An anthropomorphic deformable phantom for brain shift simulation

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***Abstract*—The prominent soft tissue deformation during a neurosurgical procedure, the so called brain shift phenomenon, affects the accuracy of the surgery greatly. Although the feasibility of numerous intraoperative modalities is investigated for the brain shift compensation, another state-of-the-art interventional imaging modality C-Arm CT is rarely studied in this context. Due to the lack of clinical data, a suitable anthropomorphic deformable phantom is indispensable. The purpose of this study is to describe and determine the characteristics of a multi-modal deformable brain phantom made out of polyurethane and ceramic composite bone material. The phantom is made of six parts: skin, skull, brain, blood vessels, ventricles and an inflatable tumor. Fluid can be filled into the blood vessels, the ventricles and the tumor in order to simulate the brain shift phenomenon. Such an anthropomorphic phantom is both visible with MR and C-Arm CT scanner. In order to evaluate the clinical relevance of our phantom, we induce deformations with different degrees by in- and deflated the embedded tumor in 5 steps. Both MR and C-Arm CT (cone beam CT) images are acquired in each step. The induced deformation is estimated by performing mono-modal deformable registration with symmetric normalization method (SyN) both on MR and cone beam CT (CBCT) acquisitions. The maximum displacement estimated with MR and CBCT pair is 29.6mm and 28.1mm. This result correlates the clinical findings.**

I. Introduction

THE accuracy of an image guided neurosurgery system suffers from the so-called intraoperative brain shift phenomenon. Different image modalities such as intraoperative MR, intraoperative US, Stereo Vision Cameras and Laser Range Image are used to compensate for the brain deformation during a neurosurgical procedure. However, another important interventional image modality, namely the C-Arm CT, is rarely studied in this context, although it is less expensive than intraoperative MR and is able to provide surgeons with real time high resolution data with anatomical structures such as blood vessels [1]. Consequently, due to the lack of suitable clinical data, an anthropomorphic deformable brain phantom is indispensable for the feasibility study of vessel-based brain shift compensation, where intraoperative contrast enhanced C-Arm CT acquisitions are used to update the preoperative MR images. Therefore, such a phantom should be able to simulate clinically relevant brain deformations and provide realistic images for both C-Arm CT and MR scanners.

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While an anthropomorphic digital brain phantom, such as the one presented in [2], is able to simulate the contrast enhanced C-Arm CT images, a physical phantom made out of Polyvinyl Alcohol Cryogel (PVA-C) is able to mimic the soft tissue deformation of the brain. In general PVA-C is a nontoxic industrial compound, which is a synthetic resin produced by polymerization of vinyl acetate followed by hydrolysis of the polyvinyl acetate polymer [3]. It is used as a soft tissue simulant to construct phantoms of the heart [4], the breast [5], as well as the brain [3], [6]. PVA-C is well-suited to generate brain phantoms as MR studies have shown, its T_1 values (measured with 1.5T MR scanner) are similar to values for gray and white matter [6]. However, it is not suitable for contrast enhanced C-Arm CT acquisition, because any solute liquid, such as iodine based contrast agent, will diffuse through the whole phantom [7]. Moreover, in order to maintain its mechanical properties, such a phantom needs to be stored in water within sealed containers [8].

In this study, we design and manufacture an anthropomorphic deformable brain phantom based on polyurethane and ceramic bone material to simulate the brain shift phenomenon. It is suitable both for MR and contrast enhanced C-Arm CT acquisitions. In Sec. II, we first present the design and material properties of the phantom and in Sec. III we describe the phantom experiments. Furthermore, we compute the magnitude of the simulated brain shift for both C-Arm CT and MR acquisitions using a mono-modal deformable registration approach as proposed in [9].

