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Work in Progress: Developing Ultrasound Phantoms as part of a Biomedical Engineering Design Course Sequence

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Background and Motivation

The Biomedical Engineering (BME) undergraduate program at Kansas State University is a relatively new program (started in Fall 2018). One of the unique elements of this BME program, compared to the other engineering disciplines at K-State, is the inclusion of a two-semester junior design sequence – *BME 490/1, Undergraduate BME Design Experience I/II* (Junior Design I and Junior Design II). These courses have been taught since their first offering in Fall 2020 and Spring 2021. The goal for these courses was to ease students into completely open-ended engineering design – the structure of senior design. At the same time, the instructor aimed to equip students with skillsets that would make them hirable and be more successful in senior design given it wouldn't be the first time they were using such tools. Junior Design I (1-credit hour) involved scripted laboratory exercises centered around LabVIEW, MATLAB, and Excel (automation with Macros). The course also involved a final project (with defined project requirements) incorporating data acquisition with LabVIEW and the option to perform analysis with MATLAB. Junior Design II (2 credit hours) then aimed to give students more freedom and responsibility in the design process. The hardware was provided to the student teams (Nordic Thingy52 [1]) but students had to define the project requirements and the testing/validation processes. See [2] for an overview of the BME curriculum.

Although the above approach involved hands-on learning, one weakness was that students struggled to see the benefit of learning these skillsets. They often lacked motivation and then struggled greatly close to the end of the semester, a common issue when students are given scripted exercises with no real client other than the instructor. Thus, when an opportunity arose to partner with the College of Veterinary Medicine in Fall 2023, the junior design course instructor decided to restructure the course, since student motivation and learning can be improved when there is a real-world client, especially one based in the community [3], [4], [5]. This work aims to answer the following question – does a client-based project improve students' motivation and engagement with the design process? This work in progress outlines the curriculum changes made for Fall 2023, the new phantom design project details, and preliminary data and takeaways from the first cohort to use this approach. Note that this work is exempt from human subjects review under IRB exemption category §46.104(d), which relates to research conducted in established or commonly accepted educational settings that does not disclose the identities of any human subjects (see [6]).

New Course Structure

Junior Design I is a 1-credit hour course that meets once a week for 3 hours in the Fall semester. Junior Design II is a 2-credit hour course with a lecture (50 minutes) and lab (3 hours) component. The main course objectives are: 1) Learn how to implement a complete design cycle, from initial concept to final implementation, 2) Enhance your oral and written communication skills, 3) Learn to work effectively in teams, and 4) (unique to Junior Design II) refine design objectives/parameters and perform testing and validation procedures. Note that these course objectives were not changed during the restructuring.

Early in the semester of Junior Design I, Dr. Clay Hallman, an Assistant Professor and Veterinary Radiologist in the College of Veterinary Medicine, provided a guest lecture covering the diagnostic utility of radiography and ultrasound. This provided students with a basic understanding of the problem at hand, and why ultrasound phantoms are needed as a training tool. It was emphasized to the students that it was not expected of them to create an entire canine phantom. Instead, student teams were instructed to focus on a single organ, and aim to have their phantoms reflect the echotexture, acoustic impedance, and anatomical structures typically viewed under ultrasound. Additional considerations included replicability, shelf life, durability, affordability, and material accessibility.

For the remainder of the course, relating to the ultrasound project, student teams were given smaller assignments throughout the semester to help them hit certain milestones along the way (design reviews, presentations, etc.). Additionally, teams visited the Veterinary teaching hospital to learn firsthand how ultrasound scans are performed on live animals and receive training on performing scans themselves. The ultimate goal of Junior Design I was for teams to develop a proposal that they could then use as a guide during Junior Design II when they would develop the phantoms and iterate on their designs.

For the Fall 2023/Spring 2024 sequence this new course structure was offered, 20 students (4 teams) completed the sequence. Two teams focused on the liver, one team chose the kidney, and one team selected the bladder as their organ of interest.

Phantom Design Process

The Veterinary College provided students with CT scans of an entire canine abdomen. Using 3D Slicer, students adjusted brightness and contrast levels to isolate the organ, creating an STL file for further modification in SolidWorks. The anatomical models were printed using the available 3D printers in the Tong Family Biomedical Education and Innovation Laboratory (2 Prusa Minis, an Original Prusa i3 MK3S+, and a Formlabs 3b). Once the structure was validated, teams focused on matching acoustic properties.

