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An Anthropomorphic Polyvinyl Alcohol Triple-Modality Brain Phantom based on Colin27

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Abstract. We propose a method for the creation of an anatomically and mechanically realistic brain phantom from polyvinyl alcohol cryogel (PVA-C) for validation of image processing methods for segmentation, reconstruction, registration, and denoising. PVA-C is material widely used in medical imaging phantoms for its mechanical similarities to soft tissues. The phantom was cast in a mold designed using the left hemisphere of the Colin27 brain dataset [1] and contains deep sulci, a complete insular region, and an anatomically accurate left ventricle. Marker spheres and inflatable catheters were also implanted to enable good registration and simulate tissue deformation, respectively. The phantom was designed for triple modality imaging, giving good contrast images in computed tomography, ultrasound, and magnetic resonance imaging. Multimodal data acquired from this phantom are made freely available to the image processing community (<http://pvabrain.inria.fr>) and will aid in the validation and further development of medical image processing techniques.

1 Introduction

The human cerebrum is a topologically complex organ with deep fissures and sulci over its lateral and medial surfaces, as well as fluid filled ventricles of complex form in its interior. The creation of a physical model capable of depicting the complex form of the cerebrum is not trivial due in part to these deep structures. Previous works in creating brain phantoms have either reduced the depth of the sulci [2], or only recreated the brain's form superficially with dessert gelatin molds [3, 4]. Although these phantoms bear a cursory resemblance to the human cerebrum, they do not accurately depict its anatomy. Registering these phantoms to their acquired multi-modality images may also not be straight-forward since

the landmarks on the phantom are not easy to find or image. This may be due to the structures being smaller than image resolution or insufficient contrast of the markers with respect to the surrounding tissues. For instance, Reinertsen and Collins [4] rely on the presence of bubbles in their phantom to act as landmarks for validation.

Our goal is to create a triple modality human brain phantom containing anatomically realistic structures and physically realistic texture. The phantom will then be scanned and the multimodal images made publically available. The material that we elected to use for constructing this phantom is polyvinyl alcohol.

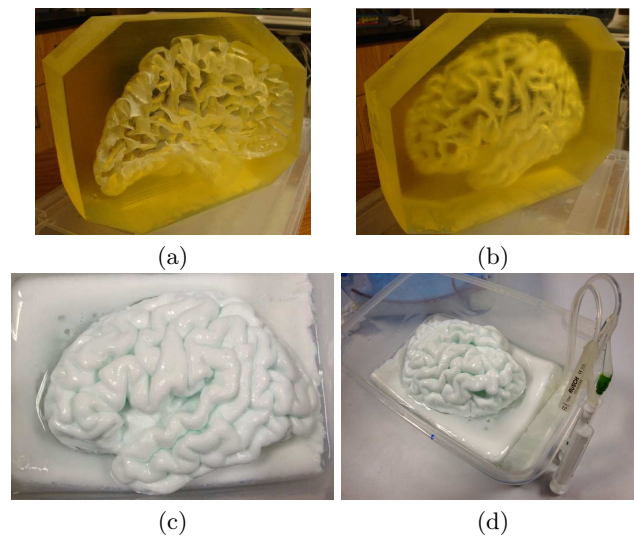


Fig. 1. Two views of the elastic Colin27 based brain phantom mold from (a) the inside. (b) The PVA-C phantom casted from our mold using our PVA solution recipe. Note the deep sulci and insular regions of the phantom. (c) The setup for scanning the phantom with the catheters used to inflate the phantom on the right.

Polyvinyl alcohol (PVA) is a synthetic polymer synthesized from polyvinyl acetate through hydrolysis of the latter's acetate groups [2]. When liquid PVA solutions undergo a specified period of freezing at a set temperature and is then allowed to slowly thaw to room temperature, this freeze-thaw cycle (FTC) transforms the liquid PVA solution into a elastic semi-opaque gel know as polyvinyl alcohol cryogel (PVA-C) [5–8].

PVA-C is used in biomedical research for producing soft tissue phantoms in studies to develop, characterize, and refine different imaging or image processing methods [9–11]. It is a good material for such studies since it has similar texture, mechanical properties such as compressibility and elasticity, and similar water content to many soft tissues [2, 4, 9–13]. PVA-C has been used in the construction of phantoms for studying a wide variety of tissues including that of

the heart [14], breast [10, 11], prostate [13], arterial vasculature [8, 2], the brain [4, 2], as well as their abnormal tissues in the form of lesions and tumours [10, 11, 13].

In the following sections, we describe the methods we used to build our brain phantom. The contributions of our phantom to the literature include:

Anatomical accuracy : Deep cortical structures of the Colin27 cerebrum, such as the sulci, the insular region and the ventricles are realistically represented in the casted phantom.

