Investigation of a method for creating neonatal chest phantom using 3D printer

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Abstract. Newborns and children are more sensitive to radiation and have a longer life expectancy than adults. Therefore, efforts should be made to reduce unnecessary exposure by optimizing the dose when conducting radiological examinations. In order to optimize the dose in neonatal X-ray examinations, we studied a method to create inexpensive and precise neonatal chest heterogeneous anthropomorphic phantoms using a 3-dimensional (3D) printer. Phantoms were created by constructing segments of computed tomography (CT) volume data acquired from the chest of a 6-month-old, excluding the bone and lung tissue, using 3D image analysis software. The material used for 3D printing was polylactic acid; multiple printing densities were investigated. Gypsum and urethane foam were used as bone- and lung-equivalent substances. The CT values of the lung tissue in the phantom were almost the same as those of the air, and those of the bone tissue showed a range of CT values dependent on the print density. By visual evaluation, it was established that the shapes of the original lungs and heart were reproduced in the images of the phantom. The creation of an inexpensive and precise neonatal chest phantom using a 3D printer is useful.

1. Introduction
Radiology is widely used as the basis of medical diagnosis and treatment because of its usefulness. However, strict control is required to minimize ionizing radiation exposure and the related risks. If the radiation dose is too low, disease may be difficult to diagnose and therapeutic effects may be reduced. Moreover, too high a dose may not only impair proper diagnosis and treatment but also cause unnecessary exposure. The International Commission on Radiological Protection (ICRP) recommends the justification and optimization of radiation diagnostics [1]. In addition, the use of diagnostic reference levels (DRLs) as guidelines for patient dose is recommended to promote protection in radiology [2]. A DRL indicates a particular radiation dose in a standard-type radiological examination that serves as a guide for the standardization of imaging conditions at individual facilities. DRLs are set worldwide [3-6].

While efforts are being made to reduce medical radiation exposure in general, this is especially true for newborn and infant exposure. Very young children are more radiosensitive than adults and have a longer life expectancy, which inevitably increases the risk of carcinogenesis. Thus, infant and newborn radiation exposure requires more attention than that of adults. Regarding data on medical exposure, various measured values, estimated values, and indicators have been published in the literature, but there is perhaps insufficient information on general radiography, fluoroscopic examination, and computed tomography (CT) examination of newborns and infants [7-15]. Human body phantoms for newborns and infants are commercially available for radiographic practice. However, dosimeters cannot be
inserted into the phantoms for radiographic practice. In addition, dosimetry phantoms cannot be used for detailed evaluation of organs. Having the use of a phantom also helps in the quality control of X-ray equipment [16,17].

In recent years, 3 dimensional (3D) printers have become popular. By creating a three-dimensional polygon dataset, even phantoms with complicated shapes can be created, and these are widely used in the medical field [17-20]. We hypothesized that by using a 3D printer, it might be possible to create a heterogeneous anthropomorphic phantom at a relatively low cost from only the 3D printed material and injected tissue-equivalent materials. The purpose of this study was to examine the method for preparing a precise and accurate chest phantom for newborns using a 3D printer.

2. Material and methods

2.1. Materials
To create an infant chest heterogeneous anthropomorphic phantom, a CT volume dataset acquired from a 6-month-old male chest (slice thickness, 0.5 mm; 239 slices) was used. The data was acquired by the ethics review committee of the Kyushu University Institute of Medicine. To create 3D polygon data, 3D image analysis software 3D Slicer version 4.8.1 was used and 3D engraving software Meshmixer version 3.5.475 was used to edit data. 3D printer output software Cura version 15.04.3 was used to control the printer. The 3D printer used was the 3DP-23 instrument (HICTOP, China), which is a fused deposition modeling (FDM) type printer. Polylactic acid (PLA; density, 1.24 g/cm³) was used for the filament, i.e., the 3D printing material. For the equivalent substances, gypsum was used as a bone-equivalent substance, and urethane foam was used as a lung-equivalent substance.

