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Feasibility of Fabricating Variable Density Phantoms Using 3D Printing for Quality Assurance (QA) in Radiotherapy

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The variable density phantom fabricated with varying the infill values of 3D printer to provide more accurate dose verification of radiation treatments. A total of 20 samples of rectangular shape were fabricated by using the Finebot™ (AnyWorks; Korea) Z420 model (width×length×height=50 mm×50 mm×10 mm) varying the infill value from 5% to 100%. The samples were scanned with 1-mm thickness using a Philips Big Bore Brilliance CT Scanner (Philips Medical, Eindhoven, Netherlands). The average Hounsfield Unit (HU) measured by the region of interest (ROI) on the transversal CT images. The average HU and the infill values of the 3D printer measured through the 2D area profile measurement method exhibited a strong linear relationship (adjusted R-square=0.99563) in which the average HU changed from −926.8 to 36.7, while the infill values varied from 5% to 100%. This study showed the feasibility fabricating variable density phantoms using the 3D printer with FDM (Fused Deposition Modeling)-type and PLA (Poly Lactic Acid) materials.

Keywords: Variable density phantom, 3D Printer, Infill value, Hounsfield unit

Introduction

The objective of radiotherapy is to deliver the maximum radiation dose to a tumor, while minimizing the radiation exposure in the surrounding critical organs, and selects the optimal radiation treatment plan among the various treatment plans available to administer radiation therapy.[1,2] Before radiation treatment, complex radiation treatment plans, such as intensity modulated radiation therapy (IMRT), require a quality assurance (QA) procedure to ensure consistency between the dose calculated in the Radiation Treatment Planning (RTP) system and the dose measured from the phantom.[3-7] If the difference between the measured dose and the calculated dose is not within the acceptable tolerance (the gamma index (3% in dose and 3 mm in distance) is 95% or higher in this medical center), another procedure is required to identify whether the result is an error in the calculation, an error in the measurement, or an error in the operation.

A recent our study[4] published the latest 3D printing technology in this complex's intensity-modulated radiation therapy (IMRT) facility to fabricate an anthropomorphic patient-specific head phantom, reporting that its application for QA is highly feasible. However, current 3D printing technology has a limit in application for QA purposes because the 3D printer cannot realize various densities of the human body using only one material for a single printing. In other words, the phantom fabricated through the current 3D printer is composed of a uniform density, but the inside of the human body is different from the phantom due to its various organs such as bone, skin, and blood.

When the radiation is exposed, the effect of the radiation varies greatly depending on the density of the material being irradiated.[8-11] For that reason, the QA process using a fabricated phantom with a uniform density is inaccurate, degrading the accuracy of radiation treatment QA.

3D printing technology has been gaining attention in QA for dose verification of RTP calculations,[4,12,13] and generating higher demand for more flexible printing parameters. As mentioned above, despite various attempts to fabricate a phantom using 3D printing technology, a single density phantom does not resolve the problem.

To overcome this challenge, this study investigated the feasibility fabricating variable density phantoms using the 3D printer with FDM (Fused Deposition Modeling) -type and PLA (Poly Lactic Acid) materials.

Materials and Methods

1. Fabrication of variable density phantom

As shown in Fig. 1, using the Finebot™ (AnyWorks; Korea) Z420 model, a total of 20 samples were fabricated with a rectangular shape (width×length×height=50 mm×50 mm×10 mm) by varying the infill values from 5% to 100%. Here, the infill values follow the definition provided by Madamesila et al.[13]

The infill value ranges between 0% and 100%, which is the ratio of printed thermoplastic volume to air volume.

The set values of the 3D printer for all the samples include a layer height of 0.3 mm, a shell thickness of 0.8

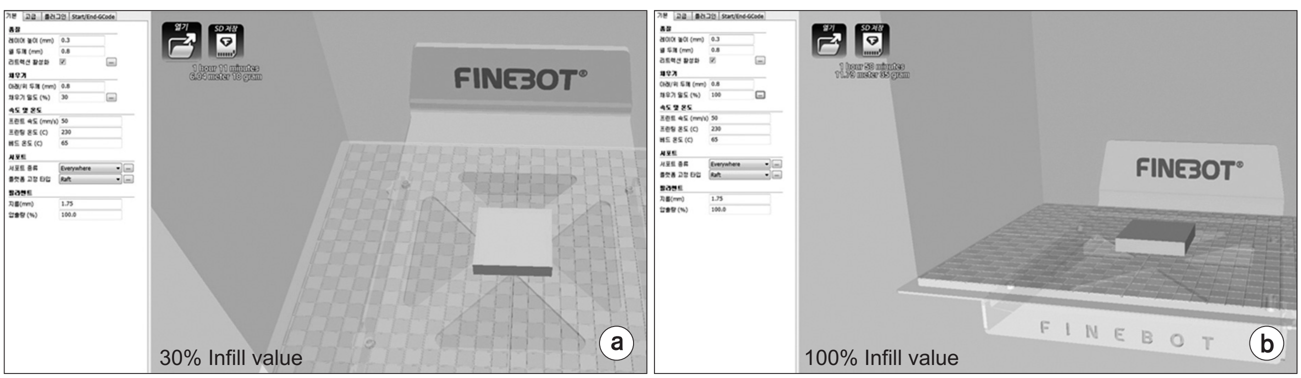

Fig. 1. A total of 20 samples with dimensions (width×length×height=50 mm×50 mm×10 mm) were fabricated for infill values ranging from 5% to 100% by using Finebot™ (AnyWorks; Korea) Z420 3D printer model.

