Fabrication of Realistic and Dynamic Human Head Phantoms*

Yukari TANIKAWA**, Daigo IMAI***, Kenji TANAKA*** and Yukio YAMADA**

Optical tomography will be a new modality of non-invasive diagnosis in medicine and biology, and is expected to image the distribution of optical properties in human bodies by measuring transmitted light at skin surfaces. In the process of developing optical tomographic imaging systems for diagnosis of disease and study of brain functions of human heads, we need realistic optical phantoms which anatomically and optically simulate human heads with complicated and multi-layered structures. In this study, we have fabricated optical phantoms based on MRI images of a human head. The phantoms had a multi-layered structure with different optical properties at five layers; i.e., skin, skull, cerebrospinal fluid layer, gray matter and white matter. Also the phantoms which were mainly made of solid resin had dynamic parts to simulate the temporal variation of physiological functions in brain. The optical properties of the liquid circulating through the dynamic part can be changed to simulate the change in oxygenation states. The material of the skin layer was a soft rubber in order to achieve a good contact with optical fibers. The fabricated optical head phantom was checked by X-ray CT to see whether air bubbles were trapped or not, and to measure the size and cavity in the phantom.

Key Words: Optical Engineering, Medical Equipment, Molding Methods, Dynamic Human Head Optical Phantom, Layered Structure, Laser Prototyping, Photolithography, Vacuum Casting

1. Introduction

Optical tomography is expected to image the distribution of optical properties in human bodies by measuring transmitted light at skin surfaces. Significant number of papers[1][2] has recently been published and many methods have been proposed toward the goal of realizing optical tomography. However, theoretical and experimental studies on photon migration have been mainly conducted on media with simple geometry such as slabs and cylinders. Time-resolved measurement using picosecond light pulse is believed to be one of the promising methods[3][4], and many people have used the diffusion approximation to predict the behavior of the light pulse propagation in tissues or tissue-like phantoms which strongly scatter and weakly absorb light. So far, most of the studies used less practical phantoms such as semi-infinite and slab materials[5][6], and only a few studies have used more practical cylindrical phantoms[7][8]. But for optical tomography we must fully understand the light propagation through complicated structures in three dimensions. More realistic human body phantoms are necessary to perform experiments for realization of optical tomography.

In this study, we have made a realistic optical head phantom based on rapid prototyping technology[9][10]. The phantom consisted of five layers corresponding to skin, skull, clear CSF (cerebrospinal fluid) layer, gray matter and white matter, respectively. The size and optical properties of the five layers were given according to those of neonatal brain or pig brain. Epoxy resin was used as the base material, and titanium oxide(TiO₂) particles and green dye were added for controlling the reduced scattering and absorption coefficients. The optical properties of each layer were estimated by using a spectrophotometer with an integrating sphere and Monte Carlo simulations. Shapes of the human heads
were taken from MRI images of a human head[18], and the prototypes of the five layers were fabricated by using a rapid prototyping based on photolithography. Also the optical phantoms with some dynamic parts are required to simulate temporal changes in physiological states. The dynamic phantoms had cavities inside the phantoms, where liquid was able to flow for the purpose of changing the optical properties.

2. Rapid Prototyping and Molding

2.1 Prototyping of human heads

Prototypes of human heads were fabricated by using rapid prototyping (SLP-5000, Denken Engineering Co., Ltd.) based on laser photolithography. Rapid prototyping can fabricate 3D shapes from sectional data (stack data) provided by such as MRI, X-ray CT, and CAD (computer aided designing). Figure 1 shows the conceptual illustration of the rapid prototyping machine. Polyacrylate resin (DF-803N, Denken Engineering Co., Ltd.) is polymerized by a blue laser beam with the wavelength of 473 nm after mixing unpolymerized liquid resin and hardener. A polymerized resin layer is generated on the surface of the base plate from the bottom by irradiating the laser beam through a transparent glass plate. Scanning in the horizontal plane is done by x-y plotting of the laser beam. x-y plotting is controlled by a personal computer which stores the stack data of the object. The scanning accuracy is 0.1 mm. After finishing the first layer, the base plate is elevated by the layer thickness and the next layer is polymerized to be added to the previous layer from the bottom. The thickness of each layer can be from 0.1 mm to 1.0 mm, and 0.2 mm thickness was found to be the best for our purpose. This process is repeated until all layers are fabricated.