II. Phantom design and material properties

The 3D Computer-aided Design (CAD) model of the phantom manufactured in this study is shown in Fig. 1a. It consists of three main components, namely, skin, skull, brain parenchyma. The material properties of the main components are summarized in Table. I. In order to simulate the brain shift phenomenon, it is necessary to create the soft tissue deformation resulting from the change in inter-cranial pressure

Components	Density[g/cm^3]	Stiffness[kPa]	T_2[ms]	HU
Skull	2.31	N.A.	N.A.	1500/600
Parenchyma	0.99	100	70	-100 – -15
Skin	1.02	740	45	-130 – -40

TABLE I: Material properties of the main components. The T_2 values are measured with a 3T MR scanner by the manufacturer of the phantom. HU stand for Hounsfield Unit.

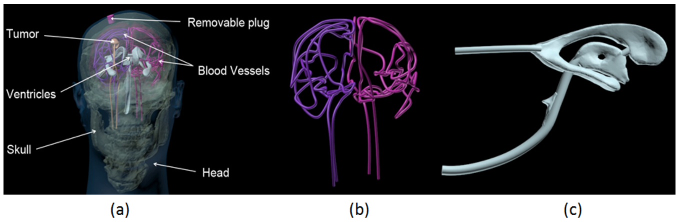

Fig. 1: Front view of the complete design of the phantom (a), the geometry of the vessel (b) and the side view of the ventricles (c).

observed following opening of the cranium. The anthropomorphic phantom is used to study the feasibility of vessel-based brain shift compensation, where intraoperative C-Arm CT images are used to update the preoperative MRI data. Therefore, the phantom should represent the anatomy of the average human brain correctly. The manufactured phantom must be visible on both MR and CT scans. To fit these criteria, we design and fabricate the phantom as follows:

The *skull* of the phantom is made out of a unique ceramic composite bone material [10]. A plastic model used to study anatomy by medical students, was employed to generate a mold and synthesize the phantom. As per the information provided by the manufacturer (True Phantom Solutions Inc., Windsor, Ontario, Canada), this represents the average shape of the skull for an adult. It gives similar MRI and CT feedback as a real human skull. The average Hounsfield unit for the cortical bone is 1500 and 600 for the diploe. The cortical bone appears dark in both the T_1 and T_2 MRIs. The diploe layer appears dark in T_1 and bright in T_2 weighted images.

An opening in the calvaria with a removable plug acts as pressure dissipative. A set of two tubes is attached through the skull to the *dura space* (a gap between skull and brain parenchyma). A liquid (e.g. water) can be injected and pumped through the tubes in order to induce a negative/positive pressure in a intracranial space of the head phantom.

The *brain parenchyma* is made out of an ultra soft polyurethane based material that mimics soft tissue and its anatomical shape was created based on the optical scan of an average human brain model used in the anatomy class for medical students. This material is stable over time, fairly chemical resistant and it does not dry out unlike the state of the art material PVA-C [8]. The embedded *vasculature* (Fig. 1b) is designed based on actual cerebral arterial structure extracted from a contrast enhanced MRI brain scan and it has been specifically modified so its entire volume can be completely filled with fluid and contrast agent. In order to ensure cerebral vasculature is modeled precisely, we implemented all blood vessels with a diameter of approximately 2mm.

Furthermore, an *inflatable tumor* is embedded in the phantom to induce different degrees of deformation in the brain parenchyma, in a manner that emulates various stages of tumor resection during neurosurgery. Initially, it has a volume of 1.3cm^3 and can be inflated up to 40cm^3. The phantom also comprises the entire ventricular system i.e. lateral, third and fourth ventricles (Fig. 1c) used to generate pressure inside the brain, and more closely approximate real cerebral anatomy. Both ventricles and the inflatable tumor can be filled out with any liquid.

III. Brain shift simulation

Initially, the ventricles and the dura space are filled out with distilled water. To enhance the vascular structure for cone beam CT (CBCT) acquisition with a C-Arm scanner, we use a solution of distilled water and Ultravist 370, a iodine-based contrast agent. The mixing ratio of contrast agent and distilled water is 1:10. In this stage, the calvaria plug is not removed in order to establish equilibrium, as in the human brain. Multiple stages of a tumor resection surgery are simulated as follows: first, the calvaria plus is removed, and 40ml of water is injected into the phantom. Subsequently, the tumor is deflated to -25ml, 15ml, 5ml and 0ml, and CBCT and MR images are acquired at each stage.

