Development, Manufacturing, and Application of Photoacoustic Test Phantoms

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ABSTRACT

Photoacoustic (PA) research is an up-and-coming field that is being applied to the medical space. As such, a device that can replicate the human body is needed. This paper shows a low-cost and simple method for creating phantoms for use in PA. The phantoms could be manufactured with the most available lab supplies. Phantom channels were made through FDM 3D printing technology. Phantoms can be adjusted for channel size, shape, and depth within the tissue simulant. A phantom blood simulant was also created to mimic the human blood PA response. A pulsatile pump was also used that could be controlled for waveform shape and amplitude. Both vein and arterial waveforms could be pulsed through the phantom with varying pressures. Multiple phantoms were created with equivalent PA response to the human body and measured with a 532nm laser diode array. A comparison between the inputted pressure waveform and outputted PA response showed very similar signals in shape and amplitude.

Keywords: Test phantom, photoacoustics, manufacturing

1 INTRODUCTION / PRIOR WORK

PA combines the use of both optics and acoustics to create a final outputted signal. Both technologies allow for a high depth penetration and signal resolution by taking advantage of both ultrasound and optics. Test phantoms are recreations of the human body that allow for consistent and accurate measurements to be made on an imaging system. Some examples of these properties can be found in other work [1]. The benefit to using a test phantom is that they are comprised of known parameters producing signals that are "expected" and signals that can be used for ground truth. This does not have similar behavior to the human body as many parameters such as blood pressure, heart rate, and blood oxygen vary from day to day. Many photoacoustic test phantoms exist in the space of PA[2-6]. These phantoms lack the advancements that allow for many comparisons to the human body. Previous work has shown the benefit of using advanced phantoms for PA development. PA phantoms were created to mimic a human finger signal [7]. The depth of the channel and channel size could be predicted through ultrasonic equations. Many similarities between the phantom signal and the human signal were observed such as the amplitude of the signal and the shape of the heart rate waveform.

2 METHODS

Manufacturing of the phantoms was designed to allow for low cost, high speed, and simplicity. The entire manufacturing process can be outlined in very few steps. First, a plastic petri dish is used to hold the tissue simulant. Solder clamps are then used to hold the 3D-printed channel rods. To get the correct height of the solder clamps, small 3D

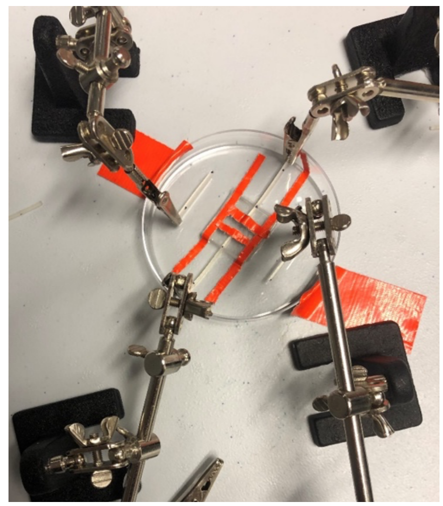

Figure 1. An image containing the solder clamps, 3D

printed discs are placed under the clamp tips. For example, if the desired depth of a channel was to be 2mm then the disc thickness can be set to 2mm when printed. Once the disc is placed under the channel, this can be used to align the channel height and also ensure that it is level. The discs can then be removed from the system entirely. With the channels at the proper depth for the phantom, PDMS can then be

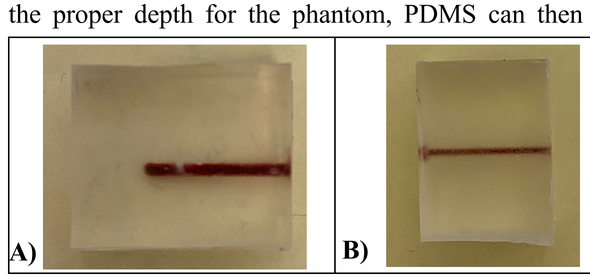

Figure 2. A) An image of a "dead-end" phantom can be seen. B) An image of a "flow" phantom. Manufactuirng

poured to fill the petri dish. An image of the phantoms in this state with solder clamps can be seen in Figure 1. Once filled the petri dish is placed in an oven at 60 C for 24 hours. After this time the phantoms are removed from the oven. The solder clamps can be carefully removed from the PDMS. The phantoms can then be cut using a razor blade into 2cm X 2cm squares. At this point, the phantom could be made a "flow" phantom or a "dead-end" phantom based on the application. For an example of both of these configurations, refer to Figure 2. The final step to manufacturing is machining an aluminum shell that acts as a rigid body for the boundaries

