Creation of a Neonatal Skill Trainer for Pericardiocentesis, Thoracentesis, and Paracentesis

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Abstract

The training of neonatal surgeons demands simulation tools that combine anatomical accuracy, ultrasound compatibility, and procedural realism. Current neonatal manikins lack anatomically correct fluid compartments, limiting the effectiveness of hands-on training for thoracentesis, abdominal paracentesis, and pericardiocentesis. These surgical operations, commonly known as TAPP procedures, are fluid and air removal surgeries for the peritoneal cavity, the pleural cavity, and the pericardium, respectively. To address this gap, our project aimed to design and fabricate an anatomically accurate neonatal manikin with refillable, ultrasound-compatible compartments representing the pleural cavity, peritoneal cavity, and pericardium. The manikin featured 3D-printed ribs and internal structures to ensure spatial accuracy, along with a durable skin-like material resistant to repeated punctures. Our specific aims were to develop the manikin with correct anatomical and functional features, enable realistic simulation of TAPP procedures using ultrasound guidance, and create a training module to ensure proper usage and care. In pursuit of these aims, we created a neonatal manikin with lifelike compartments for the peritoneal cavity, pleural cavity, and pericardium. These compartments were housed within an anatomically accurate 3D-printed rib structure. Additionally, the heart was fabricated using 3D printing. We created a peritoneal cavity with the skin material as well as a lung structure with modeling clay surrounding the heart. Each of these compartments allowed physicians to inject saline or water into them through the same ultrasound-compatible material used for the skin. The skin material used to wrap the compartments was puncture-resistant and ultrasound-compatible. Thus, the repeated injection of the surgical needles used in thoracentesis, paracentesis, and pericardiocentesis did not distress the material for several rounds of testing. The 3D-printed rib structure containing the wrapped compartments was placed inside the hollow neonate. We used another patch of the skin-like material to enclose the open abdomen. Through this innovation, we anticipate enhancing neonatal surgeon preparedness, improving procedural confidence, and reducing patient risk. The project seeks to set a new standard in neonatal surgical simulation by integrating high-fidelity anatomical replication with a durable and reusable design.

Keywords: neonatal manikin, thoracentesis, paracentesis, pericardiocentesis, TAPP procedures, peritoneal cavity, pleural cavity, pericardium, ultrasound, high-fidelity

Introduction

Surgeons require a level of skill that ensures their readiness to perform procedures on a human patient. To ensure proficiency and confidence before performing their first surgical procedure, medical professionals must have rigorous training that combines theoretical understanding with hands-on practice. This hands-on practice is crucial, as it allows surgeons to build muscle memory, improve precision, and develop quick decision-making skills in a controlled environment. One way in which surgeons enhance surgical readiness is through surgical skills practice conducted via simulation. Patient simulation in the field of medicine plays a major role in the development of surgical skills and usually involves the use of animals, virtual reality, and medical manikins. The primary method of human simulation in the medical field is via medical manikins, which are lifelike patient simulators (Khunger & Kathuria, 2016). Medical manikins look and feel as much like humans as possible to simulate human surgeries to the highest degree and come in different shapes, sizes, functions, levels of detail, and species. Simulators enable medical professionals to develop surgical skills in a low-risk setting, where potential errors have no detrimental real-life consequences. In the field, this translates to more prepared surgeons in their transition to live human patients. However, there are challenges to using these tools. Despite their benefits, simulators often fall short of fully replicating the complexity of human anatomy and physiology (Cureus, 2023), falling short of “technological progress” and limiting their educational value. Furthermore, the lack of standardized clinical validation protocols complicates efforts to measure their effectiveness and clinical applicability (Journal of Pediatric Surgery, 2019). While there are pediatric surgery simulators, they are vastly outcompeted in numbers by other areas of medicine such as otolaryngology and orthopedics. This hinders improvement in neonatal medical training.