The stack data of human head were generated from MRI images of a human head by using a software of NIH image[19]. Although our purpose was to make phantoms simulating neonatal heads, we were not able to obtain MRI data of neonates. Instead, we used MRI data of an adult head by scaling down to 55% in size. We tried to make a phantom of a part of a head above the horizontal eye plane. The size of the outer skin surface was 51 mm in height, 103 mm and 87 in longer and shorter axes, respectively. The heights of the inner tissues were 47 mm for skull, 45 mm for clear CSF layer, 44 mm for gray matter and 41 mm for white matter. The original MRI images were given with a spacing of 0.8 mm between two neighboring slices, but we needed more slices because one layer of prototyping has the height of 0.2 mm. Therefore, we interpolated three slices between the two original slices, and the total number of the slices was 249 for the height of 51 mm.

Tissues in human heads can be classified into five types from their optical properties; i.e., white matter, gray matter, clear CSF layer, skull and skin as shown in Fig. 2. Following this classification, the contours of the five tissue types were extracted in each slice by the threshold value of the brightness of each pixel in the MRI images. Then the stack data of each tissue types were generated and sent to the computer for the rapid prototyping machine. Then five prototypes having the outer 3-D shapes of five tissue types were fabricated. All prototypes had base plates with the same size for the purpose of positioning when one layer of a tissue type was cast on its inner neighboring layer in the phantom fabrication process as described in the following section. Figure 3 shows a prototype of white matter.

2.2 Molding

Next step was to make molds from the prototypes of all the tissue types. Silicone rubber (KE 1404, Shin-Etsu Chemical Co., Ltd.) was selected for molding materials because of its high flexiblility up to 400% elongation. Overhangs can be easily molded by this

![Fig. 1 Rapid prototyping system based on laser photolithography](image1)

![Fig. 2 MRI images divided into five layers](image2)

![Fig. 3 Prototype of white matter](image3)
rubber. Hardening of the original rubber material starts after mixing with hardener. The molding process is shown in Fig. 4. Release agents (Silicone Spray 006, AZ Co.; or Mold Release S, Fine Chemical Japan Co.) were used to separate the hardened rubber molds from the prototypes having complicated structures. As an example, a mold of white matter is shown in Fig. 5.

3. Phantom Casting

3.1 Casting process of static phantoms

Epoxy resin (Epothin Resin, Bueler Co.) was used as the phantom material, and TiO₂ fine particles (KRONOS KA-30K, Titan Industry Co.) were used as scatterers to be mixed in the epoxy resin. Green dye was mixed for adding absorption if necessary. The reduced scattering coefficient, \( \mu_s' \), was controlled by adjusting the volume fraction of TiO₂ particles to be mixed into the resin, and the absorption coefficient, \( \mu_a \), by controlling the concentration of the green dye. The optical properties, \( \mu_s' \) and \( \mu_a \), were given by referring to the existing data of human neonatal heads and pig experiments. However, the exact values of the optical properties, \( \mu_s' \) and \( \mu_a \), listed in Table 1 were measured by applying the integrating sphere method to the small samples which were made using the same material cast in each tissue layer.

The casting procedure to make a layered static phantom was as follows. At first, the epoxy resin with the optical properties of white matter was cast into the mold of white matter. The white matter phantom was the innermost layer of the layered head phantom. By hardening of the epoxy resin, a phantom of white matter was completed and separated from the mold. Next step was to cast the white matter phantom by the gray matter mold, and the gap between them was filled with liquid epoxy resin having the optical properties of gray matter.

Because the thickness of gray matter was small, the gap between the gray matter mold and the white matter phantom was small. Therefore, simple casting of epoxy resin into the gap in the air could not completely evacuate all air in the gap, and some undesirable air bubbles were trapped. By employing the vacuum casting for adding gray matter, we have succeeded in avoiding undesirable air bubbles trapped in phantoms. Then the phantom had a gray matter layer covering the white matter. This process can be repeated until the skin layer is added if a static phantom is to be made.

Silicone rubber (KE-106, Shin-Etsu Chemical Co., Ltd.) was used as the casting material for the outermost layer of skin to provide softness which was necessary for optical fibers to be attached onto the surface without small air gap (Fig. 6). If the skin layer was made of epoxy resin, the ruggedness of the surface would have caused a small gap between the detecting fiber end and the skin surface.