Teams researched and explored a variety of different materials and approaches. Students quickly realized that 3D-printed filaments were unsuitable due to mismatched echogenicity and acoustic impedance. Students then explored silicone and polymers, such as agarose, ballistic gel, and gel wax. Materials of this nature provide similar acoustic properties to tissues, especially after doping with silicone dioxide or graphite powder. Teams explored how to acquire, use, alter, and manipulate these materials to match the echogenicity and echotexture of the chosen organs (e.g., using mold making kits). A generalized outline of the design process can be seen in Figure 1.

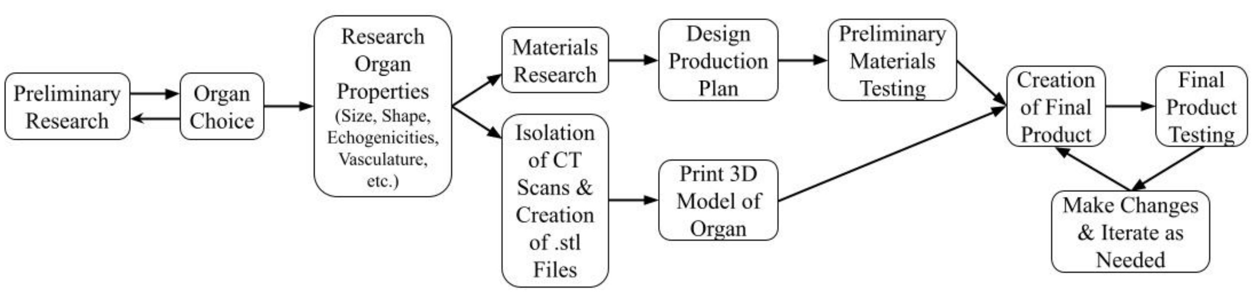

Figure 1. General phantom design and creation process outline.

Lessons Learned, Initial Results & Discussion

During preliminary materials testing, several teams found a problem with agarose – it began to dry out and lose volume when exposed to air for extended periods of time. Students explored various options to combat this issue, but ultimately, this material was no longer considered. Certain organs required additional materials and doping of graphite powder, silicone dioxide, dragon skin, and/or the addition of TPU filament (an attempt to add in vasculature). The authors would like to especially thank the Tong Family for their generous donation that made the purchasing of these supplies possible, including a Butterfly iQ+ Vet ultrasound probe.

The final products produced by the first group of students were far from perfect, but the students made a tremendous amount of progress. The kidney team provided clear layers, but the TPU filament created artifacts. Students were able to successfully create initial phantoms of different organs. For example, the bladder team excelled at creating a tapered elliptical structure with appropriate wall thickness and an anechoic lumen simulating urine. However, there is still room for improvement considering there were small, hyperechoic foci with reverberation artifact admixed within the luminal material representing air bubble contamination. The phantom liver achieves a hyperechoic outer capsule with a background echotexture similar to that of a live patient. A goal for continued improvement would be to mitigate air bubble contamination which results in numerous small hyperechoic foci scattered throughout the phantom. The phantom kidney accurately mimics the shape and smooth capsular margin of a live kidney with a well-defined renal cortex. Additional improvement could be made by exploring additional materials to accurately mimic the renal medulla without resulting in the strong distal acoustic shadowing noted in the current phantom. Comparative ultrasound images can be seen Figure 1 in Appendix A while images of the phantoms can be seen in Figures 2, 3, and 4.

From an educational perspective, the students bought in – they were invested, and it was clear that they were motivated and wanted to create useful phantoms. At the end of each semester, students completed teacher and course evaluations (Tevals). For part of that survey, students note 1) if the course increased their desire to learn about the subject, 2) the amount learned in the course, and 3) their effort to learn in the course. All on a scale of 1 (very low) to 5 (very high). These data are still being analyzed but there is a noticeable improvement in all three questions comparing the Fall 2021 cohort to the Fall 2023 cohort (see Table 1 in Appendix B). Note that a different instructor taught the BME 490 course Fall 2022. The Fall 2020 cohort scored the first two questions relatively high. This was the first time the course was offered and during the COVID-19 pandemic, so it's possible these factors influenced the results. Still, the Fall 2023 cohort had the highest response regarding their effort to learn in the course.

Throughout this project, students learned a multitude of technical and soft skills (3D printing, working with CT scans, the engineering design process, teamwork, project planning, and time management). Student feedback regarding the project has been incredibly positive after the first year. The second iteration with a new student group just started in Fall 2024, with the list of addressed organs/anatomy continuing to grow.