While many manikins exist for adult patients and basic neonatal care, there is a critical gap in realistic, anatomically accurate simulators specifically designed for neonatal fluid removal procedures such as thoracentesis, paracentesis, and pericardiocentesis. These surgeries involve the removal of fluid from the peritoneal cavity, pleural cavity, and pericardium, respectively, and all require high levels of precision (Doniger, 2014). Without access to anatomically accurate, durable training tools, aspiring neonatal surgeons are limited in their ability to practice these high-stakes surgical interventions effectively. Without these specialized simulators, surgeons at the University of Virginia (UVA) hospital practice neonatal TAPP procedures by filling up balloons with water and inserting them loosely into the abdomen of a neonatal manikin. This impedes surgical accuracy, proficiency, and proper practice as the balloons are not in the correct anatomical position and are prone to popping, disrupting the learning cycle in the process. While the method used is sufficient for basic practice, it overlooks anatomical accuracy, which is essential for building confidence in the procedure. It also fails to provide surgeons with the opportunity to practice ultrasound-guided needle insertion, which is needed given the precision required for these procedures. Without a proper device to practice these fluid removal surgeries, neonatal surgeons are left with inaccurate techniques for these surgeries, which can lead to surgical errors in the real world. Precision is far too important to ignore in these procedures; thus, there was a necessity for a device to fill that gap.

Due to the current limitations in neonatal medical manikins, Dr. Jaclyn Wiggins with the University of Virginia (UVA) Hospital Department of Neonatal Perinatal Medicine asked us to create a neonatal model for practicing these surgeries. Her main request in the creation of this model was that it be both anatomically accurate and durable. The requirements for our simulator were that it was ultrasound compatible, since TAPP procedures require ultrasound guidance, fluid retentive because the surgeries involve fluid compartments, and puncture resistant since practicing the surgeries requires needle punctures.

Our specific aims for this project were thus to design an ultrasound-compatible, anatomically correct neonatal manikin and to use it to simulate neonatal pericardiocentesis, thoracentesis, and paracentesis. Additionally, our project aimed to train aspiring neonatal surgeons to use the neonatal manikin for practicing these high-stakes, fluid-removal procedures. By achieving these goals, the neonatal surgical manikin provided both a realistic and effective training tool to improve physician preparedness and skill in performing these critical interventions. Thus, our three aims included: the design of the manikin, the validation and use of the manikin for fluid and air removal surgeries, and the training of surgeons by providing simulation with the manikin.

Our innovative design filled a critical gap in current medical training by incorporating anatomically accurate fluid compartments into a neonatal manikin. Our design included compartments representing the pleural, peritoneal, and pericardial cavities. These compartments were made from ultrasound-compatible material, thus enabling surgeons to visualize needle placement. The inclusion of these compartments allowed for realistic needle insertion, water injections, and, most importantly, fluid drainage, simulating surgical scenarios with accuracy and precision.

What set our manikin apart was its durability and reusability. By using advanced, puncture-resistant, ultrasound-compatible materials, the manikin withstood repeated use without compromising its integrity, as was demonstrated in our validation testing. Our design thus helped cut down costs and minimized the maintenance required for practicing these surgeries. This was crucial for neonatal surgical training, where repeated practice was critical to ensuring that healthcare providers gained the practice and precision necessary for real-life scenarios.

By filling this void in neonatal simulation, our manikin will help train surgeons to develop the muscle memory, precision, and decision-making skills necessary for successful intervention, ultimately improving patient outcomes and enhancing surgical readiness (Cahoon Roberts, 2024). This tool aims to set a new standard in neonatal medical simulation, ensuring better-prepared surgeons and safer, more efficient care for the most vulnerable patients.

Specific Aims:
The specific aims were as follows:
Specific Aim 1: To design an ultrasound-compatible, anatomically correct, neonatal manikin.
Specific Aim 2: To use the validated neonatal manikin to simulate neonatal pericardiocentesis, thoracentesis, and paracentesis.
Specific Aim 3: To train aspiring neonatal surgeons on how to use the manikin to simulate these procedures.

