Applications of Additive Manufacturing in Ultrasound Phantoms

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Abstract

An ultrasound phantom is a model of known geometric and material composition, often used in the calibration and testing of medical imaging devices. Typically, phantoms are created from a single gel-like material cast into a mold. There are many applications in ultrasound imaging for anatomically correct models composed of materials mimicking the acoustic properties of tissue. Additive manufacturing (AM) has been proposed as the construction method for creating these complex models. With AM, intricate geometries can be created that would be difficult or impossible using traditional fabrication methods. This study focuses on the assessment of materials for their suitability for such an application. The acoustic properties of bone, muscle, tendon, cartilage, fat, and soft tissue were compiled for comparison with the properties of various manufacturing materials. Samples of materials were obtained through donations from various companies and the Milwaukee School of Engineering’s (MSOE) Rapid Prototyping Center (RPC). Some of the samples were infiltrated with paraffin wax and epoxy resin in an attempt to alter their acoustic properties and then encased in an agar-silica gel. Recommendations are given for a Milwaukee School of Engineering Senior Design team, who will continue this line of inquiry in the upcoming school year.

Keywords: Ultrasound, Phantom, Additive Manufacturing

1. Background

Ultrasound devices function by emitting high-frequency acoustic waves, typically 1-5 MHz. An electric current is applied to a piezoelectric crystal in the transducer probe, causing the crystal to vibrate and generate acoustic waves. These waves travel into the body until they reach a transition between tissue types, at which point some are transmitted and others reflected, as illustrated in Figure 1.

Figure 1: Diagram of ultrasound wave travelling through tissue
The reflected waves travel back to the probe and impact the piezoelectric crystal, generating an electric current. The ultrasound machine uses this signal to calculate the distance from the probe to the barrier based on the acoustic-wave speed in the soft tissue and the time of the echo’s return. The 2D image formed on the display represents the distances and intensities of the echoes. The intensity, or power density, of a wave is defined as “the instantaneous power flowing through a unit area perpendicular to the direction of propagation of the wave as one elemental volume of the fluid acts on a neighboring element.”

This study focused on the density, velocity of sound through the medium, and acoustic impedance. Table 1 displays these acoustic properties of various biomaterials, averaged from several sources. These tissues make up most of the elements in the human body. The density and acoustic wave velocity of tendon and cartilage were unavailable, thus those cells were left blank.

Table 1: Average acoustic properties of biomaterials³⁻¹⁰

<table>
<thead>
<tr>
<th></th>
<th>Density (g/cm³)</th>
<th>Velocity (mm/µs)</th>
<th>Impedance (MRayl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat</td>
<td>0.941</td>
<td>1.453</td>
<td>1.38</td>
</tr>
<tr>
<td>Tendon</td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Soft Tissue</td>
<td>1.06</td>
<td>1.540</td>
<td>1.63</td>
</tr>
<tr>
<td>Muscle</td>
<td>1.073</td>
<td>1.581</td>
<td>1.70</td>
</tr>
<tr>
<td>Cartilage</td>
<td></td>
<td></td>
<td>1.85</td>
</tr>
<tr>
<td>Bone</td>
<td>1.787</td>
<td>4.080</td>
<td>7.526</td>
</tr>
</tbody>
</table>

The acoustic impedance (Z) of a material is the density (ρ) multiplied by the acoustic-wave velocity (V) through the material, as shown in equation (1).

\[
Z = \rho V
\]  

(1)

Wave transmission and reflection is determined by acoustic impedance. A plane acoustic wave encountering a straight boundary between two different mediums will both reflect and transmit. The amplitudes of the reflected and transmitted waves are dependent on the impedances of the two media. If the incident wave was normal to the boundary, the reflected wave coefficient (R) can be computed as shown in equation (2).¹¹

\[
R = \frac{Z_2 - Z_1}{Z_2 + Z_1}
\]  

(2)

When \( Z_1 = Z_2 \), \( R = 0 \) and there is no reflected wave. So, there must be a mismatch in acoustic impedance in order to produce a reflection for the ultrasound machine. As the difference in impedance increases, so does the amount of reflection. When the difference in impedance becomes very large (such as the difference between \( Z_{\text{air}} = 341 \times 10^{-6} \) MRayl and \( Z_{\text{water}} = 1.5 \) MRayl), \( R \) approaches ±1 and almost all of the incident power is reflected, with very little transmitted. That is why it is so difficult to image the lungs with ultrasound: the air provides a barrier that the wave cannot penetrate.¹²

2. Previous Approaches

2.1 additive manufacturing materials

One study fabricated the skull for a neonatal head phantom using the powder-binder combination of ZP130 and ZB58 in a Z510 Spectrum 3D printer. Once completed and de-powdered, the part was baked in an oven to eliminate moisture and ensure the full curing of the binder. Then the part was infiltrated under vacuum with Clear Coat epoxy resin. The vacuum was released before the part was extracted, causing the infiltrant to penetrate further. After extraction, the part was wiped clean of excess resin and left for 72 hours to cure."
2.2 non-AM tissue mimicking materials

Most studies regarding ultrasound phantoms do not involve additive manufacturing. Instead, they tend to use agar or gelatin as a main ingredient in their tissue mimicking materials. One such study showed that ultrasound phantoms created with water, 2% agar, and 3% silicon dioxide (silica) by mass adequately mimic soft tissue with a density of $1.03 \pm 0.01$ g/cm$^3$, an ultrasound speed of $1490 \pm 10$ m/s, and an acoustic impedance of $1.54 \pm 0.01 \times 10^6$ kg/(m$^2$s). There were many additives used that each targeted a property of the material. Formaldehyde was employed as a preservative and a cross-linking agent, decreasing the likelihood that the material would crack under slight to moderate pressure. Adding safflower oil lowered the Young’s modulus, which measures the stiffness of the material. The addition of finely-powdered solids increased the attenuation. Iso-propyl alcohol or n-propanol was added to increase the speed of sound through the material.