Realistic texture : Recipes of PVA-C with textures most similar to human cerebral tissues were determined through the feedback of an experienced neurosurgeon who knows the tactility of the human brain and tumour tissues.

Multimodal imaging : PVA-C formulations that can be imaged effectively with high contrast CT, US, and MR are used to construct the phantom and its implants.

Freely available data : Images acquired using the US, MR, and CT scanners are made available through our website to researchers and the general public. Images for this phantom were acquired using magnetic resonance imaging (T1 and T2 weighted, PD, FLAIR, and DTI), ultrasound imaging, and computed tomography, to ensure that the phantom exhibits similar contrast to images of the live cerebrum acquired using these imaging modalities.

2 Phantom Construction

2.1 PVA Solution Preparation

The PVA solutions used to cast the brain phantom and its various components were prepared using 99-100% hydrolyzed PVA with an average molecular weight of 86 kilodaltons (Code:418120010) from Acros organics (Geel, Belgium).

Master solutions of 5% and 8% mass percentage (w/%w) PVA solutions were prepared by heating distilled water and adding a percentage weight of PVA to the water. The mixture was constantly stirred until the PVA particles were well hydrated upon which the holding vessel of PVA and water mixture was placed in an oven at 93-95 degree Celsius for 7 hours. Small quantities of distilled water was added back into the solutions according to the amounts lost during preparation of the PVA solution. PVA solutions with different mass percentage can be subsequently produced by heating the master solutions and mixing in additional water.

2.2 PVA-C Preparation

PVA-C was prepared by completely freezing and thawing PVA solutions, which resulted in semi-translucent flexible gel. The solutions were placed in a room temperature (25 degree Celsius) chest freezer and cooled to around -25 to -20 degree Celsius. After 12 hours of freezing at the aforementioned temperatures, the freezer was shut-off and its interior was allowed to rise back to room temperature over another 12 hour period. These freeze thaw cycles (FTC) were repeated as needed to vary the consistency of the produced PVA-C.

2.3 Brain Mold

The mold for our brain phantom was based on the polygonal surface mesh segmented from the left hemisphere of the Colin27 data set. This mesh was then subtracted from a rectangular prism mesh to create a “negative” of the cortical surface. The model is saved in the STL file format used in stereolithographic printing.

We utilized the services of RedEye On Demand (Eden Prairie, MN, USA) for the fabrication of our brain phantom mold using the TangoPlus Polyjet Resin (FC-930) as the material. This clear rubber-like photopolymer is deposited layer by layer in order to produce a finished three dimensional object (See Fig. 1a). We found that the mold made using this material was able to accurately model the sulci and insular region of the cerebral hemisphere. It also has enough flexibility to allow demolding without damaging the PVA-C phantom and reverts itself to its original shape when deformed.

The bottom of a plastic tub was cut-out and glued around the opening of the flexible rubber mold. This allows us to cast a base for our demolded phantom and limit its relative movement when placed and imaged in another plastic tub of the same size.

The mold component for the left ventricle of the phantom was constructed separately using silicone bathroom caulk. Layers of caulk approximately 2mm in thickness were applied to vellum traces from life-size printouts of segmented 2mm sagittal sections of the left ventricle. These layers were then assembled medially to laterally and aligned using cross-hairs on the printout traces to maintain placement accuracy of the sagittal sections and then covered with additional silicone rubber caulk to smooth the mold component surface.

2.4 Approximating Live Brain Texture

An array of PVA-C samples was prepared with either 1, 2, or 3 FTCs and 4%, 5%, 6%, or 8% PVA solutions, producing 12 different PVA-C samples. The samples were palpated at room-temperature by a gloved neurosurgeon who is familiar with the texture of human brain and brain pathologies.

The experienced neurosurgeon was then asked to rate each sample from 0 to 10 with the former being nothing like live brain and the latter being exactly like live brain, while noting whether the sample was softer or firmer. The neurosurgeons were then asked to choose 2 of the samples which felt most like low grade gliomas.

The surgeon rated the PVA-C sample created from 6% PVA solution at 1 FTC as being similar to palpating the surface of a live brain and the 4% PVA at 3 FTC as being similar to palpating a low grade glioma.

We measured the elastic modulus of the 6% PVA 1 FTC PVA-C sample using a 3369 Dual Column Testing System (Instron, Norwood, MA, USA) and found that it has a value 4.6kPa, which is within the range found for human brain tissue [15].

2.5 Implants

To make our phantom useful for tests in image guidance and registration, structures created from various formulations of PVA-C were included into the phantom.

