ID3801: Open Ended Lab Project

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Final Report

Project Topic:

Ultrasound Phantom Development for Microvascular Applications

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1 Introduction

Ultrasound imaging is a well-established clinical imaging technique providing real-time, quantitative anatomical and physiological information in humans. The lack of ionizing radiation and relatively low purchase and maintenance costs results in it being one of the most frequently used clinical imaging techniques with increasing use for guiding interventional clinical procedures.

To enable newer developments in ultrasound imaging, there is the necessity to have large-scale pre-clinical studies. Phantoms are objects designed to mimic the properties of human tissue and are employed for such pre-clinical developments. The development of phantoms that accurately and reliably mimic the properties of human tissue is extremely important. A variety of calibrated commercial phantoms for use with ultrasound imaging are available, however, they are very expensive.

The microvascular system in the human body plays a crucial role in local blood perfusion and is responsible for conducting blood–tissue exchange. They usually have a complex network of branching and interconnected structures. For studying vascular diseases, guiding therapeutic interventions, and understanding and experimenting on microvascular veins are necessary.

The ultrasound phantom made for the study of microvasculature mimics the vessel size, geometry, flow dynamics and tissue properties of the vessels. These phantoms enable the validation and understanding of ultrasound techniques specific to this vascular domain they also are valuable tools for understanding further microvascular physiology and improving patient care in vascular medicine, reconstructive surgery, etc.

2 Literature Review

Vascular ultrasound studies can benefit significantly from using flow phantoms with anatomically accurate geometry and high acoustic compatibility. Polyvinyl alcohol (PVA) phantoms are used extensively as models for validating ultrasound acoustic approaches. Tissue-mimicking phantoms are used to validate imaging approaches for quality control and clinical training purposes in ultrasound, we have adapted various phantom preparing procedures [1, 2, 3] for imaging.

2.1 Acoustic Properties of Tissues

Tissue substitutes must possess acoustic properties similar to the tissues of interest. The most relevant acoustic properties for tissues include the speed of sound, characteristic acoustic impedance, and attenuation and are summarized in Table 1 [1].

Table 1: Accoustic Properties of Tissues [1]

Material	Velocity m/s	Density kg/m^3	Attenuation $dB/cm\ MHz$	Acoustic Impedance $MRayl$
Air	330	1.2	-	0.0004
Blood	1584	1060	0.2	1.68
Fat	1478	950	0.48	1.4
Soft Tissue	1561	1043	0.54	1.63
Brain	1560	1040	0.6	1.62

2.2 Tissue Mimicking Materials (TMM)

Soft tissues are mainly composed of muscles, fibrous tissues, fat, blood vessels, etc, The acoustic variation among tissues is relatively small, and due to this, it is desirable to prepare a homogeneous TMM phantom that mimics the broader tissue category. A brief summary of the various soft tissue substitutes as reported in literature useful for mimicking tissues is presented in Table 2 and explained in the subsequent sections.

Table 2: Acoustic properties of soft tissue substitutes [1]

Material	Velocity m/s	Density kg/m^3	Attenuation $dB/cm\ MHz$	Acoustic Impedance $MRayl$
Agarose-based	1498-1600	1016-1100	0.04-1.40	1.52-1.76
PVA-based	1520-1610	-	0.07-0.35	1.6-1.77
Gelatin-based	1520-1650	1050	0.12-1.5	1.6-1.73
Water-based	1518-1574	1000+	-	1.48-1.60
Ecoflex 00-20	1043	1.05	33.9	1.074
BMF	1570-1595	1.05-1.055	1.5 - 2.2	1.65-1.68

Agarose Based:- Agarose-based techniques are the most widely used of the soft tissue substitute preparation techniques described in the literature. The broad use of agarose-based substitutes is a result of their well- characterized performance, the ease of fabrication.

PVA based:- PVA-based phantoms are more advantageous compared to others because they have high structural rigidity, indefinite longevity, and low cost.

Gelatin Based:- These materials were reported to have high stability near room temperature over a period of four months, provided that the samples were stored in a closed container below a layer of distilled water.[4]

Water Based:- Water has been used as a tissue substitute since the early days of medical ultrasound, and even though water has a strong dependence on temperature, its ease of use makes up for this limitation.