<table>
<thead>
<tr>
<th>Tissue Type</th>
<th>Reduced Scattering Coefficient ( \mu_s'(mm^{-1}) )</th>
<th>Absorption Coefficient ( \mu_a(mm^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>White matter</td>
<td>5.9</td>
<td>0.009</td>
</tr>
<tr>
<td>Gray matter</td>
<td>2.8</td>
<td>0.019</td>
</tr>
<tr>
<td>Clear CSF layer</td>
<td>0.0</td>
<td>0.003</td>
</tr>
<tr>
<td>Skull</td>
<td>1.1</td>
<td>0.025</td>
</tr>
<tr>
<td>Skin</td>
<td>0.73</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Fig. 4 Molding process

Fig. 5 Mold of white matter

Table 1 Optical properties of tissues inside a head model in the wavelength of 780 nm

Fig. 6 Skin layer
refractive index of the silicone rubber is 1.40 and that of epoxy resin is 1.58. The ratio of those is 1.58/1.40 = 1.13. Then, the reflectance of the light normal to the interface between the silicone rubber and epoxy resin is calculated as 0.013 by using the Fresnel equation. On the other hand, the reflectance at the air–silicone rubber boundary is 0.082. Therefore, the reflection at the interface between silicone rubber and epoxy resin can be negligible.

3.2 Making a dynamic part

In order to include a dynamic part in the phantoms, we should have some cavities inside phantoms, to which two conduits are connected for a liquid to flow in and out. The liquid is circulated by a circulation system outside the phantom and has the optical properties representing some physiological states. The liquid can be either artificial scattering and absorbing media, artificial media with the addition of blood, whole human or animal blood, etc. The optical properties of the liquid can be changed arbitrarily by changing the concentration of scattering particles, the concentration of absorbing dye, or oxygenation state of blood. Then we can obtain dynamic phantoms. In the following we describe the process of making cavities inside solid phantoms with conduits connecting the cavities to outside the phantoms. The method of making only one cavity in the regions of gray and white matters is explained below as shown briefly in Fig. 7, but multiple cavities at any area are possible.

After making a phantom having gray and white matters in the process described in the previous section, a part of the phantom was removed to make a cavity by machining. Then two holes for liquid inlet and outlet were drilled from the bottom to the cavity. Two plastic tubes were glued to the two holes and the tubes were connected to a liquid circulating system. The machined phantom with a cavity was again put into the mold of gray matter and melted paraffin was cast into the cavity through the tube. After the paraffin was solidified in the cavity the phantom was taken out from the gray matter mold and put into the skull mold. The epoxy resin having the properties of skull was cast in vacuum into the skull layer gap. After the skull layer was hardened, the phantom was taken out from the skull mold. This phantom was heated so that the melted paraffin was removed to make a cavity. The skin layer was then added and the whole dynamic phantom was completed.

The liquid circulating system to change the optical properties of the dynamic part was connected to the cavity of dynamic phantom as shown in Fig. 8. The liquid media were prepared by using latex suspension with containing absorbing dye (Greenish Brown, Chugai Kasei Co., Ltd.) or black ink without scattering.

3.3 Examination of phantoms by X-ray CT

After completion of the whole dynamic phantom, it was checked by X-ray CT (DensiScan 1000, Scanco Medical Co.) to see whether air bubbles were trapped in it or not, and to measure the size and position of the cavity in the phantom as shown in Fig. 9. The volume of the cavity was slightly less than 1 ml, the volume of the conduits was slightly larger than 1 ml. The total volume of the cavity and the conduits was 2 ml which was about 1% of the whole volume of the phantom of

Fig. 7 Making a dynamic part

Fig. 8 Circulating system

Fig. 9 X-ray CT image of optical phantom
235 ml.

4. Summary

In order to simulate the brain damage or brain functions, we need realistic optical head phantom which include dynamic parts where the optical properties can be artificially controlled. We have fabricated a dynamic optical phantom having a dynamic part inside it. Also in order to prevent air bubbles trapped in the phantoms during casting process we have employed vacuum casting and it was successful. The outer most layer of skin was made of a soft silicone rubber to have good contact between the surface and optical fibers. These phantoms can be used for experiment of photon migration in human heads and for experiment of optical tomography.

Acknowledgement

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References


(17) Private communication from Yamada, Y. et al.