Aim 1 focused on the design of the neonatal manikin, which matches the anatomical accuracy of the average neonate brought to term during pregnancy. To achieve this aim, we designed anatomically correct fluid compartments within a 3D-printed rib structural support. We created the peritoneal cavity, pleural cavity, and pericardium by surrounding the area of the peritoneal cavity, the lungs, and the 3D-printed heart with our skin replicate material to match the size, shape, and texture of these organs correctly. We wrapped the cavities in the skin replicate material that is puncture-resistant and ultrasound compatible to ensure reusability. Designing the manikin this way addressed the major gap in the exclusion of these compartments and hopefully will contribute to more accurate surgical training in the future and thus improved surgical competence and patient outcomes (Edward, Nichols, & Bakerjian, 2023). Aim 2 focused on the implementation and validation of the neonatal manikin, which we tested by puncturing the skin material multiple times in the practice of neonatal TAPP procedure's technique. The material did well for our purposes and simulated the procedures to a suitable accuracy. The puncture-resistant material also permits the reuse of the neonatal manikin to train neonatal surgeons accurately for years to come. Aim 3 focused on the training of surgeons with the neonatal manikin. We wanted to create a training module for surgeons to familiarize themselves with the proper use of the neonatal manikin. This would include proper care of, proper surgical practice with, and proper storing of the neonatal manikin. Well-structured training programs are shown to lead to fewer medical errors (Lopreiato, 2018), thus improving surgical aptitude and confidence in neonatal surgeons. By recommending simulation scenarios in our training module, we also hope to improve patient morbidity and mortality, as is shown in studies completed by Jasmina Sterz and co-authors. (Sterz et al., 2022).

Results

The final prototype of the neonatal manikin met the primary goals of anatomical and procedural realism, ultrasound compatibility, and reusability. To evaluate its performance, we conducted a series of structured trials that tested the manikin's ultrasound sensitivity, material puncture durability, and anatomical and functional realism. These tests validated the efficacy of our design and revealed areas for improvement, possibly helping to improve future iterations of the manikin.

Ultrasound compatibility was an important specific aim of the manikins' design, as all three procedures rely on real-time ultrasound imaging, and the current methods of training are not ultrasound-compatible. We filled the internal compartments of our manikin with a soap solution in order to simulate realistic tissue echogenicity and remove any air gaps from the skin-like material on the exterior of the manikin to the pockets themselves. We then conducted ultrasound testing using a clinical-grade ultrasound probe.

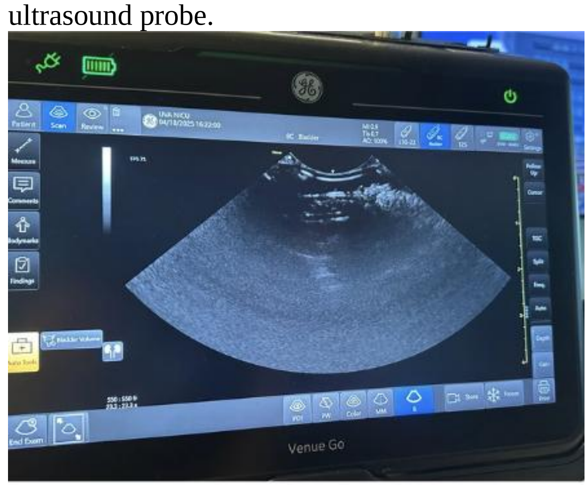

Figure 1: Ultrasound Image of Ribs and Heart
Ultrasound image of the manikin's chest during simulated thoracentesis, demonstrating the accurate rib structure

As seen in Figure 1, the rib structures were identifiable on the ultrasound image to individuals with ultrasound experience, such as neonatal surgeons who are aiming to practice these surgeries, allowing Dr. Wiggins to navigate the intercostal spaces for thoracentesis. The needle poking through the intercostal space is visible in this image, which is very important in completing these surgeries accurately using simulated ultrasound guidance.