To create spherical registration markers, we used a harder PVA-C made from 8% PVA solution that has undergone 2 freeze-thaw cycles (FTC). These were molded using the containers for reflective passive spheres used in optical tracking and are approximately 12mm in diameter. A PVA-C “tumour” was also created using 4% PVA solution with 2 FTC and then implanted into the phantom. The tumour was molded using the plastic case from inside a Kinder surprise (Ferrero, Pino Torinese, Italy). When the phantom is completed, the markers and the tumour will each have undergone 3 FTC.

These PVA-C structures are skewered and suspended using 0.45mm monofilament fishing lines inside the phantom at the desired location. The left ventricle mold component was clamped and also suspended with fishing lines in a similar fashion.

Finally, we placed the inflatable head of a urinary catheter into the frontal lobe of the phantom and another in the medial portion of the phantom in the cast base of the mold. Each urinary catheter can be inflated with up to 10ml of water using a syringe in the manner described by Reinertsen and Collins [4] to vary the extent of deformation on the phantom.

3 Triple Modality Imaging Contrast

Commonly available chemicals were used to change the contrast of our phantom for imaging in US, MR, and CT. A PVA-C with the PVA concentration and FTC resembling textures similar to a living human cerebrum was chosen to be the base solution for dissolving the contrast enhancing chemicals.

To increase back-scattering of sound waves in US imaging, solutions containing talcum powder at 4%, 2%, 1%, and 0.5% weight of the base solution were mixed. Each of the samples was immersed in water and imaged with a Sonosite 180 Plus (Sonosite, Bothell, WA, USA) diagnostic ultrasound system tracked using a Stealth neurosurgical station (Medtronic, Minneapolis, MN, USA) and visually examined for contrast with the surrounding water and implanted PVA markers spheres.

For increasing phantom contrast in CT imaging, a powdered barium sulphate (BaSO_4) preparation used for colon enema (Guerbet Micropaque Colon, Guerbet, Villepinte, Île-de-France, France) was mixed into our PVA solutions. Solutions were prepared with 8%, 6%, 3%, and 1% weight BaSO_4 of the initial base solution. PVA-C samples were made from each of these solutions and imaged using a LightSpeed 16 VCT scanner (GE Healthcare, Little Chalfont, Buckinghamshire, UK).

To enhance the signal in T1 weighted images, copper sulphate (CuSO_4) was added to the PVA mixture in small quantities. Minute quantities of CuSO_4

dramatically increase the contrast of the PVA sample in T1 and T2 weighted images. To find an optimal concentration of CuSO_4 , we prepared 0.2%, 0.1%, 0.05%, and 0.025% anhydrous CuSO_4 PVA-C samples and imaged them with T1 and T2 imaging sequences on a Verio 3T MR scanner (Siemens Healthcare, Erlangen, Germany).

We found that for the phantom brain tissue, PVA-C made with 6% PVA solution at 1FTC containing concentration of 2% BaSO_4 , 0.025% CuSO_4 , and 1% talcum as contrast agents worked well for CT, MR, and US, respectively. For our triple modality image markers, we found that a gel made from a 8% PVA solution with 5% BaSO_4 , 0.2% CuSO_4 , and 5% talcum as contrast agents worked well for CT, MR, and US, respectively. Although, CuSO_4 diffuses rather quickly out of the PVA-C, it did not affect the quality of the images greatly if they were acquired within the week when the phantom was built. The texture of the PVA-C did not change dramatically with the addition of these quantities of contrast agents.

4 Image Acquisition

Multimodality images with deformations were acquired for the phantom using the same models of MR, CT, and US imaging devices that we used for determining imaging contrast (See Fig. 1b,c). The phantom was first scanned in the MR with T1 weighted spin-echo (TR=668ms, TE=8.9ms, Flip Angle=70°, 1×1×3mm) and gradient-echo imaging (TR=1900ms, TE=3ms, Flip Angle=9°, 1mm isotropic), T2 weighted imaging (TR=6530ms, TE=840ms, Flip Angle=150°, 1×1×3mm), proton density (PD: TR=6530ms, TE=9.4ms, Flip Angle=150°, 1×1×3mm), fluid attenuated inversion recovery (FLAIR: TR=5000ms, TE=273ms, TI=1800ms, Flip Angle=120°, 1mm isotropic), and 30 direction diffusion weighted (DWI, calculated from fractional anisotropy, apparent diffusion coefficient, and trace weighted images: TR=9300ms, TE=94ms, Flip Angle=90°, 1×1×2mm) MR sequences. A CT scan (491 axial slices at 1.25mm thickness) was then acquired for the phantom followed by the acquisition of a series of tracked B-mode US images (44 images of 4-6 sweeps at each 5.2cm and 7.1cm depth).

All of the images were acquired one after the other to ensure that the phantom is in the same state in the set of images. After each series of multimodality imaging, the phantom was deformed by inflating each of the two implanted urinary catheters in the phantom with 0ml, 5ml or 10ml of water through 5 rounds of inflations (See Fig. 2).