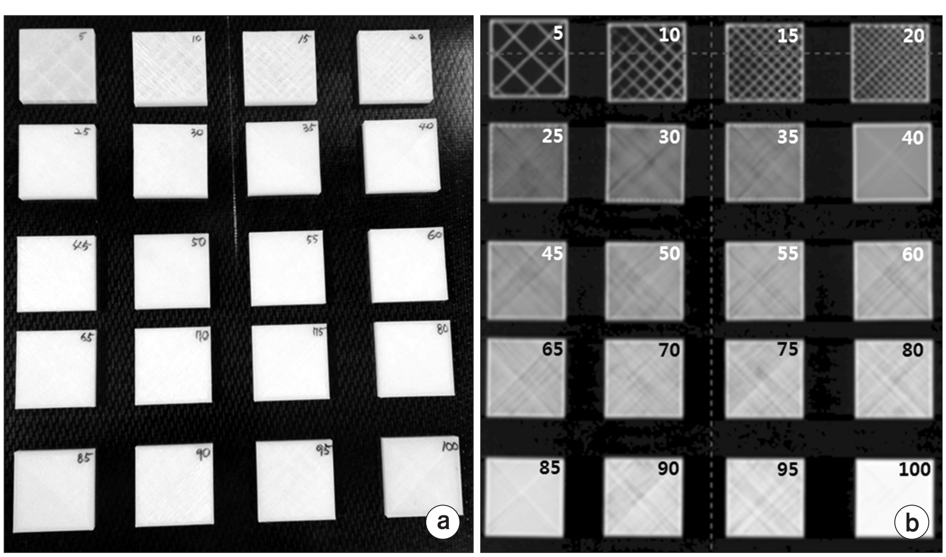

Fig. 2. (a) Photograph of samples with infill values from 5% to 100%, (b) Frontal image of samples with infill values from 5% to 100% obtained by CT scan.

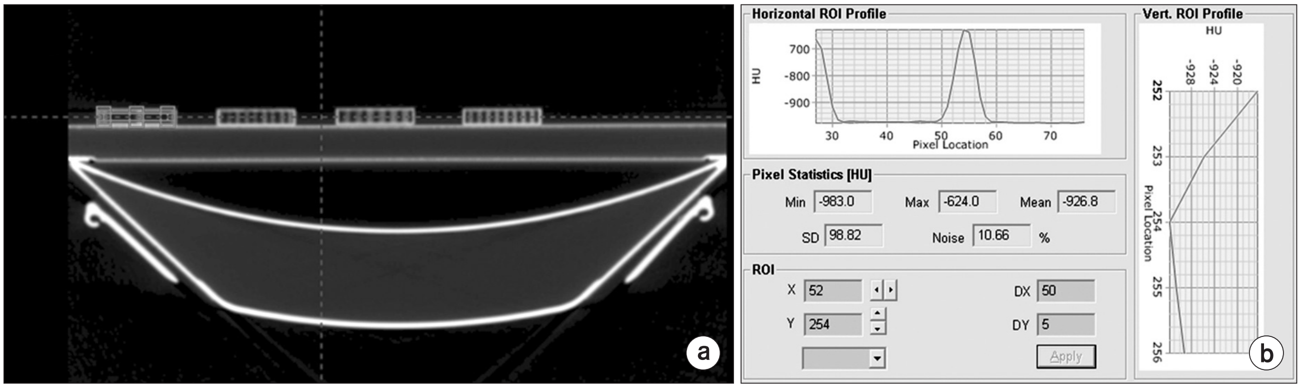

Fig. 3. (a) HU was measured by using a two-dimensional area profile function at the center of the sample on a transversal image by CT scan. (b) Horizontal ROI Profile, vertical ROI Profile, pixel statistics, and ROI for the measured area of the sample with infill value of 5%.

mm, a 0.8 mm thickness available for filling, a printing speed of 50 mm/s, printing temperature of 230°C, bed temperature of 65°C, and a diameter of 1.75 mm. The samples were fabricated by varying the infill values by factors of 5%. The samples were printed in a grid pattern by using PLA material with a physical density 1.2 g/cm^3 and the fused deposition modeling (FDM) method.