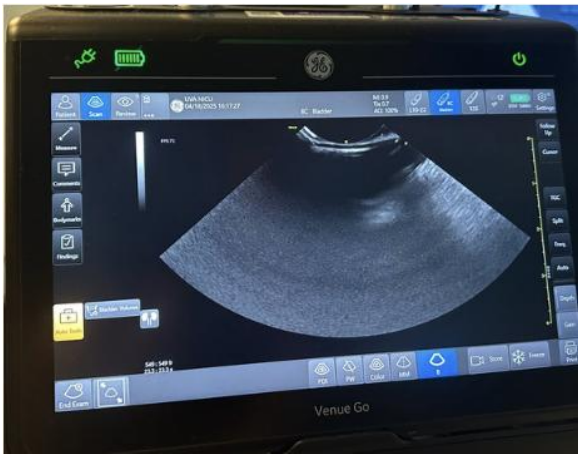

Figure 2: Ultrasound Image of Peritoneal Cavity
Ultrasound image of the manikin's peritoneal cavity during simulated thoracentesis.

As seen in Figure 2, the peritoneal cavity also generated a strong image, as the fluid-filled sac is visible in the dark space on the image. Thus, demonstrating how ultrasound worked effectively with the neonatal manikin and can be used to simulate neonatal TAPP procedures with surgical precision.

To systematically evaluate ultrasound sensitivity, Dr. Wiggins performed repeated scans on all three compartments using the soap-filled model. While the peritoneal compartment provided sufficient clarity, the pleural and pericardium were slightly more difficult to visualize consistently. The pleural cavity and heart were further buried within the manikin, making it difficult to visualize under ultrasound. However, the rib structure itself was easily visible, making the location of the heart easy to find and the surgeries able to be simulated well. This analysis does suggest that future improvements should be performed to enhance the echogenicity of these internal structures.

To test the manikins' durability, Dr. Jaclyn Wiggins conducted controlled stress tests on both the outer chest material and the peritoneal compartment. In one series of tests, she inserted a 22-gauge needle into the same location on the outer chest wall repeatedly until she observed failure of the material. A failure was classified as a rip or a hole in the material, rendering the compartment unsuitable for additional testing. As seen in Figure 3, according to Dr. Wiggins, the chest material remained fully functional through 14 punctures, after which its integrity gradually declined. By approximately 23 punctures, it required replacement, becoming unusable by the 25th puncture.

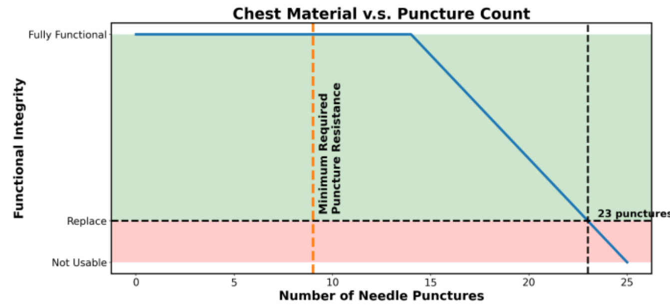

Figure 3: Chest Material vs. Puncture Count
Line graph of Chest Material vs. Puncture Count. The chest material stays fully functional through 14 punctures, then its integrity declines steadily and must be replaced at roughly 23 punctures, dropping to failure by 25 punctures.

This performance exceeds the minimum durability requirement of 9 punctures, corresponding to the expected number of fellows who would use the manikin during a training cycle. As seen in Figure 4, Dr. Wiggins performed a similar stress test on the skin surrounding the peritoneal cavity and, due to its smaller surface area, did not need to be replaced until after 40 punctures.
In addition to repeated punctures, Dr. Wiggins tested a range of needle gauges to assess the material performance of different surgical needle sizes.