2.3 Silicone Based TMM phantom

Silicone based tissue mimicking phantoms are easily preparable and have a longer shelf life compared to the TMM's made from organic materials. The fabrication process of these phantoms includes mixing silicone elastomers like Ecoflex 00-30 with various additives and fillers like TiO_2, Plastic microspheres, and Silicone oil to vary the mechanical and acoustic properties of the phantom to make it match human tissue. Also including scattering particles like Glass beads, Graphite powder, etc help to replicate the scattering properties of tissue. The speed of sound for this material was determined to be about 1000m/s

2.4 Microvascular Phantoms

Microvascular phantoms are artificial constructs that are used to replicate the structural and functional properties of microvessels in the human body for studying and validating imaging techniques, research microcirculatory diseases, and developing new therapeutic solutions/approaches. These phantoms can provide a platform with which many complex styles of microvessels can be easily duplicated and studied which further helps in clinical research purposes.[5]

The figure shows microvasculature present in the fingertip that was imaged during the *in-vivo* study.

3 Materials and Methods

This project focuses on ultrasound-compatible low-cost phantoms that mimic the properties of general human tissue which can be used for the study of microvascular vessels in flow imaging. The initial step is to create a Computer-Aided Design (CAD) model of the desired phantom mould, and a physical replica of this model is to be 3D printed. The CAD model includes a Phantom mould, Connectors, and a Wire mould.

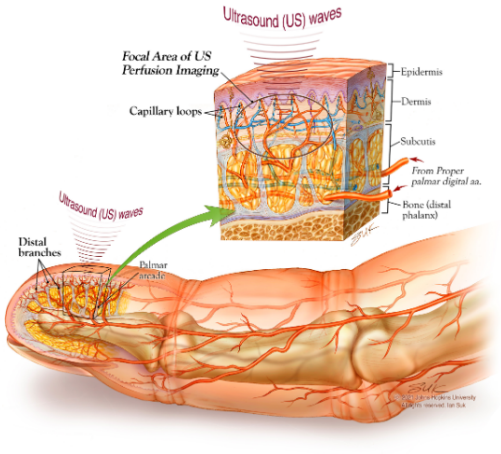


Figure 1: Schematic of the blood vessels and the complex network of microvasculature in a human finger. [6]

3.1 Overview of 3D Print process

A CAD model of the flow phantom was designed utilizing the software FUSION 360. A cubic-shaped vessel with one vascular-mimicking structures at a depth of 2.5 cm from the phantom surface.

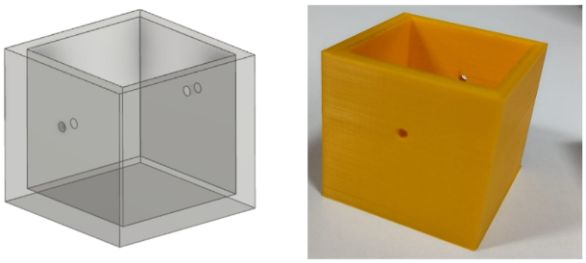


Figure 2: (a) Single vessel Mold Design (b) 3D printed Mold

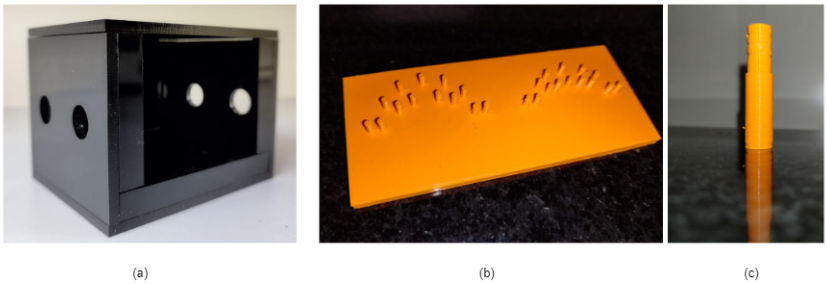


Figure 3: (a) Microvascular Phantom Mold (b) Microvasculature Mold (c) Connector

3.2 PVA Flow Phantom

3.2.1 Procedure

To prepare the PVA phantom, 10% (w/v) PVA powder is mixed with DI water that has been heated to 80°C. The mixture is then further heated to 90°C. To prevent aggregation, stirring is done every 90 seconds. The next step involves degassing the mixture using a vacuum chamber maintained at -1 bar. Again, stirring every 90 seconds is necessary to prevent aggregation. The mixture undergoes a second round of degassing in the vacuum chamber at -1 bar. Afterwards, the mixture is left at room temperature for 30 minutes. To remove any impurities, the top layer of the mixture is carefully removed. Subsequently, the mixture is poured into the desired mold. To facilitate solidification, the mold is covered with saran wrap and placed in the refrigerator at 4°C for 30 minutes. Once the Freeze-Thaw cycle is complete, store the phantom in DI water[3],[7].