2. CT scan

A total of 20 samples with infill values ranging from 5% to 100% were scanned with 1-mm thickness using a Philips Big Bore Brilliance CT Scanner (Philips Medical, Eindhoven, Netherlands), as shown in Fig. 2. Images were obtained under the conditions of 120 kV and 200 mA. Fig. 2a is a photograph of the samples fabricated according to infill value changes, and Fig. 2b is a frontal image obtained through a CT scan of the aforementioned samples.

3. Measurement of hounsfield unit (HU)

A Hounsfield Unit (HU) is defined as follows.[2)]

$$H = \frac{\mu_{tissue} - \mu_{water}}{\mu_{water}} \times 1000$$

where μ_{tissue} is the linear attenuation coefficient of the tissue, and μ_{water} is the linear attenuation coefficient of distilled water. HU ranges from −1,000 for air to +1,000 for bone, with zero set as the value for distilled water.

As shown in Fig. 3a, all HU measurements such as maximum, minimum, mean, and deviation values were

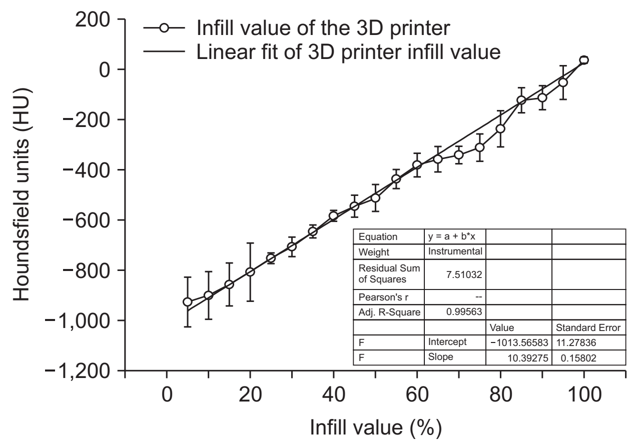

Fig. 4. Correlation between infill value (%) and Hounsfield unit (HU) of the 3D printer.

obtained by using a two-dimensional area profile function at the center of the sample. The region of interest (ROI) was set as dX (50 mm) and dY (5 mm) on the transversal image produced through the CT scan. Fig. 3b shows the horizontal ROI profile, the vertical ROI profile, the pixel statistics, and the ROI for the measured area of the sample with an infill value of 5%.

Results and Discussion

Fig. 4 shows the relationship between infill value (%) and Hounsfield unit (HU). The relationship is related to the average HU measured by using the 2D area profile measurement method for a total of 20 samples by increasing the infill values of the 3D printer from 5% to 100% in increments of 5. As a result, the HU was obtained by varying the infill values from 5% to 100%, and thus, changing the average HU from −926.8 to 36.7.

The equation that represents a linear relationship is as follows.

$$y=a+b\times x$$

where a=−1013.56, b=10.39, and the adjusted R-square is 0.99563, which indicates high linearity.

Studies have recently been conducted on the application of 3D printers in QA, which is a required safety measure in radiation treatment. The studies on 3D printer designs for radiation treatment have been proceeding in two main directions. The first is to fabricate a patient-customized bolus by modeling the irregular skin surface and printing the model using a 3D printer.[14,15] The second is to verify the measured radiation dose and the radiation dose calculated using a patient-customized phantom in the QA of potential radiation treatments, for which studies have been improving the accuracy.[4,12,13] Although the morphology of an actual patient could theoretically be accurately reproduced to fabricate a customized phantom, current 3D printer technology can print using only one material at a time, so the actual density of the patient body cannot be reproduced. Thus, accurate dose verification is difficult. To overcome this challenge, this study investigated the feasibility of using 3D Printing to fabricate variable density phantoms by varying the infill values. A similar study by Madamesila et al.[13] reported that 3D printing is useful for fabricating variable density phantoms for QA purposes by using FDM-type Rostock Delta printers and high-impact polystyrene (HIPS) materials. On the other hand, our study has confirmed the feasibility of 3D printing with PLA material, which is a material more widely used in the 3D printer field, in fabricating variable density phantoms by using a FDM-type Finebot™ (AnyWorks; Korea) Z420 model.

Thus, one limitation of our study was that we covered with the organs for the low densities except for the high density such as the bone.

Another limitation was that we only considered 2D profile of the transversal image for the measurement of the average HU in this study. But, if we use the 3D profile of the 3D printed-samples, the average HU may also have altered slightly.

As a result of this study, variable density phantom by varying the infill values using the FDM-type 3D printer and PLA materials can be expressed with heterogeneities of the air (−1000 HU), lung (−400~−600 HU), fat (−50~−100 HU) and soft tissue (40~80 HU).

Conclusion

This study showed the feasibility fabricating variable density phantoms by varying the infill values using the FDM-type 3D printer and PLA materials. If the further study is performed, variable density phantom using the 3D Printer can improve the accuracy of the quality assurance (QA) of radiotherapy.

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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