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Creation of a 3D printed human head phantom

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Abstract: Deep brain stimulation (DBS) is a neurological intervention to treat neurological diseases such as Parkinson's disease. The postoperative position determination of the electrode is critical to determine if the surgery was successful. This study aimed to develop a human head phantom by using additive manufacturing (AM). With these phantom new findings in postoperative position determination on computed tomography images can be gained. Necessary to that end, the head phantom should be as anatomically correct as possible. Furthermore, the brain and the bones should be represented with realistic CT values on computed tomography (CT) images. The first measurements showed that the CT values of the 3D printed skull correspond to the CT values of the human skull and the CT values of the phantom's brain are equivalent to values slightly above these of the human brain.

I. Introduction

Deep brain stimulation is an established therapy for neuronal disorders. It is used for the treatment of Parkinson's disease, essential tremor, dystonia, and epilepsy [1], [2]. In deep brain stimulation, electrodes are implanted permanently in the brain. As the target areas in the brain are only a few millimeters big, accurate placement is vital for the clinical success of the therapy. However, on the reconstructed computed tomography (CT) images, the implanted electrode leads to artifacts, which make position determination difficult. For this purpose, a head phantom is constructed to improve the position determination on postoperative CT images by developing new algorithms. The head phantom should be as anatomically correct as possible. Besides, it should comply with the requirements to represent the skull and the brain with tissue-equivalent CT values on CT images. Manufacturing the head phantom was done by 3D printing the bones of the skull and filling the phantom with silicone, which is supposed to simulate the brain. This study aims to present the workflow of the creation of this head phantom.

II. Material and methods

A CT dataset of an adult patient from the head and neck was used. To generate a 3D model from the CT dataset, the software Mimics Innovation Suite (Materialise, Leuven, Belgium, Version 23.0) was used. The workflow starts with a segmentation of the bones to generate a first approximation of the 3D model. Next, postprocessing of the segmentation was necessary. In addition to the cranial bones, the cervical spine and the shoulders were also segmented. These three parts were manually removed. Because holes were visible in the eye socket, these were closed by a manual segmentation, as otherwise, the silicone would run out. Furthermore, the air-filled cavities between the thin bone structures of the nose and paranasal sinus were segmented manually and thus printed entirely with print material, as these structures are very delicate and would otherwise break off during the printing process. In the final step of the postprocessing procedure, a dilatation was applied to increase the wall thickness of the 3D model because CT measurements of a test phantom showed that the bones can only be seen very thin on the CT images. The 3D model was exported to Standard Tessellation Language (STL). Because the individual slices of the dataset were visible, a Laplacian smoothing filter was applied. In order to correct inverted triangular faces, postprocessing of the triangulation was applied. The 3D model was then divided into two parts in the eye-ear plane so that the upper part can be filled with brain simulating material in which the electrodes can be placed. A plug-in principle was used to connect the two pieces for CT measurements. Before both parts were printed, they were checked again for triangulation errors.

They were printed using the selective laser sintering method (SLS) using the material PA 3200 GF (EOS, Krailing, Germany). PA 3200 GF is a glass-filled polyamide 12 powder. The 3D Printer was a EOSINT P760 (EOS, Krailing, Germany). A layer thickness of 0.1 mm was used for the printing process. In the next step, the 3D printed parts were manually postprocessed so that both parts better fit together. Afterward, the upper part of the phantom was filled with 1446 g silicone, which is supposed to simulate the brain. We used the SF00-RTV2 silicone (Silikonfabrik, Ahrensburg, Germany), which has a shore hardness of 00 ShA. This silicone consists of two components which are thoroughly mixed in a ratio of 1:1. When both components were mixed, air bubbles were emerged due to the physical procedure. Therefore, the silicone was evacuated for five minutes in a vacuum chamber before being filled into the upper part of the head phantom.

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III. Results and discussion

The head phantom is characterized by a high print quality, including the representations of details. Only a small gap is visible after the two parts have been stuck together (see Fig. 1).

Figure 1: Photograph of the 3D printed head phantom.

The upper part has a length of 148.30 mm, a width of 184.09 mm, and a height of 144.53 mm. The lower part has a length of 133.94 mm, a width of 181.26 mm, and a height of 92.54 mm. The material cost for the 3D print and the silicone is 565.25€. The cost of a commercially produced head and neck phantom for CT, X-ray, and radiotherapy is 17.825,01€ [3]. So, the price of the commercial phantom is well above the costs of the constructed head phantom. Photographs of the silicone-filled upper part and the lower part are shown in figure 2. The SF00-RTV2 silicone is elastic enough to place electrodes for a simulation of DBS in the material.

Figure 2: Left, a photograph of the 3D printed upper part of the phantom. Right, a photograph of the 3D printed lower part of the phantom.

The analysis of a CT measurement, which was acquired at a tube voltage of 100 kV and 210 mAs, shows mean and standard deviation for the PA 3200 GF material of 380.92 ± 20.33 HU and for the silicone 169.14 ± 40.45 HU. Human bones have CT values greater than 300 HU [4]. Therefore, the CT values of the print material PA3200 GF are in the range of the CT values of bones. Because the CT values of the brain are between 20 HU and 45 HU [4], the values for this area are significantly above the desired range. The evaluation of the CT measurement also shows that the silicone is free of air bubbles (see Fig. 3). The Dice coefficient was used to determine how much the final result diverges from the segmentation of the bones in the initial dataset. The Dice coefficient results in a value of 0.66 and, therefore, it can be concluded that there is only a low similarity between the two segmentations. Therefore, the assumption is that the manual segmentation during the postprocessing step and the applied dilatation results in a low dice coefficient. In order to quantitatively evaluate how the size of the head phantom has changed compared to the dataset used, the maximum Hausdorff distance was calculated. The value was calculated between the 3D segmentation of the bones in the head phantom and in the initial dataset.

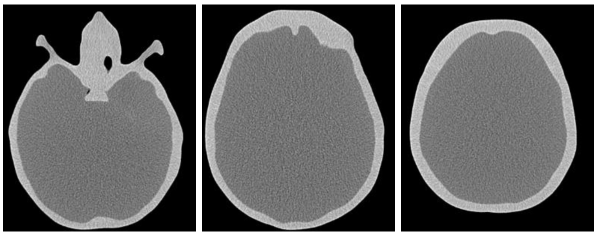

Figure 3: Three selected axial CT slices of the silicone filled upper part of the head phantom.

The maximum Hausdorff distance of 37.77 mm shows that the constructed head phantom is smaller than the dataset. With the Laplacian smoothing filter applied, each vertex is moved in the direction of the center of the neighbor pixel [5]. Therefore, it can be concluded that the Laplacian smoothing filter has contributed to a shrinking of the constructed head phantom.

IV. Conclusions

In this study, a human head phantom was constructed from an adult patient CT dataset. By using 3D printing technologies, we were able to create an anatomically accurate human head phantom that represents the bones with realistic CT values. Only the CT values of the brain-simulating silicone are slightly above the CT values of the brain. In the future, other elastic brain-simulating materials with CT values in the range of brain tissue will be considered. Nevertheless, this human head phantom is very suitable for CT measurements to determine the position of the electrodes in the brain because the electrodes can be implanted in different positions and at different angles in the brain. Further studies regarding this topic are currently ongoing.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study.

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