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How to design and construct a 3D-printed human head phantom

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Abstract

In this paper, we will provide a methodology for head phantom development based on *in vivo* imaging data attained utilizing MRI. The anthropomorphic phantom can be designed to mimic human anatomy.

In medical physics, phantoms are physical and/or numerical tools created to represent specified characteristics of human anatomy [1–5]. Phantoms are a less expensive approach for testing and validation of a variety of applications, such as communication or medical diagnostic imaging tools [1,5–7]. Phantoms offer the capability to perform safety testing of diagnostic imaging tools and potentially minimize harmful exposure to a human. A variety of simple commercial [8] and geometric [3,5] phantoms have been used in various medical applications. The development of anthropomorphic phantoms dates back to the 1960s [9,10].

Additive manufacturing, referred to as 3D printing, has become an increasingly useful tool to develop these complex and anatomically accurate phantoms [11]. In a recent review [12],

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Filippou *et al.* reported that 162 publications, published between 2007 and 2018, focused on phantoms and the authors revealed that the imaging modality most frequently used as an application to characterize the phantom is computed tomography (CT), which is closely followed by magnetic resonance imaging (MRI) and ultrasound. The articles revealed an upward trend in articles focusing on 3D-printed phantoms from 2013 to present.

Commercially available MRI phantoms are designed using simple shapes and filled with homogeneous material. Most commercial whole-body MRI scanners provide a spherical phantom filled with saline water as an acceptable quality assurance sample load for the MRI system. In this paper, we will provide a methodology for head phantom development based on *in vivo* imaging data attained utilizing MRI. The anthropomorphic phantom can be designed to mimic human anatomy.

Materials & methods

Prior to designing and building a head phantom, the design requirements must be well understood. Design parameters should consider the need, application, available resources and budget expenses for the phantom in order to filter the various options available. For example, Wood *et al.* determined the need of the designed phantom was to mimic the electromagnetic behavior of the anatomy during an MRI scan [1]. Five key steps were outlined in Figure 1 within study [1] that provide a general workflow to designing a head phantom using 3D printing technology. Table 1 provides criteria that anyone can follow to design a head phantom based on specific parameters that can be determined through answering specific questions.

Imaging

Mimicking the head anatomy into the head phantom leads to a precise reproduction of the desired characteristics of the human. The first step in the design of the head phantom is the selection of the imaging modality that is most compatible for the acquisition of human anatomical data for the phantom construction. Several imaging modalities such as CT, MRI, positron emission tomography, ultrasound and single-photon emission computed tomography have been used to develop various phantoms designated for various medical applications. Similarly, it is important to consider the level of detail and accuracy required in the phantom anatomy. This detail directly impacts the image acquisition and protocol used. Using MRI is beneficial due to its excellent differentiation between different soft tissues. Depending on the design need, the MRI protocol could use multiple sequences to obtain better details and accuracy. Wood *et al.* reported the use of MRI as a technique for acquiring an anatomical imaging dataset of a healthy volunteer. T1-weighted images were used to obtain a good segmentation of the various brain tissues and 3D isotropic acquisitions yield more flexibility to manipulate and segment the 3D images. For that phantom, it was imperative to include the neck and shoulders in order to predict the interactions between the electromagnetic waves and biological tissues during an MRI experiment [13].

Classification

To identify and later reconstruct the tissues from the imaging dataset, the tissues must be classified according to a human head atlas [14]. Segmentation is the process used to classify tissues within an imaging dataset. Segmentation software allows automatic as well as manual segmentation. iSeg (ZMT Zurich MedTech AG, Zurich, Switzerland) can be used as a useful segmentation software. That being said, there are many segmentation software available based on cost and functionality; iSeg offers useful features such as the ability to extract volumetric and surface coordinate files that can be used for rendering. The segmentation software should have the capability to read and properly import the imaging data. The volumetric data can be used for numerical modeling applications as it is a voxel-by-voxel representation of the 3D imaging dataset. Figure 1A–C shows the 3D visualization and axial views of the designed head phantom where eight different tissues were classified in iSeg and prepared for 3D rendering.

