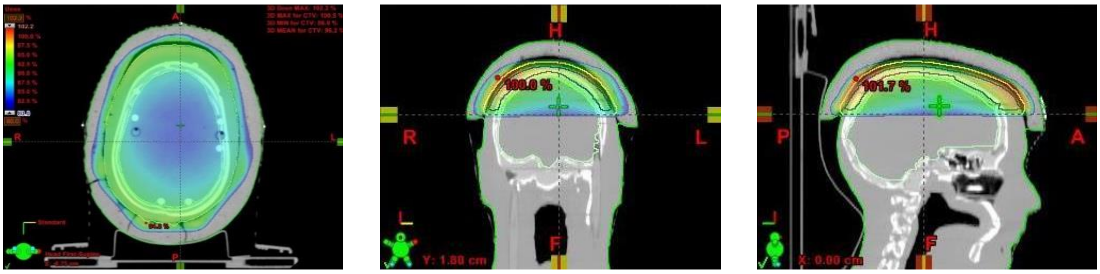
Bolus	MWB	GTE	PW	VG	PLA
HU	53.2±35.4	-47.1±11.6	-116.5±64.1	-165.3±38.8	108.6±21.1

MWB: M3 wax bolus, GTE: Gel tessuto-equivalente, PW: Paraffin wax, VG: Vaseline gauze, PLA: Poly Lactic Acid

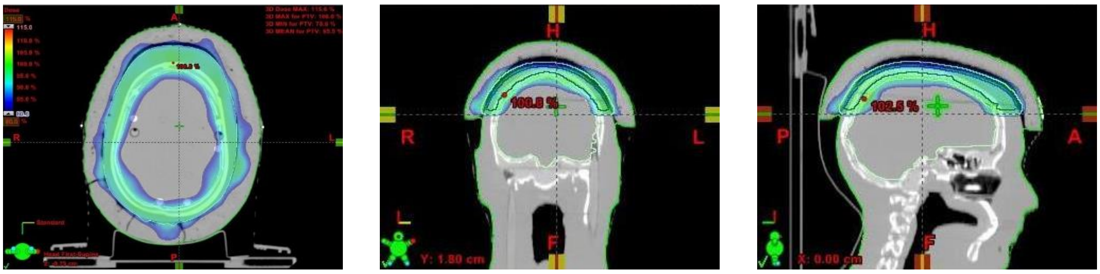
Table 3. Planning tumor volume dose on the scalp
Unit: cGy

Plan	Measurement point	Planning dose	MOSFET dose (Error rate, %)	EBT3 film dose (Error rate, %)
3D CRT	Anterior	196.4	188.9±1.1 (-3.8)	187.0±0.5 (-4.8)
	Right	193.2	188.2±2.9 (-2.6)	184.1±0.3 (-4.7)
	Left	186.8	176.6±0.9 (-5.5)	176.1±0.8 (-5.7)
IMRT	Anterior	184.8	182.4±3.8 (-1.3)	175.1±0.8 (-5.2)
	Right	187.8	181.4±3.4 (-3.4)	174.7±0.5 (-7.0)
	Left	193.4	187.4±2.8 (-3.1)	183.6±0.6 (-5.1)

3D CRT: 3D conformal radiation therapy, IMRT: Intensity-modulated radiation therapy



(a)



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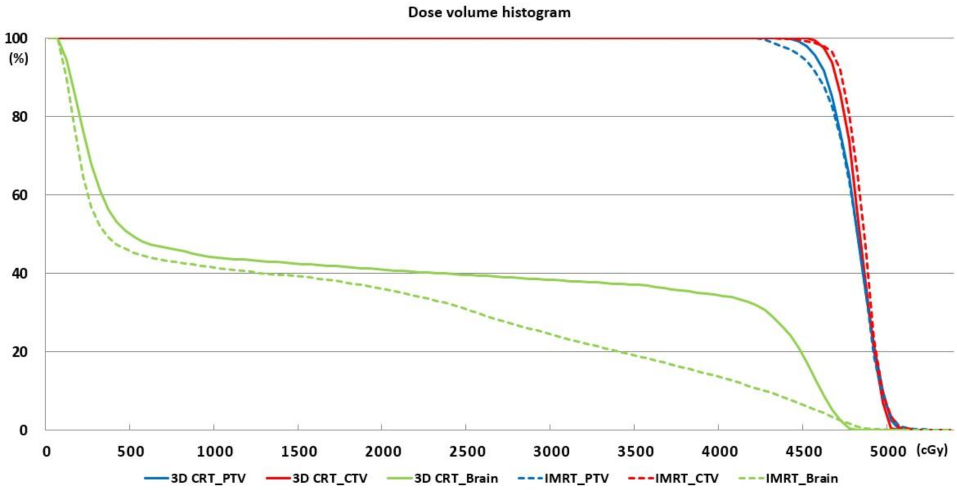

C)

Figure 4. a) Dose distribution of 3D conformal radiation therapy(Axial, Coronal, Sagittal), b) Dose distribution of intensity modulated radiation therapy(Axial, Coronal, Sagittal), c) Dose volume histogram

Brain dose-volume histogram (DVH) was delivered to 43.9%, 40.8%, 38.2%, and 34.1% in V10, V20, V30, and V40 of 3D CRT. On the other hand, in V10, V20, V30, and V40 of IMRT, brain DVH was delivered to 41.3%, 35.7%, 24.1%, and 13.2%. Brain DVH of IMRT reduced to 6.0%, 12.4%, 36.9%, and 61.4% at V10, V20, V30, and V40, as compared to 3D CRT. D2% of 3D CRT was 4,920 cGy, D98% =4,490 cGy, and mean dose= 4,790 cGy. On the other hand, D2% of IMRT was 4,890 cGy, D98%=4,340 cGy, and mean dose=4,775 cGy. HI was 0.09 using 3D CRT and 0.12 applying IMRT (The excellent as closer to 0). The PTV of the 3D CRT was 603.1 cc. The volume covered 95% of the PTV was 552.1 cc, and the volume covered 95% of the phantom was 642.0 cc. The PTV of the IMRT was 603.1 cc. The volume covered 95% of the PTV was 527.6 cc, and the volume covered 95% of the phantom was 568.1 cc. CN was 3D CRT 0.79 IMRT 0.81 (The excellent as closer to 1).