Figure 3. A complete phantom setup containing the

shell, and hose barb connection to the pump. This can

of the phantom. This can be slipped around the phantom and the phantom can be connected to the pump via a hose barb connection. At this point, the phantom is finished with manufacturing and is ready to be tested. The entire process from start to finish takes 1.5 days. During this time the actual manufacturing can be done in less than 2 hours between 3D printing, aligning the clamps, and making the PDMS. The total cost of one phantom is around 1 USD in lab supplies. An image of a completed phantom can be seen in Figure 3. A 10-step process flow list for the manufacturing of a phantom is shown below.

1) Channel rods are designed and 3D printed using PVA filament.
2) PVA channel rods are positioned in the petri dish for the desired application and held with solder clamps.
3) Leveling discs of specific channel height are used under the channel and solder clamps.
4) PDMS is vacuumed to remove bubbles.
5) PDMS is poured into the petri dish.
6) Petri dish and solder clamps are placed into the oven at 60 C for 24 hours.
7) The Petri dish is removed from the oven and the solder clamps are removed from the PDMS.
8) Phantoms are cut using a razor blade to the desired size for the application.
9) Using water, the PVA filament is dissolved from the PDMS.
10) An aluminum shell is machined to fit around the phantom and hold it in place.

2.1 3D Printed Channels

One of the main components in the manufacturing of a test phantom is the 3D printed channel. Fusion deposition modeling (FDM) is used with a Creality CR-10 3D printer. To easily remove the filament from the PDMS, a specific filament comprised of polyvinyl alcohol (PVA) filament was used. This is a unique filament that is water-soluble due to the chemical properties of PVA. With its solubility, we no longer need to invasively remove the filament that is embedded within the PDMS. This prevents tearing of the PDMS and creates a more reliable manufacturing process. Another benefit to using FDM to create the channels is that

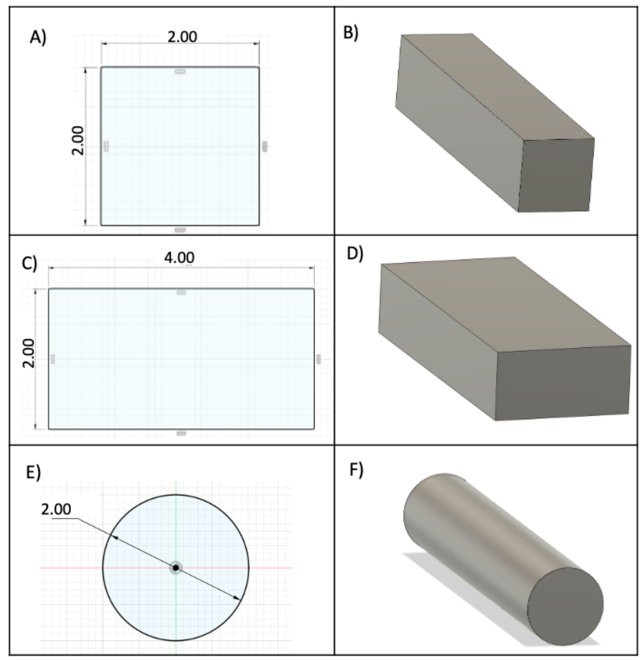

Figure 4. 3 different configurations of a 3D printed

capabilities of customized channels. Any channel shape, size, or length can be printed and applied in the same way. All measurements are in mm. A) A dimensioned square channel of size 2mm x 2mm. B) The full square channel extruded to a length of 10mm. C) A dimensioned rectangle channel of size 4mm x 2mm. D) The full rectangle channel extruded to a length of 10mm. E) A dimensioned cylinder