References

[1] " Nordic Thingy:52," Accessed Jan 17, 2024. [online] https://www.nordicsemi.com/Products/Development-hardware/Nordic-Thingy-52.

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Appendix A – Initial Phantom Results (Fall 23, Spring 24 Cohort)

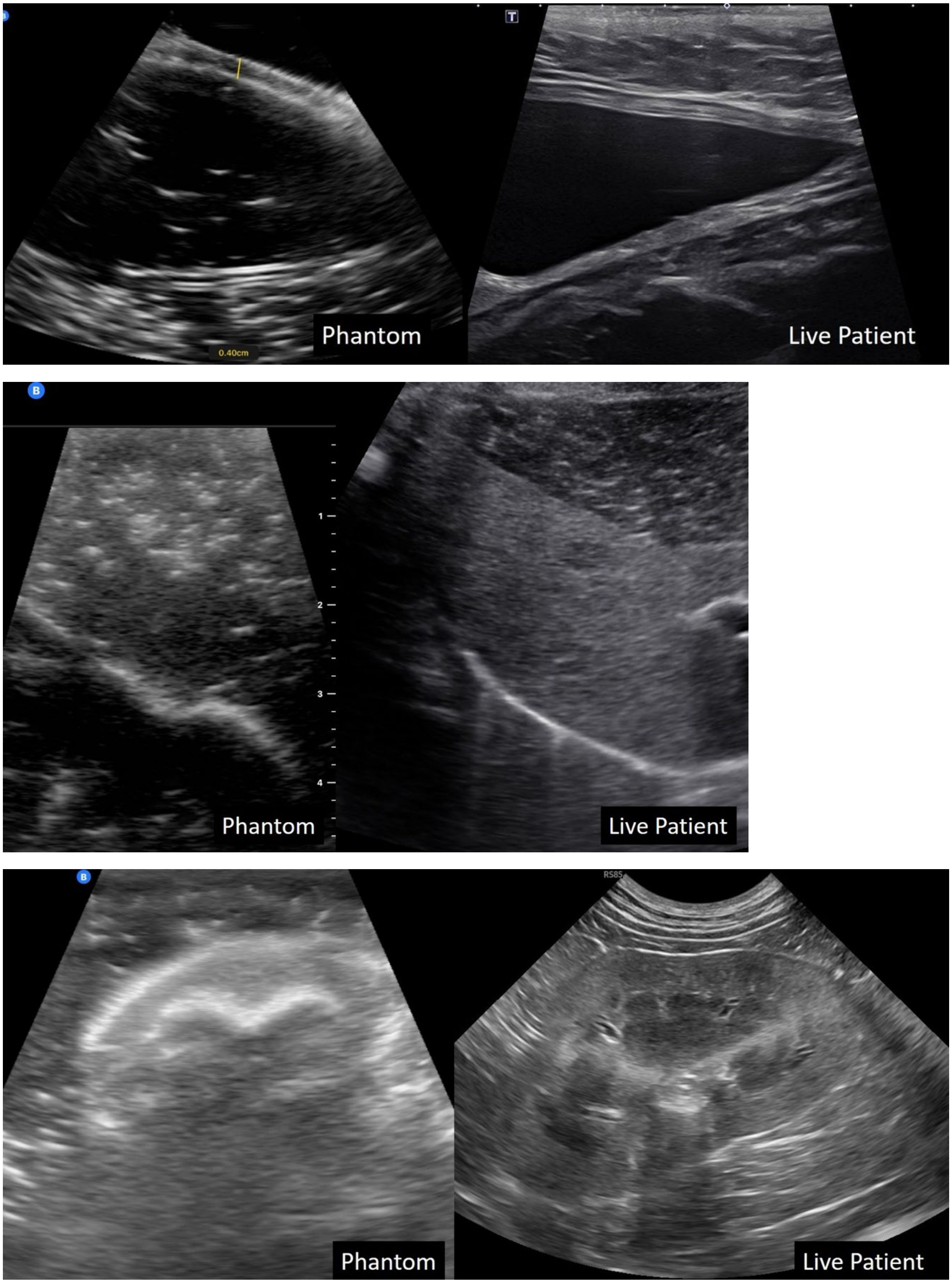

Figure 1. Ultrasound image of a student created phantom (left) compared to a standard ultrasound image (right) of a bladder (top), a liver (middle), and a kidney (bottom).