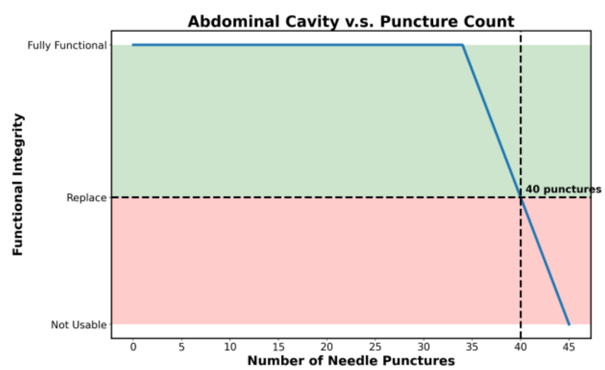

Figure 4: Abdominal Cavity vs. Puncture Count
Line graph of Abdominal Cavity vs. Puncture Count. The abdominal material maintains full integrity until about 34 punctures, then degrades linearly and must be replaced at roughly 40 punctures, and falls toward unusable by 45 punctures.

The outer chest material withstood repeated punctures from needles ranging from 26 to 20 gauge without any significant tearing or loss of integrity. However, when punctured with a 19-gauge needle, the material exhibited tearing and was no longer suitable for additional testing. These results suggest the manikin is best suited for procedures using needles within the 20-26 gauge range, which aligns with those typically used by neonatal surgeons during TAPP procedures.

The anatomical realism of the manikin was verified through both dimensional comparison and procedural usability. Compared to the current practice of placing balloons loosely inside a manikin's abdomen, our design allowed for significantly greater procedural accuracy. According to the clinicians, the structural constraints of the ribcage and the materials used created a "realistic experience" that had anatomical limitations that mimicked live patient scenarios.

Across all tests, the manikin demonstrated reliable reusability. The tattoo skin maintained its structural integrity through the procedural cycles and only required resealing after concentrated puncture testing. The soldering iron proved to be effective for quick maintenance between uses; however, in the future, a more efficient resealing method should be developed to minimize the need for the clinicians themselves to perform repeated manual repairs. The internal use of soap solution, while beneficial for the ultrasound reflection, introduced some minor messiness and required emptying and refilling if the manikin needed to be moved. In future iterations, this should be replaced with a more stable medium that maintains ultrasound compatibility without the associated maintenance burden.

Overall, the neonatal manikin was anatomically accurate, ultrasound-compatible, and reusable for the simulation of neonatal thoracentesis, paracentesis, and pericardiocentesis. The materials used withstood real-world testing, and the neonatal manikin enabled surgeons to practice in ways the current training tools do not. Despite not finalizing the training module during the project timeline, the manikin lends itself to building a well-defined simulation curriculum.

Discussion/Conclusion

The final neonatal manikin developed through this project successfully met the three specific aims of anatomical accuracy, procedural realism, and reusability for the simulation of thoracentesis, abdominal paracentesis, and pericardiocentesis in neonates. The data that was collected during hands-on testing validated the manikins' clinical relevance. The puncture durability tests demonstrated that the skin-like tattoo skin material maintained integrity through 14-40 punctures, depending on the region. This far exceeded the minimum use requirement for a full training cohort. Ultrasound imaging tests confirmed that key anatomical structures such as the rib cage and peritoneal cavity were visible under clinical ultrasound conditions, which allows for real-time ultrasound-guided simulation. Clinical expert Dr. Jaclyn Wiggins affirmed the manikin's anatomical and procedural realism and endorsed its future adoption as a training tool in UVA Hospital's neonatal surgical training programs.

The broader implications of the manikin are substantial. It fills a critical void in current neonatal surgical simulation by elevating the preparedness of surgical trainees. Compared to current rudimentary models, such as the balloons inserted loosely into hollowed-out manikins, our design offers an improvement in both training realism and clinical translation. It enables ultrasound-guided needle insertion and fluid removal in anatomically accurate compartments, which helps cultivate procedural confidence amongst trainees, which is extremely important for these high-stakes neonatal surgeries. Widespread use of our manikin could contribute to increased trainee preparedness, which would lead to better patient outcomes.