Computer-aided design

Computer-aided design (CAD) software is a tool used to design the details and desired fabrication of the head phantom. Voxelize and surface coordinate files, in other words, Standard Tessellation Language (STL) format, are rendered upon extraction from the segmentation software. Wood *et al.* used 3D CAD software (Geomagic Studios 2012, Geomagic, NC, USA) to render the phantom, but other CAD software, varying in cost, can be used to render the phantom. The smoothness of the phantom can be rendered based on the design criteria. The wall thickness of each volume should be carefully rendered. CAD models allow an analysis of the supports and stress within the phantom design. A well-designed CAD model will reduce manual modifications required in the physical assembly of the phantom. It is necessary to analyze the model for smoothness, strength of inner parts and the elimination of holes. The CAD model should be exported into an accurate file based on 3D-printing format. The build volume of the 3D printer determines the assembly design of the phantom. The entire head to shoulder phantom may not be possible to print in one print job, Wood *et al.* printed the phantom, as shown in Figure 1L, M & O, in five parts due to the limitations of the 3D printer's build size.

3D printing

3D printing is the application used to build the physical phantom model as shown in Figure 1N, P & R. Since several 3D printing technologies are available, choosing the correct 3D printer is determined by the design criteria derived from Table 1. Each 3D printer is determined by print film material, layer thickness, accuracy, build frame and cost. The design criteria for the phantom in study [1] was to choose a durable material that was hydrophobic to eliminate leaks and the need to use hydrophobic coating. Thus, stereolithography (SLA) resin (DSM Somos WaterShed XC 11122, IL, USA) was chosen and the phantom was printed with the Stratasys 3D printer (Stratasys, MN, USA). SLA resin is one of the costlier 3D printing materials. Other studies [7,15–19] have used various 3D printer film material for the casing of the MRI phantoms. These materials are polycarbonate, acrylonitrile butadiene styrene, polylactic acid thermoplastics and selective laser sintering (SLS) material. Each print will have inner structural supports that require manual removal.

Engineering

The physical assembly requires consideration of the well-designed CAD model and assembly materials that are MRI compatible [20,21]. Each fillable region should have at least two filling ports designed through CAD where one is used to fill and the other is used to release trapped air. A combination of epoxy adhesive (DP100 Plus Clear, 3 M Scotch-Weld, MN, USA), latches, silicon rubber foam and nylon screws and threads can be used to make the phantom robust and properly sealed.

Wood *et al.* characterized the electrical properties of the phantom with a dielectric probe, network analyzer and an MR scanner. The phantom was filled with in-house mixtures of distilled water, sodium chloride (NaCl) and/or denatured ethanol (C₂H₆O) measured at room temperature. The characteristics of any designed head phantom should be considered and validated properly. Some studies have determined that either agar gel or silicone were enough to fill a head or brain phantom. These studies [7] have also considered developing separate molds to assemble the phantom.

Discussion

This work presents a methodology that researchers can follow to build a head phantom using 3D printing technology based on the work of Wood *et al.* [7]. Table 1 emphasizes a design criterion that determines resources required to 3D print a head phantom and highlights alternative strategies that various groups have used and found to be successful.

In general, the researcher chooses the image modality from which the phantom is derived. Studies support that MRI offers better resolution capabilities in comparison to other modalities that allow the physical model to be more detailed and accurate. Resolution is no longer limited by the 3D printing resolution, instead it is constricted by the imaging modality resolution [22].

Time is an important design criterion that impacts the general design workflow and must be carefully considered. It will take time in researching, training and execution to image, segment, postprocessing in CAD design, cure the phantom parts, 3D print and assemble the head phantom. Understanding the resources available and limitations will determine the necessities and alternatives to what this paper has proposed. For example, if commercial segmentation software is not readily available, then there are several open-source segmentation software available as shown in Table 1.

