Development and Validation of Bone Phantoms for pMUT-Based Ultrasound Imaging

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***Abstract*—Piezoelectric micromachined ultrasonic transducers (pMUTs) are a promising technology for non-invasive bone imaging. To validate the performance of a novel pMUT system, it is essential to develop accurate, easily reproducible, and cost-effective bone phantoms that mimic both the mechanical and acoustic properties of human bone.**

I. Introduction

There is a growing interest in developing innovative imaging technologies, particularly ultrasound ones. One area of interest is the miniaturization of this technology through the use of pMUTs. [2] With the development of new imaging modalities, there is a need for a way that can test these systems in a cost-effective, but accurate way.

This work focuses on the development of cost-effective, easily reproducible, and accurate bone phantoms for the testing of a novel pMUT system that measures biological age via growth plates. This work focuses on the development of two different phantoms: one of the growth plates between the distal and middle phalanx and one between the radius and the ulna.

Using phantoms is essential for the rapid testing of imaging technologies because they allow for safe, repeatable, and testing of imaging technologies.

II. Methods

A. Overview

This section describes the methods used to design, fabricate, and validate the bone phantoms for testing a pMUT system. This process included 3D modeling, material selection, phantom fabrication, and testing for the phantom's reliability.

B. Phantom Design

The 3D model of the distal/middle phalanx and radius/ulna are made from medical grade 3D models provided by the Centre of Anatomy and Human Identification at the University of Dundee. Based on this, a CAD model was created in Fusion 360 to design varying growth plates from 0mm to 3mm, an enclosure, and custom supports for the model that maximize its integrity and placement accuracy while curing, while not impeding on the quality of the image. (Figure 1) The length of the finger was adjusted to the average length of the distal and middle phalanx of 4.47 cm. [3]

The supports on the beam were designed to make sure the spacing between the growth plates remained constant, and that the structure could be printed properly. Another consideration was the fact that these models were suspended in the case with thin wire using these supports to hold it up during the curing process. (Figure 2)

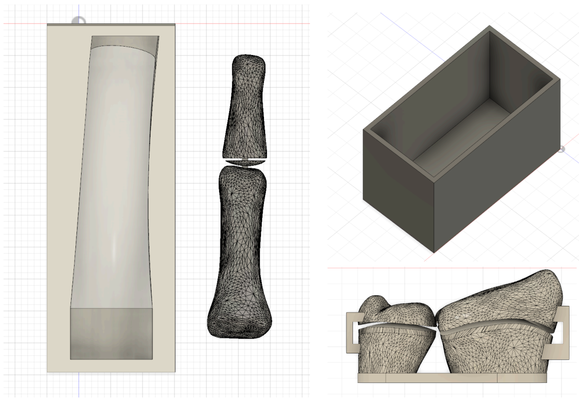

Figure 1: 3-D models of the distal/middle phalanx phantom and casing (left) and radius/ulna phantom and casing(right)

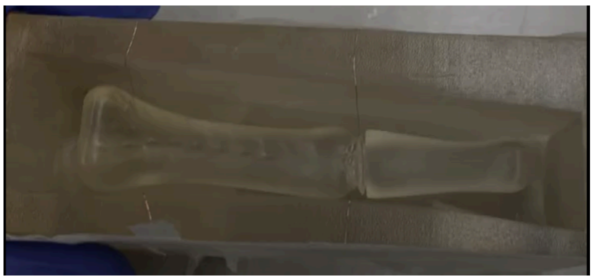

Figure 2: Distal/middle phalanx phantom held up by thin wires before the molding process.

C. Material Selection

The bone and the exterior casing were both made using an ABS-like SLA resin for its high print resolution. The bone was not printed with FDM due to it floating in the gel. The flesh was made from a two-part platinum silicon rubber coated in a powder conditioner to easily release the mold. The silicone was used because it provides high structural integrity while providing similar acoustic impedance to the flesh. [1]

Fig. 3: Phantom of the distal/middle phalanx with 1 mm growth plates.

Figure 4: Phantom of the growth plate at the radius and ulna with 2 mm growth plates.

D. Phantom Fabrication Process

The process begins with printing the casing and bone models using an SLA printer with ABS-like SLA. After printing, the bone was suspended on the casing, looping a thin wire through the supports, avoiding the growth plates, and taping the wires to the side of the casing. (Figure 2) The bone is adjusted so that it sits around 2 to 3mm above the casing. The two-part platinum silicone rubber is then mixed in a beaker and degassed in a vacuum chamber for over 30 minutes to ensure no bubbles are present in the solution. The silicone is then poured into the casing and the suspended bone. Immediately afterward, the entire caste is then degassed again for another 30 minutes to ensure no bubbles are present at any interface. This degassing process is extremely important and the main challenge of this fabrication process. Improper degassing leads to the formation of bubbles all over the phantom that severely negatively affect the quality of the produced image. The mold is then given 48 hours to cure before the phantom is released.

III. Results

The fabricated bone phantoms were tested using an existing ultrasound system to validate their ability to produce realistic signal reflections and visualizations similar to human bone.

When the ultrasound system was applied to the bone phantoms, clear echo reflections were observed and the signal patterns closely resembled those expected from cortical bone in prior tests with real bone samples.

Figure 4 shows the ultrasound scan of the bone phantom. The image clearly shows the bone-like structure and the growth plate. The defined signal reflections are similar to those seen in clinical imaging of real finger bones. These test results give insight into how the phantom would simulate the behavior of real bones under the pMUT system.

While quantitative measurements such as specific acoustic and material properties were not performed, the qualitative results demonstrate the phantom's ability to mimic the essential features of bone in ultrasound imaging.

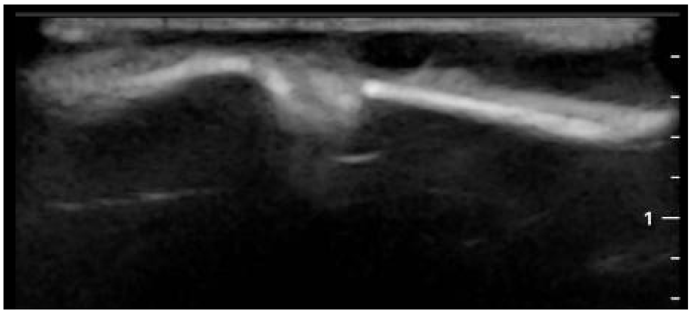

Figure 5: Ultrasound image of the distal/middle phalanx phantom using Butterfly iQ.

IV. Conclusion

The objective of this work was to develop realistic bone phantoms for testing a new pMUT system designed to image bones in the finger and wrist for bone age assessment. The fabricated bone phantoms successfully replicated key structural features of human finger and wrist bones. Testing with an existing ultrasound system demonstrated clear visualizations, validating the phantom's ability to simulate real bone behavior. These results show the potential for these phantoms to serve as reliable test models for evaluating bone imaging systems.

Future work will involve quantitative validation of the phantom's acoustic properties and testing with the newly developed pMUT system. Additionally, expanding the design to include more complex bone structures could enhance its utility for a wider range of imaging applications.

V. Acknowledgment

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