2.2. Chest phantom preparation
We imported CT volume data into the 3D Slicer software and created segments excluding lungs and bones, which have lower and higher densities, respectively, than soft tissue (figure 1). This segment was saved using a stereolithography (STL) format, which is a standard file format for three-dimensional shape data. The created STL data files were imported into the Meshmixer package and the number of polygons was optimized. By reducing the number of polygons from 2,567,872 (158 MB) to 275,114 (17 MB), the data volume is significantly reduced (figure 2). After that, in order to inject gypsum and urethane foam, which are, respectively, the tissue-equivalent substances for the bone and lung, the prepared STL data were divided into four parts, with the coronal plane passing through the center of the body and the sagittal plane forming the dividing lines between the parts (figure 3).

Using the Cura software, the print density can be adjusted. This is the density of the filament within the printer during the printing process. To investigate the optimum print density, that is, to generate a phantom with X-ray absorption as similar as possible as that of the human body, phantoms consisting of only the left-rear section were made using print densities of 0%, 50%, 80%, 90%, and 100%. In addition, a phantom for the entire chest was created with a print density of 50% (figure 4).
**Figure 1.** Created segments excluding lungs and bones from CT volume data using 3D slicer. (a) axial image, (b) 3D surface rendered image, (c) sagittal image, (d) coronal image.

**Figure 2.** Comparison of the chest volume data before and after reducing the number of polygons. (a) before reduction (number of polygons, 2,567,872; data volume, 158 MB). (b) after reduction (number of polygons, 275,114; data volume, 17 MB).

**Figure 3.** Prepared chest phantoms, divided into four parts. (a) front-view photograph of two front parts of chest phantom, (b) internal views of phantom sections acquired before and after filling the bone and lung regions with gypsum and polyurethane, respectively. (c) photograph showing the four parts adhered by tape.
Figure 4. Visual differences resulting from print density. (a) 0% printing density. The printing time is short, but there are holes in the center of the phantom. (b) 50% printing density. The mesh can be confirmed by the printing direction.

In the created rear-left partial chest phantom, gypsum was injected into the bone regions, as a bone-equivalent substance, using a syringe. Further, urethane foam, as a lung-equivalent substance, was injected into the lung region.

The created phantom was radiographed from the front using a conventional X-ray imaging device UD150 L-30 (Shimadzu Corp., Kyoto, Japan) and computed radiography system FCR5000 (FUJIFILM Medical Co, Ltd., Tokyo, Japan) under the following conditions: tube voltage, 60 kV; tube current, 100 mA; irradiation time, 50 ms. In addition, CT imaging was performed by using an Alexion Access imaging system (Canon Medical Co., Japan) at a tube voltage of 120 kV, a tube current of 100 mA, a slice thickness of 1.0 mm, and a rotation time of 1 s.

3. Results

3.1. Evaluation by X-ray imaging
X-ray images of phantoms created with print densities of 50%, 80%, and 100% are shown in figure 5. In these phantoms, gypsum, which is used as the bone-equivalent substance, was injected only into the regions corresponding to the bone. The images allow us to conclude that the X-ray absorption by the bone tissue in the vertebral body was effectively reproduced by the gypsum in the model. Further, the lower the printing density, the more the mesh was apparent.

Figure 5. X-ray image of a phantom created with print densities of 50% (a), 80% (b), and 100% (c). In the phantom with a print density of 50%, a mesh can be seen in the location of the liver in this frontal view. At a printing density of 80%, no mesh is seen in the image of the phantom. It can be confirmed that the phantom printed with a density of 100% absorbs X-ray radiation more strongly than that printed with a density of 80%.
3.2. Evaluation by CT imaging

CT images of the 100%, 80%, and 50% phantoms injected with the bone-equivalent substance are presented in figure 6, and those of the 90% and 0% phantoms with soft tissue region are shown in figure 7. The Hounsfield units of the soft tissue region, lung, and bone in each of the phantoms are listed in Table 1. For the soft tissue, the lower the print density, the lower the CT value. Comparing these values with the corresponding values for the image of the 6-month-old male chest used to construct the phantoms, it can be concluded that the CT value of the soft tissue is best approximated by preparing the phantoms with a print density of between 90% and 100%. In the lung region, the CT value was close to that of air, regardless of the print density. In order to achieve a CT value closer to that of the actual lung tissue, another equivalent substance should be considered as a replacement for the urethane foam. Only the bone areas in the 100% printing density phantom had high CT values. This is thought to be because for the lower printing densities, holes were more easily formed inside the phantom, and thus the gypsum leaked into the rest of the phantom from the bone regions.