Future work could focus on several key enhancements. First, improving the echogenicity of some of the internal structures, particularly the heart and the lungs, would allow for better ultrasound visibility. This could be done by possibly experimenting with different contrast agents or layered internal materials. Second, transitioning from the soldering iron-based cavity resealing to a more user-friendly resealing mechanism would most likely reduce clinical maintenance and improve workflow efficiency. Future iterations of the manikin should also aim to refine the modularity of the internal components, allowing a way for individual compartments to be replaced without the need to disassemble the entire model. Finally, as discussed in our final specific aim, a structured training module should be implemented, which would support the standardized training using our manikin.

In conclusion, our neonatal manikin represents a significant advancement in simulation-based surgical training. It bridges the gap between anatomical realism and practical durability and will be implemented within UVA Health Children's Hospital as a way to enhance neonatal training and ultimately contribute to better patient outcomes.

Materials and Methods

We implemented our three specific aims into our product, with our end goal of creating the most physiologically relevant and multi-procedure applicable neonatal manikin. The most important takeaway from this invention was its use in training neonatal surgeons. Our design provides physicians with hands-on experience in performing high-risk neonatal TAPP procedures, which will aid those surgeons in increasing their confidence and skill. By providing physicians with a means to simulate neonatal TAPP procedures, we anticipate the training process for these procedures will become more effective, which will result in greater procedure preparedness for surgeries with real patients (Lopreiato, 2018). While these metrics can not necessarily be measured currently, we hope to see procedural accuracy improvements in future neonatal TAPP surgeries performed by UVA Hospital surgeons.

Our first hurdle in completing the implementation of our specific aims was finding a suitable skin material that was ultrasound-compatible, moldable, fluid-retentive, and puncture-resistant. We found that materials made with silicone are ultrasound compatible, so we focused on finding materials made with silicone for the skin material. We attempted one moldable silicone-based material called EcoFlex, but that material's end product was too sticky and not skin-like enough to practice TAPP procedures with. After trial and error with that material, we tried a tattoo skin material that could be melted together as shown in Figure 5.

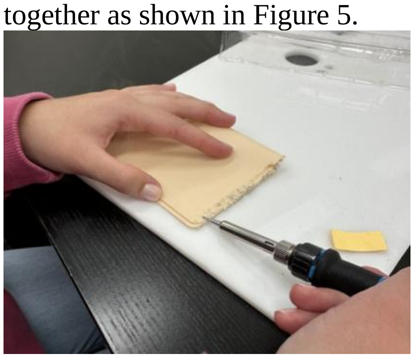

Figure 5: Tattoo Skin Melting Process
We used a tattoo skin to stimulate the abdominal cavity, periodontal cavity, and pleural cavity. These cavities were sealed using a soldering iron.

We ensured the ultrasound compatibility of the material, shown in Figure 6, as well as the puncture resistance by repeatedly puncturing the material. We deemed our tests successful, as the internal structures were visible through the tattoo skin, and no large holes emerged after puncturing the skin.

Figure 6: Testing Ultrasound Compatibility
Our advisor Dr. Wiggins tested the manikin with ultrasound.

Because both of these tests were successful, we then made sure that the tattoo skin could be melted together to mold it to the shapes required for this project. In order to test its melting, we acquired a soldering iron. We used this tool to then melt the skin together to form seamless closed pockets. This was necessary for our project, which required the skin material to mold closely around the structure to best simulate anatomical accuracy. After completing this initial testing on our skin material, we moved forward with the next portion of our project, which was 3D modeling.