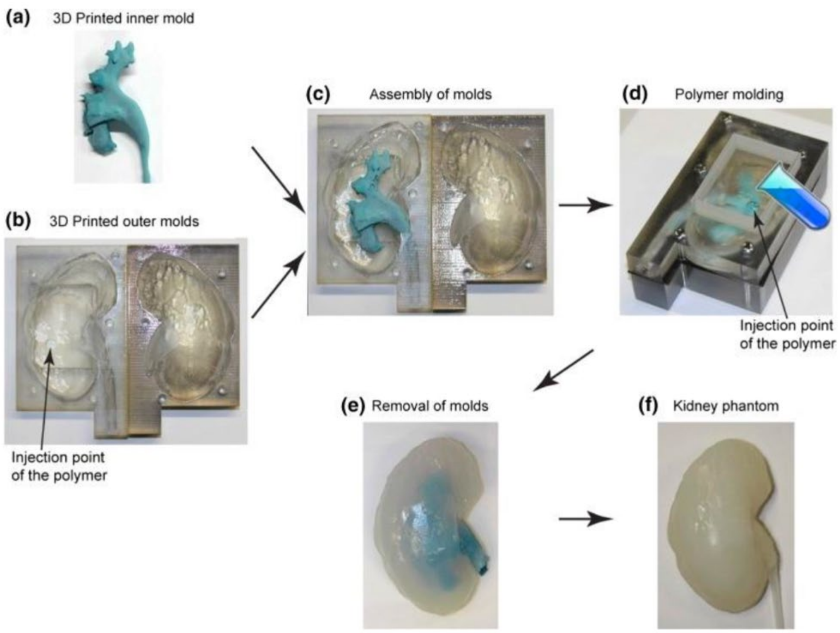

Figure 2. Kidney team's design process

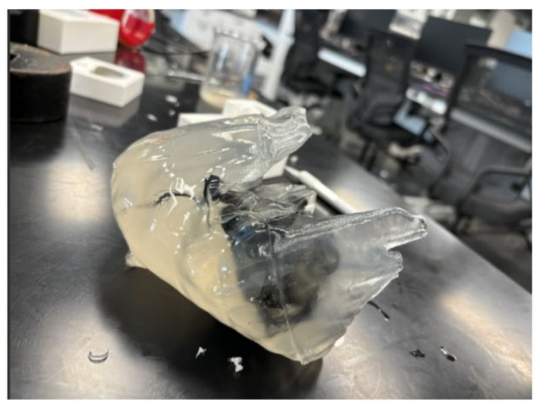

Figure 3. Liver phantoms. Agar-based (left) and gel wax (right).

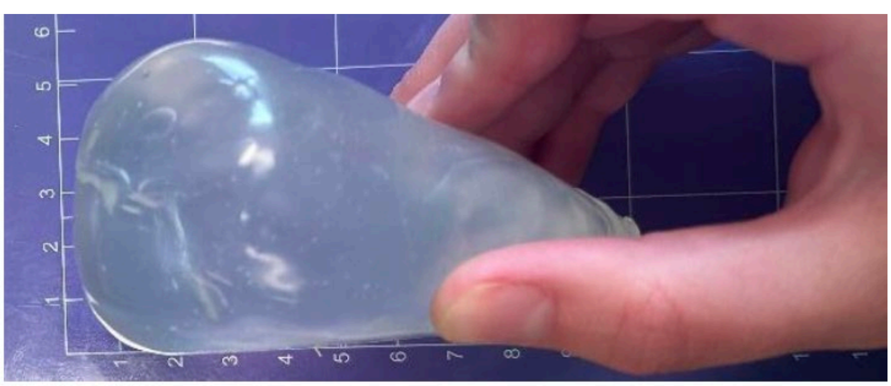

Figure 4. Gel wax-based bladder phantom.

Appendix B – Initial Teval Results

Table 1. BME 490 Teval results for Q1 – Course Increased Desire to Learn About the Subject, Q2 – Amount Learned, and Q3 – Effort to Learn. The new structure of the course was introduced Fall 2023.

Semester	**Q1**	**Q2**	**Q3**	**Number of Responses**
Fall 2020	4.5 +/- 0.7	4.7 +/- 0.6	4.2 +/- 0.6	13 out of 25
Fall 2021	3.6 +/- 1.5	4.1 +/- 0.8	4.0 +/- 0.8	11 out of 22
Fall 2023	4.6 +/- 0.7	4.5 +/- 0.5	4.7 +/- 0.5	10 out of 20
Fall 2024	5.0 +/- 0.0	4.6 +/- 0.5	4.8 +/- 0.4	5 out of 20