The CBCT images are acquired with a Siemens Artis zee system using the 10s 3D Head DCT protocol. The acquisitions were reconstructed on a 512x512x398 grid with a voxel resolution of 0.48mm^3. The MR acquisitions are performed with a 1.5T scanner (Siemens Magnetom Aera) using 3D flash sag isotropic sequence, where the Repetition Time (TR) is 10ms, the Echo Time (TE) is 3.25ms, and the Flip Angle is $5°$. The acquisitions are reconstructed on a 192x192x160 grid with a voxel resolution of $1.04\text{x}1.04\text{x}1.0\text{mm}^3$. Examples of the MR and CBCT acquisitions are shown in Fig. 2a, b and Fig. 2e, f, respectively.

In order to estimate the magnitude of the simulated brain shift and compare the results with the clinical observations, we use the symmetric image normalization method (SyN) within the Advanced Normalization Tools (ANTs) to perform mono-modal registration on the CBCT and MR acquisitions. This registration method was chosen as it has been shown to outperform 14 state-of-the-art approaches [11].

The following parameters are chosen to perform the non-rigid registration on both CBCT and MR data: 1) 5 level image pyramid with 1200, 1200, 600, 200, and 20 iterations for each level, 2) mean square difference as similarity metric and 3) 32, 16, 8, 4, and 2 as downsampling rate for each level. Exemplary results are visualized in Fig. 2c and 2f, where both CBCT and MR acquisitions with the tumor at maximum inflation, are registered to their maximum deflated counterparts. The maximum displacements estimated for the CBCT and MR image pairs are 28.1mm and 29.5mm, respectively. This result correlates with the clinical observations reported in [12], [13] and indicates that the anthropomorphic phantom presented in this study is able to simulate the brain shift phenomenon with high clinical relevance.

IV. Conclusion

In this work, we present an anthropomorphic deformable phantom for brain shift simulation made out of ultra soft polyurethane and ceramic cortical bone material. It contains prominent anatomical structures such as cerebral vasculature and ventricles. Our experiments show that the phantom is able to simulate brain shift in a manner that emulates a real clinical scenario.

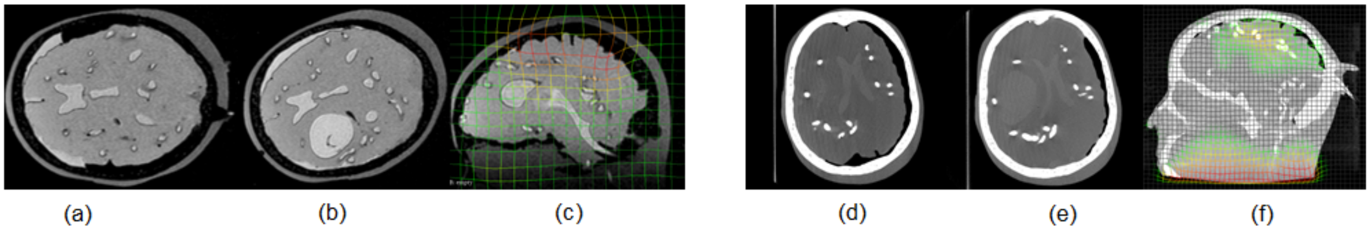

Fig. 2: Examples of MR (a)-(b) and CBCT (d)-(e) phantom acquisitions. (a) and (d) show the acquisition with maximum deflated tumor, while (b) and (e) present the maximum inflated tumor. The displacement fields estimated with symmetric normalization registration method (SyN) are solely based on MR or CBCT image pairs and are shown in (c) and (f), respectively.

Disclaimer: The methods and information presented in this work are based on research and are not commercially available.

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