you can customize the channel shape and size for any application. Figure 4 shows 3 separately shaped channels that can be embedded into a phantom. Some applications require a square or rectangular channel when calculating the exact depth of the channel concerning the acoustic receiver. A flat edge that is consistent displays a signal bound for the front edge of the channel concerning the acoustic receiver. A cylinder-shaped channel more accurately represents an artery that is seen in the human body. These are slightly more complicated to work within a PA space as the front edge with respect to the acoustic lens is variable due to the curve of the cylinder.

2.2 Tissue Simulant

To have a phantom that accurately represented the human body, a tissue simulant was used to encapsulate the 3D printed channel. For these phantoms, PDMS or Polydimethylsiloxane was used. The reason for choosing PDMS is that it is a flexible rubber that can take many high-precision shapes when cured through the mold. This allows for complex channels that bend and shrink down to feature sizes of a half millimeter. PDMS is also capable of achieving multiple different values for Young’s Modulus based on the ratio of base to catalyst mix ratio [8]. The manufacturer recommended a mix ratio of 10:1. This allows for a shore 00 hardness to be measured at roughly 80. To get hardnesses similar to the human body the ratio of mixing for the PDMS was changed. Increasing the ratio, for example to 20:1, will make a softer lower modulus material that is more easily distended with pressure. Multiple different mix ratios were made for phantoms and compared. Based on the application, the hardness can be changed to meet the desired location in the human body.

2.3 Pulsatile Pump

All preliminary testing was conducted using a centrifugal pump called the Gampt M2. This pump is renowned in the ultrasonic space for producing very realistic waveform shapes. The Gampt M2 pump allows for the selection of 3 unique waveforms that represent human heart signals. The options include, “vein-like”, “artery-like”, and “sawtooth”, all of which have some real representation in the human body. For most testing, the artery-like waveform was used as for our application we were targeting the human arteries. The pump also allows for an adjustment of pulse frequency and pulse pressure. This can be done live-time and seen directly through the strain of the phantom itself. The pump can be set up in two different configurations. The first configuration is for “dead end” phantoms, as shown in Figure 5. This setup has a tube go directly into the input of the phantom. There is no flow through the phantom, and only a pressure signal can be seen in the channel itself. This would not have any flow information for a doppler ultrasound application. A flow splitter before the phantom must be used in this test setup to maintain a constantly filled reservoir. A second configuration can be used for the “flow” phantoms. For this configuration, a hose barb is placed at the beginning and end of the phantom. The flow splitter can then be attached to the tube at the outlet of the phantom. This creates a continuous loop that moves fluid that passes through the phantom into the reservoir.

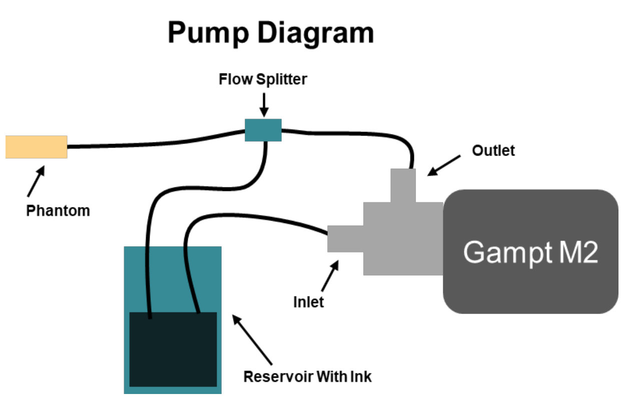

Figure 5. Diagram of a system set up in the dead-end configuration. The black lines represent tubes filled with ink. The flow splitter is labeled and used to split the ink flow to the phantom and the reservoir. The gampt M2

3 RESULTS

Utilizing the test setup that is shown in Figure 5, phantoms were placed on a PA testbench with a 532nm laser wavelength, and data was captured. An “artery-like” waveform was pulsed through the phantom with the Gampt M2 pump. This waveform was meant to closely mimic the pressure and shape of the human artery heart rate waveform.