3.3 Silicone Flow Phantom

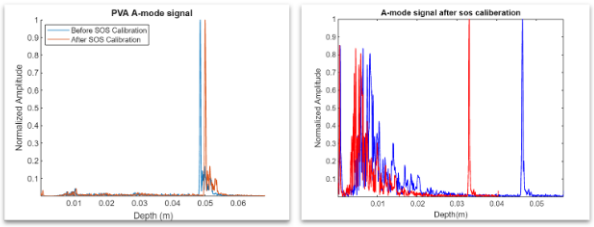
3.3.1 Procedure

Ecoflex 00-20 was used to make a Tissue Mimicking Flow phantom [5]

To prepare the phantom, the base (Part A) and catalyst (Part B) of Ecoflex 00-20 need to be measured in a 1:1 ratio. Both parts should be poured into separate containers and mixed thoroughly to ensure homogeneity. Once each component is well-mixed, part B is then poured into part A, and the mixture is thoroughly blended. To eliminate any trapped air bubbles, the mixture is degassed by placing it in a vacuum chamber. Subsequently, the degassed mixture is poured into the desired mold. The filled mold is left at room temperature to cure.

3.4 Speed of Sound Estimation

The speed of sound was estimated by placing an aluminum sheet beneath the phantom. A-mode ultrasound image data was then obtained, and using Matlab, A-mode plots were generated. From these plots, the speed of sound (SOS) could be accurately calculated.



PVA A-mode signal Silicone A-mode signal

Material	Velocity (m/s)
PVA	1587
Silicone	1094
Water	1540

Figure 4: Phantom A-mode signal and estimated velocity

4 Experiment Results and Discussion

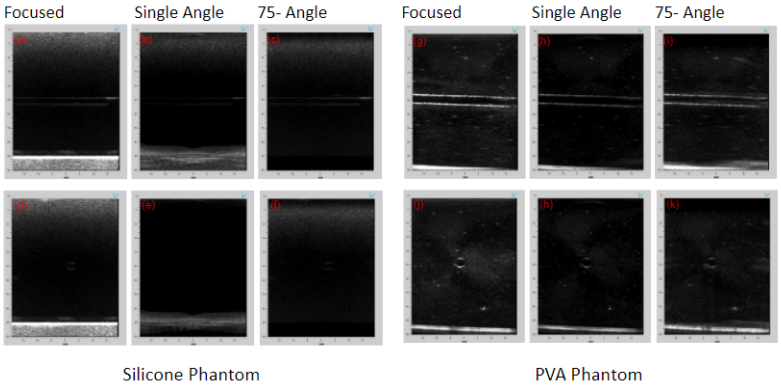


Figure 5: US image of both PVA and Silicone phantoms using 3 modes

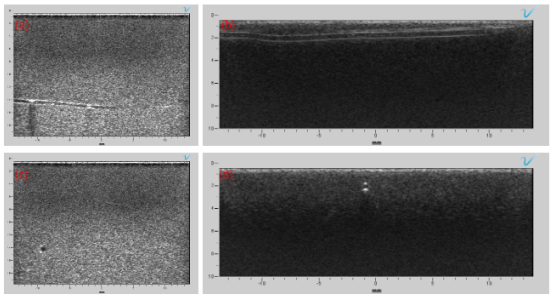


Figure 6: (a) Silicone microvessel longitudinal (b) PVA microvessel longitudinal (c) Silicone microvessel cross-section (d) PVA microvessel cross-section

5 Conclusions and Future Work

The fabrication process for both PVA and Silicone phantoms was carried out with great success. These phantoms were meticulously designed and fabricated to mimic the ultrasound properties of tissue. In order to validate their effectiveness, the speed of sound within each phantom was accurately estimated, and the results aligned with the expected values as documented in references [6] and [5]. The phantoms considered for this study was that of straight vessels. This confirms that the phantoms possess the desired acoustic characteristics.

Looking ahead, future endeavours in this research field aim to replicate more complex and intricate vasculature patterns within the phantoms. By incorporating contrast enhancement media, the goal is to improve imaging quality and enhance the visibility of smaller blood vessels and other microvascular structures.

The successful fabrication of PVA and Silicone phantoms, along with the accurate estimation of the speed of sound, serves as a foundation for further research and development in the field of ultrasound imaging. These advancements pave the way for improved imaging techniques and hold promise for enhancing diagnostic capabilities in various medical applications.

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