Limitations to fabrication design & alternative strategies to consider

Each study [1,7,15–19,23] provides strategies and limitations to head phantom development. Thus, it is imperative during the phantom design to develop alternative strategies to address these limitations. All studies indicated that the phantom design was limited in some manner when determining the classification of phantom tissue. Khan *et al.* expressed that there are limitations from making a phantom from a generalized dataset like Alzheimer's Disease Neuroimaging Initiative and suggested utilizing a patient-specific dataset. Wood *et al.* and Graedel *et al.* determined that using 3D-printed plastic material presented some limitations in obtaining appropriate thermal and electromagnetic properties. Both concluded that using

the plastic material is great to represent cortical bone and provide mechanical support within the phantom. Wood *et al.* recommended to print the skin tissue separately and Graedel *et al.* recommended to separately print the bone and fat. The artificial boundary within the phantom are also limitations but the advancement of 3D printing may allow an alternative to representing tissues with no boundary. Altermatt *et al.* built a brain phantom with a combination of agar gel, polylactic acid thermoplastic and platinum-cure silicone rubber. This design does not require artificial tissue boundaries; instead, the cortical thickness was increased by 20 mm and a hydrophobic coating was applied – similar to Graedel *et al.* – in order to prevent leakage. Ploch *et al.* were also successful in printing without the boundaries while performing a mechanical assessment. Each study conveyed that the phantom was limited to only being comparable for the characteristics for which it was developed, in other words, electrical and relaxation properties.

Future of phantom design

In the early 1990s, additive manufacturing (3D printing) was the solution to developing anatomical models for medical applications [24,25]. Its use was constricted for some time by the computing performance of CAD software and the printing precision of 3D printers. 3D printing was forecasted to be used for anatomical model fabrication and replacement of anatomical features, such as the bone, during surgery. The early 2000s focused on 3D reconstruction and taking full advantage of the evolution of computers and 3D printing material to mimic organs and other human anatomy [26]. Anatomical phantoms were either designed as a homogeneous anatomical phantom [27] or a specified anatomy of the head [17]. Later, multitissue MR phantoms were developed and validated [28–30]; and multitissue MR phantoms [7,15,31,32] became more robust in the 2010s by utilizing the evolving 3D printing technology and enhanced neuroimaging tools.

The future of 3D printing phantoms and its use to help model human anatomy has a vast array of applications. Future phantoms will have the possibility to 3D print the fillable compartments based on the desired phantom characterization [24,33]. Phantoms have become increasingly capable of modeling not only the structural characteristics of human anatomy but also the functional attributes. Many phantoms are trending toward having functional attributes and various studies have begun to develop functional phantoms [34–38] with vascular anatomy.

Conclusion

It is feasible to develop an accurate human head phantom using 3D printing technology and MRI datasets. This work presents the methodology and provides a design assessment with mirrored examples that can be used to develop a head phantom.

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Figure 1. An example of classifying tissues in the imaging dataset, various views of the computer-aided design files of the phantom using Geomagic and a comparison between the designed computer-aided design models and their corresponding physical rapid prototyping.

(A) The tissue legend describes 8-segmented tissue types that were segmented using iSeg.

(B) Sample axial views at arbitrary axial depths from the middle of the ventricles to the mid jawbone. (C) 3D reconstructed view of the full segmentation with all tissues displaying the head to upper shoulders. (D) A compiled transparent view of all 8-segmented tissue types within the head phantom. (E) The skin compartment. (F) The muscle compartment. (G) The fat compartment. (H) The bone compartment. (I) The cerebrospinal fluid compartment. (J) The brainstem compartment. (K) The eyes compartment. (L) The brain compartment. (M) The bottom build modified for the 3D printer's build size. (N) The physical picture of the head phantom during the printing process. (O) Model of the head phantom in the same position as (N). (P) The physical structure of the brain compartment. (Q) Model of the brain compartment, similar to (P). (R) The physical structure of the cerebellum compartment. (S) Model of the cerebellum compartment, similar to (R).

CAD: Computer-aided design.

Table 1.

Determining the design criteria of the phantom by considering various factors in the categorical areas.