Polyvinyl alcohol (PVA) cryogel is another tissue mimicking material. One study concluded that its acoustic properties were similar to those of arteries, with the velocity of sound through the material at $1538$ m/s, acoustic impedance $1.6 \times 10^6$ kg/(m$^2$s), and attenuation $0.6$ dB/cmMHz @ 5MHz. The cryogel was subjected to several freeze-thaw cycles, each cycle stiffening the gel and making slight changes to its other properties. For example, each freeze-thaw cycle increased the velocity of sound through the gel by 5 m/s.

3. Methods

The Milwaukee School of Engineering (MSOE)’s Rapid Prototyping Center (RPC) provided tensile-bar samples of materials that they use. These included Duraform PA (3D Systems Corporation, Rock Hill, SC), Duraform Flex (3D Systems Corporation, Rock Hill, SC), Accura 25 (3D Systems Corporation, Rock Hill, SC), ZP-131 (3D Systems Corporation, Rock Hill, SC), ABS-M30 (Stratasys, Eden Prairie, MN), Polycarbonate (Stratasys, Eden Prairie, MN), Watershed XC11122 (DSM Somos, Elgin, IL), PPSF (Stratasys, Eden Prairie, MN), and Ultem 9085 (Stratasys, Eden Prairie, MN). The bars were cut into roughly 1.5-inch lengths and the edges were sanded down for smoothness and uniformity.

3.1 infiltration

Infiltration was performed as an attempt to alter the acoustic properties of the additive manufacturing materials and fill some of the miniscule holes that typically permeate a 3D printed part, as illustrated in Figure 2.

![Figure 2: Diagram of part before and after infiltration](image)

Gulf Wax (Royal Oak Enterprises, Roswell, GA), a brand of household paraffin wax, was melted in a beaker over a steam bath. Once the wax was melted, each sample was submersed for ten minutes. During that period, they were occasionally tapped with a glass stir rod in order to release the air bubbles collecting on their surfaces. After the ten-minute period, the samples were extracted and wiped clean of excess wax. They were then set aside to cure at room temperature for 72 hours.

Clear Coat epoxy resin (System Three Resins, Auburn, WA) was used to infiltrate a second set of samples. After mixing the epoxy according to the manufacturer's instructions, the samples were submersed in the epoxy and then placed in a vacuum chamber for ten minutes. Afterward, the vacuum was released and the samples removed and cleaned of excess resin. Then the samples were set aside to cure for 72 hours at room temperature.
The dimensions of each of the samples were measured with calipers before and after infiltration. Except for Duraform Flex, the dimensions of which are given in Table 2, none of the samples’ dimensions changed noticeably.

Table 2: Dimensions of Duraform Flex samples

<table>
<thead>
<tr>
<th>Infiltrant</th>
<th>Original Dimensions (inches)</th>
<th>Final Dimensions (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraffin wax</td>
<td>$0.135 \times 0.745 \times 1.655$</td>
<td>$0.136 \times 0.754 \times 1.670$</td>
</tr>
<tr>
<td>Clear Coat Epoxy</td>
<td>$0.136 \times 0.500 \times 1.367$</td>
<td>$0.145 \times 0.522 \times 1.439$</td>
</tr>
</tbody>
</table>

3.2 agar-silica gel

Once cured, the samples were embedded in an agar-silica gel whose acoustic properties mimicked that of soft tissue. The gel consisted of water, 2% agar, and 3% silicon dioxide. 10.5g of agar was dissolved in 500mL of distilled water and heated to 90°C in order to allow the agar to melt. 15.8g of silica was added and the mixture was stirred for 30 minutes. Then a shallow layer was poured into a pan and left to harden at room temperature. Once cooled and firm, samples were placed on top and more gel was created and poured to encase the samples. The gel was then stored in a refrigerator.

4. Recommendations

4.1 experimentally measure the acoustic properties of the modelling materials

In a previous study, a transducer and hydrophone were used in conjunction with a water bath to measure the acoustic properties of the samples. This setup is illustrated in Figure 3.

![Experimental setup](image)

**Figure 3:** Experimental setup, attached to an oscilloscope to gather and display data

The speed of sound through the sample was calculated by measuring the amount of time it took to for the signal to travel from the transducer to the hydrophone with and without the sample present. Since the speed of sound through water is known, it is possible to calculate the speed of sound through the material. The attenuation coefficient can be calculated by recording the amplitude of the pulse in the trials with and without the sample. The acoustic impedance can be calculated by multiplying the velocity of sound through the material by its density. The density can be calculated by dividing the mass of the sample by the volume of water it displaces.\(^\text{17}\)

4.2 avoid aeration

Air pockets often arise naturally in the creation of both AM and non-AM materials. The acoustic impedance of air is about 3,500 times smaller than that of soft tissue. If the signal were to hit an air pocket, this mismatch would cause most of the signal to be reflected and very little transmitted, obstructing the ultrasound. For AM materials, infiltration could solve this problem. For non-AM materials, aeration could be avoided by using a vacuum to remove air and syringes to transfer samples.
4.3 investigate the possibilities of additive manufacturing in mold making

In the event that additive manufacturing materials with suitable acoustic properties cannot be found to mimic every tissue, it may be feasible to print a mold and cast some of the parts. It is likely that these molds would have to be treated, perhaps through infiltration, so that they will not absorb the material which is being cast.

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6. References