Dose Evaluation

The doses of TPS on the following measurement points: anterior, right, and left for the 3D CRT plan of MWB were calculated at 196.4 cGy, 193.2 cGy, and 186.8 cGy, respectively. Moreover, the doses measured three times with the MOSFET dosimeter were 188.9±1.1 cGy, 188.2±2.9 cGy and 176.6±0.9, respectively. The error rates were each -3.8%, -2.6% and -5.5%, respectively. The doses measured by the EBT3 Film were 187.0±0.5 cGy, 184.1±0.3 cGy, and 176.1±0.8 cGy, respectively. In addition, the error rates were reported as -4.8%, -4.7% and -5.7%, respectively. The dose of TPS on the following measurement points: A, B, and C on the IMRT plan were 184.8 cGy, 187.8 cGy, and 193.4 cGy, respectively. The doses measured three times with the MOSFET dosimeter were 182.4±3.8 cGy, 181.4±3.4 cGy, and 187.1±2.8 cGy, respectively. Moreover, the error rates were stated as -1.3%, -3.4% and -3.1%, respectively. The does measured by the EBT3 Film were 175.1±0.8 cGy, 174.7±0.5 cGy, and 183.6±0.6 cGy, respectively. In addition, the error rates were calculated at -5.2%, -7.0%, and -5.1%, respectively (Table 3; Figure 4).

Discussion

A patient-customized helmet was manufactured with the application of MWB to be used in scalp malignant tumor radiation therapy. It aimed to improve the existing bolus treatment method, especially, to address the problems associated with helmets manufactured with PLA filament material using a 3D Printing.

Achieving reproducibility during radiotherapy in radiation therapy room is difficult in conventional GTE bolus used for scalp malignancies. PW has an HU of -116.5±64.1 and is close to adipose tissue in soft tissue. On the contrary, MWB demonstrates excellent reproducibility in the radiation therapy room; moreover, it has an HU of 53.2±35.4 and is close to the scalp soft tissue (Table 2) [9]. Radiation therapy with MWB can reduce dose uncertainty owing to differences in the density of the border between the bolus and the scalp soft tissue [16], delivering a more stable dose to the patient. In addition, MWB can be melted and reused like an alloy block without being discarded after use. A level of less than 750 cGy on the brain, eye, and optic nerve, and less than 350 cGy on the brain stem, spinal cord, pituitary gland, and parotid gland at a total delivered dose of 5,000 cGy has been recently stated as the recommended dose for the scalp radiation treatment plan. To maintain this low dose, the treatment plan should be processed using IMRT, VMRT, and tomotherapy, and the thickness of the bolus should exceed at least the build-up area [17,18]. In the present study, the treatment plan was established manufacturing 2-cm-thick MWB to deliver an adequate dose to the scalp and reduce the high doses delivered to the brain. In particular, IMRT radiotherapy can effectively reduce the brain DVH to 36.9% and 61.4% in V_{30} and V_{40}, respectively, as compared to 3D CRT, without a significant difference between HI and CN. This indicates that radiotherapy in PTV remains good and reduces the dose of organs at risk (Figure 4).

When scalp radiation therapy is performed using a bolus, tomotherapy shows an excellent HI, as compared to the electron beam and volumetric modulated arc therapy. Tomotherapy also reduces the dose delivered to the brain and hippocampus [6]. It is recommended that the bolus should not exceed 2 cm for radiation therapy with electron beams. In addition, the dose produces a maximum error of 2.5% [7]. 3D Printer's polyamide-12 (-10 HU) and acrylonitrile butadiene styrene (ABS; 1.04 g/cm^3) deliver a dose similar to that of GTE (1.03 g/cm^3) and provide the patient with a very close contact bolus [8,19].

According to a study conducted by Varadhan, the total error in all measurements of the MOSFET dosimeter is within 4.6% [20]. In this study, the error rate was -4.0% on average at 3 points of 3D CRT. The dose was delivered with an average error of -3.9% for the 3D CRT and -2.6% for the IMRT. The maximum error of the EBT3 film was -7.0% measured as the right point of IMRT, and the average dose was calculated at -5.4% which was less than the MOSFET. This can be regarded as uncertainty due to the direction-dependence of the 7-port, even though the EBT3 film was located within a sufficient build-up area of 2.0 cm. The standard deviation of the MWB used in the present study was reported as ±35.4 since some parts were heterogeneously mixed. This may cause dose uncertainty in radiotherapy. Moreover, the smoothing technique to achieve a perfect fit with the ART phantom was not used in the present study. Therefore, it is recommended that future studies use more homogeneous materials and techniques, such as Laplacian smoothing, to show ART phantoms and obtain perfect results.

Conclusion

As evidenced by the obtained results, the use of MWB manufactured by casting type using a 3D Printing is expected to increase due to the short duration of the manufacturing and being more cost-effective than PLA using a 3D Printing. Furthermore, there is a possibility of the reuse and maintenance of a low dose to the surrounding tissue during scalp malignant tumor treatment.

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