Design criteria to build a 3D-printed head phantom									
Needs assessment	Medical imaging		Classification		CAD design		3D printing		Applications
What is the overall purpose of building this phantom?	What specific physiology is required for the phantom?		What is the finite number of tissues required for the phantom?		What are physical attributes of the phantom?		What are the required attributes of the 3D printer to properly print the head phantom?		
			What segmentation method is required to meet needs assessment?						
What resources are available? (i.e., tools, personnel, manufacturing, budget and time) What is the durability and desired lifespan of the phantom? What are the desired physical dimensions and mechanical and electrical properties? What is the experimental procedure to validate the phantom characteristics?	Imaging modality		Method to classify Atlas		Rendering		Material		<ul style="list-style-type: none">• RF coil testing/RF pulses [2]• RF Thermom [2]• RF Field Distribution [1,2]• T1 Structure and Intens [3]• Neurosurg Training a Preoperati Planning f• Microwav applicatio [7]• Model for Neurosurg Planning f
	<ul style="list-style-type: none">• Choice and specifications• 1.5 Tesla MRI scanner [2,4]• 3 Tesla MRI scanner [1,3,6,8]• Sequence parameters• 3D Tl-weighted• MPRAGE [1,3,4,6–8]• 3D-SPGR [2]• TSE• Resolution• 1 mm [1,3,4,7,8]• 1.3 mm [2]• Functional• Structural	<ul style="list-style-type: none">• Based on book• Trained Neuroradiologist [2]• 30 tissue atlas [2]• 10 tissues [1]• 8 tissues [7]• Virtual Family Model	<ul style="list-style-type: none">• Outline Files STL [1–4,6,7]• Thickness of intersecting surface meshes [1,2,7]• Inner Structure/Support [1]• Laplacian Smoothing [2,3,7,8]	<ul style="list-style-type: none">• Stereolithography resin ((DSM Somos WaterShed XC 11122) [1]• Polycarbonate [2,4]• Acrylonitrile Butadiene Styrene (ABS) [6]• PLA thermoplastics [3]• SLS material					
			Segmentation style		CAD software		Printer		
			<ul style="list-style-type: none">• Automatic and/or Manual [1]• Semi-automatic thresholding [1,3]• Semi-automatic wire-frame and edge detection [1,4]• Adaptive region growing [8]	<ul style="list-style-type: none">• Commercial• Geomagic Studios [1]• Autodesk [3]• SolidWorks• MeshLab [8]• VRMesh [8]• Free• FreeSurfer Marching Cubes Algorithm [2]	<ul style="list-style-type: none">• Print within an Academic Resource• Redeye [2]• University 3D printing facility [1,7]• 3D Printing Manufacturer• Stratsys [2]/Fortus [2,4]• 3D Systems Viper [1]• Makerbot ® ReplicatorTM + 3D printer• FlashForge Creator Pro Dual Extrusion 3D printer [6]• DTM Sinterstation [7]• Z510 Spectrum [8]				
	Origin of consented dataset		Segmentation software						
	<ul style="list-style-type: none">• Patient Specific• Healthy volunteer [1,2,7]• Patient with tumor [8]• Averaged dataset from consortium data• Alzheimer’s Disease Neuroimaging Initiative (ADNI) [4]	<ul style="list-style-type: none">• Commercial• iSeg [1]• MATLAB [7]• Free• FreeSurfer [2,3,6]• 3D Slicer [3,4]• ITK Snap [4]• Amira [4]• FSL [8]• SPM8 [8]							
							Sealants		
							<ul style="list-style-type: none">• MR compatible		

Design criteria to build a 3D-printed head phantom					
Needs assessment	Medical imaging	Classification	CAD design	3D printing	Applications
	<ul style="list-style-type: none"> Numerical Model Virtual Family Duke Model 			<ul style="list-style-type: none"> DP100 Plus Clear [1] Silicon Mold (Rebound 25) DWR plastics [3] Epoxy [2] 	

The needs assessment offers guiding questions for the design criteria. The methodology offers criteria to consider in the design based on the methodology sections indicated by Wood *et al.* [1] in Figure 1. Examples of the design resources used to develop and 3D print a head or brain phantom for MRI and electromagnetic applications.

CAD: Computer-aided design; DWR: Durable water repellent; MRI: Magnetic resonance imaging; PLA: Polylactic acid; RF: Radiofrequency; SLS: Selective laser sintering.