![Figure 6](image6.png)

**Figure 6.** CT images of phantoms injected with a bone equivalent substance. It can be confirmed that the Hounsfield unit (HU) of the soft tissue is dependent on print density (a) 100%, (b) 50% and (c) 80%. In addition, the HU in the area of vertebral bodies and ribs injected with gypsum is high. Note that in the phantom with a printing density of 50%, injected gypsum could not be retained within the rib regions.

![Figure 7](image7.png)

**Figure 7.** CT images of phantoms injected with a lung-equivalent substance. (a) phantom prepared with 90% printing density for the soft tissue. (b) phantom prepared with 0% printing density for the soft tissue. The polyurethane-foam lung-equivalent material can be observed upon careful inspection of the images, but it is apparent that its HU value is almost equal to that of air.

![Table 1](image1.png)

**Table 1** Differences in Hounsfield unit (HU) in CT images in the soft tissue, lung, and bone areas for phantoms with different printing densities and for the 6-month-old male chest used to make the phantoms.

| Print density | 0%  | 50% | 80%  | 90%  | 100% | Original CT images |
|--------------|-----|-----|------|------|------|-------------------|
| Soft tissue  | -995.8 | -460.9 | -124.0 | -22.6 | 100.6 | 49.0 |
| Lung         | -939.2 | —   | —    | -945.1 | —    | -876.3 |
3.3. Visual evaluation of the entire phantom

An X-ray image of a chest phantom created with a print density of 50% is shown in figure 8. This phantom was not injected with bone-equivalent or lung-equivalent substances, and changes the printing direction between the right and left half of the phantom are apparent. Coarse-structure features such as the shape of the lungs and the shape of the heart are reproduced, the contrast is good, and no noise can be observed. Because the left half of the phantom is printed in the front–back direction, the mesh is visible.

A CT image of the same phantom is shown in figure 9. The contrast between the soft tissues is low, and the low-density printing of the phantom resembles as noise; however, features such as the coarse blood-vessel structures in the lung field and the shape of the lung and heart are reproduced.

![Figure 8. Comparison of X-ray images of phantom and chest. (a) X-ray image of the 3D-printed phantom. (b) plain chest X-ray image of the patient used to create the phantom. It can be confirmed that the shapes of the hearts are similar.](image-url)
Figure 9. Comparison of entire-chest CT images of phantoms and chest. Upper: CT images of the chest phantom created by 3D printing. (a) image is an axial cross section and (b) image is a sagittal cross section. Lower: CT images of the 6-month-old male chest used to create the phantom. (c) image is an axial cross section and (d) image is a sagittal cross section. The fine structure is not completely reproduced, but it can be confirmed that the coarse structure is similar.

4. Discussion
The lower the print density, the lower the CT value of the soft tissue, so it is possible to tune the CT value of the soft tissue by adjusting the print density. The print density may be set to a value between 90% and 100% in order to approach the CT value of a particular type of soft tissue. However, at low print densities, holes were opened inside the phantom, leading to leakages during gypsum injection. Thus, in the future, it is necessary to consider the possibility of closing the holes during injection.

The CT value of the urethane foam used as a lung-equivalent substance was almost the same as that of air. Therefore, in order to bring the CT value of the lung-tissue in the phantom closer to that of the actual lung, it is necessary to find a substance with a slightly higher density to replace the urethane foam. Specifically, styrofoam, which is a similar substance, could be used. Alternatively, filling styrofoam to the lung regions by condensing them as much as possible could produce a more accurate phantom.

The cost of the printing included the price of 30 U.S. dollar /kg for the PLA, and approximately 1 kg of PLA was required for the phantom printed with a density of 90%; the printing time was 40 h for the chest of a 6-month-old child. This cost estimate suggests that it is possible to make the phantom at a lower cost than a commercially available phantom. It is also possible that printing costs and times can be reduced by making the soft tissue part of the phantom hollow and filling it with a soft tissue equivalent substance (gelatin, urethane, etc.).

5. Conclusion
Using a 3D printer, an inexpensive and precise newborn chest phantom was created. It was possible to tune the Hounsfield unit by adjusting the print density and to create a shape similar to that of the original organ. In order to prepare more precise phantoms, it is necessary to optimize the injection method and amounts of the equivalent substances.
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