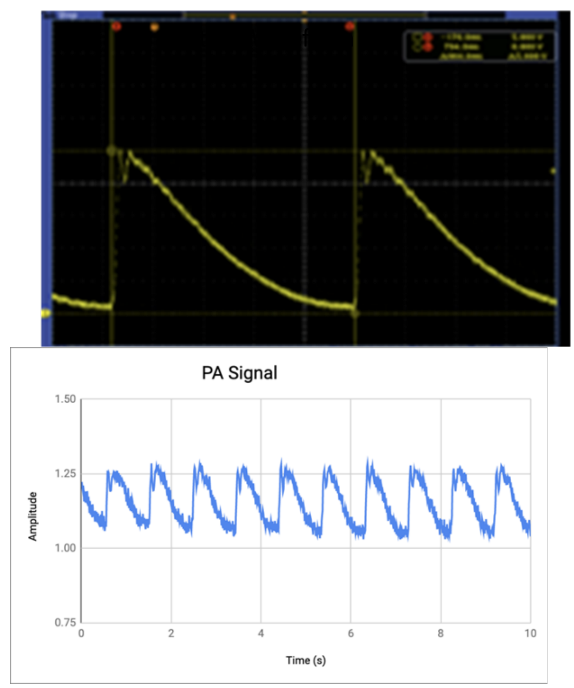

Figure 6. A series of two graps. The graph labeled “Inputted Waveform” represents the pressure signal that is being outputted to the phantom by the pump. The phantom then pulses with this waveform. After photoacoustic measurements are taken the PA signal graph can be observed. This is a graph over time that displays the aplitude of the PA signal. These two are

A PA signal overtime was collected. A comparison between the inputted signal and the outputted PA signal can be seen in Figure 6. The outputted PA signal maintained a similar shape to that of the inputted signal. The amplitude of the signal could be adjusted by changing the pump pressure and the concentration of PA ink that is used in the phantom itself.

4 CONCLUSION

A detailed 10-step process for building and testing a PA test phantom was addressed. With the same manufacturing process, similar phantoms can be made and applied to PA. Phantoms have the capability of changing multiple parameters such as multiple channels, flow vs. dead-end, overall size, channel shape, pulse waveform, and tissue hardness. 3D printed PVA channels allow for multiple benefits to the designer of the phantom. PVA allows for custom shape and ease of manufacturing as it is water-soluble and does not need to be invasively removed. Manufacturing of the phantoms can be completed following the process in roughly 1.5 days. In this time only ~2Hrs will be spent manufacturing while the rest of the time will be spent waiting for the phantoms to cure. This is much improved over other phantoms that lack complexity and are expensive to produce. Phantoms were placed over a 532nm laser diode array with an acoustic receiver and measured. An arterial waveform was pulsed through the phantom with a set pressure and frequency of 1 Hz. The outputted PA response was compared to the input from the pump. Overall the shape of the PA response very closely matched the inputted pressure signal. This means that the expected pressure wave is causing the correct pulsation in the phantom. Over large amounts of testing, leaks were observed on the hose barb connections to the phantoms.

5 FUTURE WORKS

Many improvements can be made to both the testing and the procedure for producing phantoms. While operating phantoms, it was found that over large use the phantoms began to wear out. This caused leaks to start appearing around the connection between the hose barb and the phantom. To fix this, a more intricate aluminum shell could be created that tightly holds both the fittings and the phantoms in place so that no tearing occurs over time and use. This phantom had little testing for multiple applications. In the future, we could test this phantom on PA and ultrasound and compare the two modalities. We could also just create a large testing set where all experiments have multiple averages for the collected data. Future improvements to the phantom itself can also take place. In this experimentation, we used a single square channel phantom that was centered at 5mm in a block of PDMS that was 10mm thick. We could produce phantoms with channels at multiple different heights as well as phantoms with multiple channels and channel shapes. This would produce a different PA signal that we could analyze.

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