As well, images for super-resolution image processing were acquired by scanning the phantom with MP-RAGE T1 weighted gradient echo sequence 6 times at an isotropic resolution of 0.5mm with a slight displacement of the phantom less than 1cm between each acquisition. The phantom was then scanned using a T1 weighted spin echo sequence at 1mm isotropic resolution 7 times with water and 7 times without water, again with a slight displacement of the phantom less than 1cm between each acquisition.

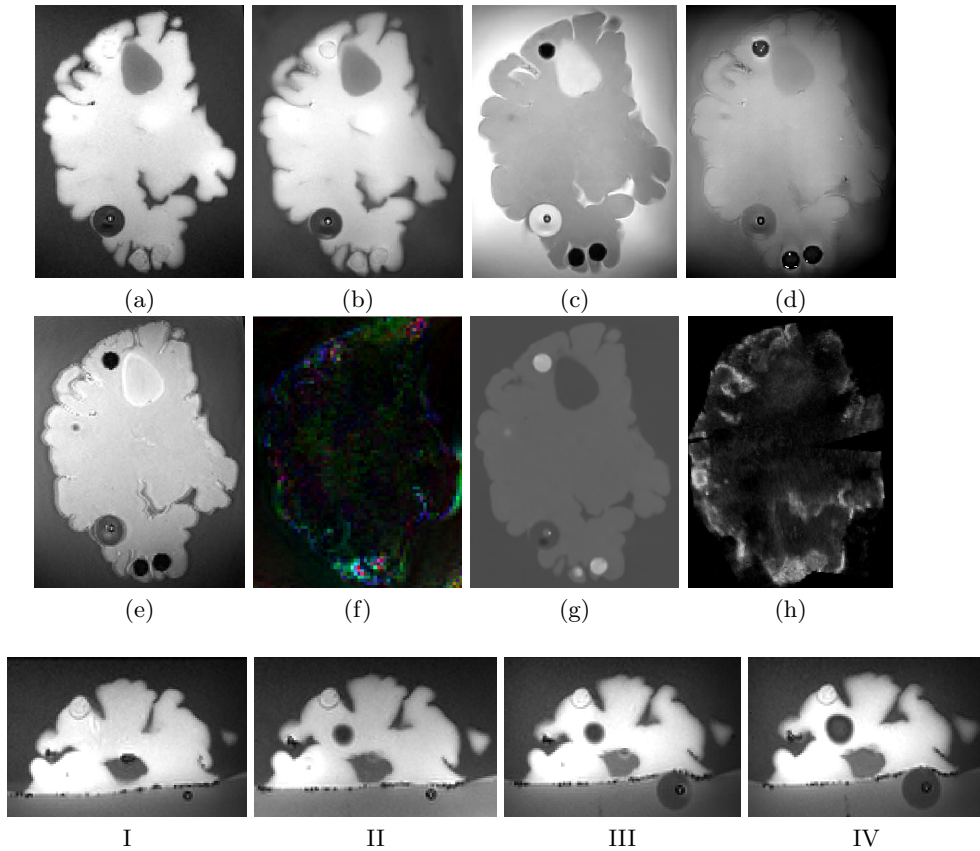


Fig. 2. A selection of PVA-C brain phantom images acquired using (a) MR T1-weighted gradient-echo (b) MR T1-weighted spin-echo (c) MR T2-weighted (d) MR PD (e) MR FLAIR (f) MR DTI colour map (g) CT (h) and the reconstructed US sweeps. Images I-IV shows the phantom imaged with T1-weighted gradient-echo at different inflations of the catheters.

5 Conclusion

An anatomically and mechanically realistic PVA-C brain phantom was created and imaged using MR, CT, and US. The images acquired from this phantom were then made publically available to the larger image processing community. We believe that the acquired multi-modal images be used for validation of many image processing techniques such as segmentation, super-resolution, image reconstruction, linear or non-linear registration, and denoising algorithms, using images acquired from one modality to act as the ground truth of another. The images are made available at: <http://pvabrain.inria.fr>

Aside from image processing, the formulation of our phantom material to approximate live cerebral brain tissue can be invaluable for improving implantation for deep-brain stimulators and simulating biopsy needle insertions. The

accurate anatomy and texture of the brain phantom as well as the low price of the starting materials can also make the phantom a useful educational tool in training medical professionals.

Much work remains to be done in order to improve the phantom. We are currently in the process of developing better multimodal imaging spherical markers for higher contrast imaging, and finding better MR contrast agents that do not diffuse. We would also like to further characterize the multi-modal PVA-C developed in the work such that the physical and imaging property of the material can be better understood. Nevertheless, the presented results and methods represent an important step in the development of multimodality imageable materials with tissue like properties, along with techniques for creating anatomically accurate brain phantoms.

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