Our original idea for this project was to 3D print an entire neonatal model. This idea was quickly replaced, though, as we needed a model that was accurate, hollow, and could have ultrasound applied to it. We thus went with a realistic model of a neonate, which we bought from Amazon. We bought one model that was far too small and had to repurchase a larger model that more accurately represented a newborn baby who might receive a neonatal TAPP procedure, as shown in Figure 7.

Figure 7: Medical Manikin Model
This is an image of our manikin with all of the components inside, including the 3D-printed ribs, the 3D-printed heart wrapped in the skin material, the clay lungs. The peritoneal cavity is shown in Figure 5, and the outer skin is attached via velcro.

This model was hollow, which allowed us to cut into it and place our structures inside of it. The first thing we did with the neonatal model was cut a wide opening into the entire abdomen. We then took the dimensions of the abdomen, which included its length, width, and depth. These measurements were required for the next part of our project, which was 3D modeling the internal structures of the neonatal model. The internal structures needed to fit perfectly inside the abdomen, so taking the measurements before printing was necessary.

After finding that both the skin material as well as the neonatal model worked well for our purposes, we moved on to perfecting the 3D structures for the heart and ribs. We found early on that 3D modeling and printing a lung structure was going to be a waste of our time, thus we decided at that time to model the lungs differently. We eventually decided to use modeling clay to model the lungs, as the most important part of their structure was that they surrounded the heart and pericardium perfectly. Using modeling clay met this need and did not take away from the ability to practice the TAPP procedures with accuracy. We decided to still model the heart and the ribs using 3D-printed structures. We found previously created 3D models for the heart and rib structure from Printables.com via Autodesk Fusion 360. We continued using this application for our 3D modeling due to our comfortability with the design and thus used it to shape, shift, and scale the 3D models to enable them to fit together well. We then 3D-printed the heart and rib structures using the UVA Libraries 3D printers, which allowed us access to a more advanced 3D printer, the Ultimaker, as shown in Figure 8.

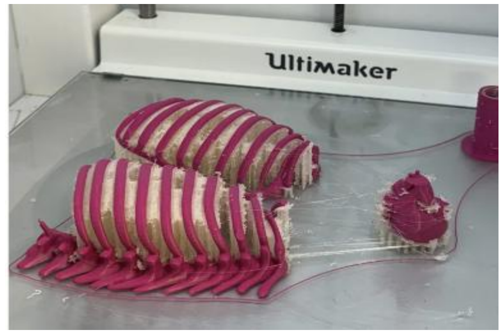

Figure 8: 3D Printed Heart and Ribs
CAD models were found at Printables.com and they were printed using the UVA Libraries 3D printing lab.

Our end products were precise models of the lungs and ribs made of Polylactic Acid, or PLA, which is a type of durable 3D-printed plastic. We ended up printing the structures twice, as the first printing resulted in minor scaling issues. Scaling the model perfectly was required, so after re-scaling it and putting it back through the 3D printer, we had deliverables for the heart and ribs that fit perfectly inside our neonatal model's hollow abdomen. The reprinted rib structure fit perfectly inside the abdomen, and the heart was scaled correctly to the size of the ribs.

We then moved on to the construction of our model. We placed the rib structure inside the hollow neonatal model, and molded clay to the bottom of the model to keep them in precise place when using the model for surgical practice. We created a hollow pocket using the skin material and the soldering iron, which is shown in Figure 5. This pocket became a peritoneal cavity, as it was able to be filled with water to become a fluid-filled space. We also created a skin-enclosed heart by wrapping the 3D-printed heart in the skin material and melting off the excess into a closed shape via the soldering iron. We wrapped that heart with the molded lungs and inserted all of the structures inside the rib cage. The lungs were able to be molded closely to the rib cage, which perfected their structure and enabled more precise placement of the simulated heart and pericardium without moving around. Finally, we placed an external layer of the skin on top of the abdomen and glued velcro on the sides of the stomach as well as on the skin material. This made it so that the top skin patch could be placed and removed with ease, and was reusable.

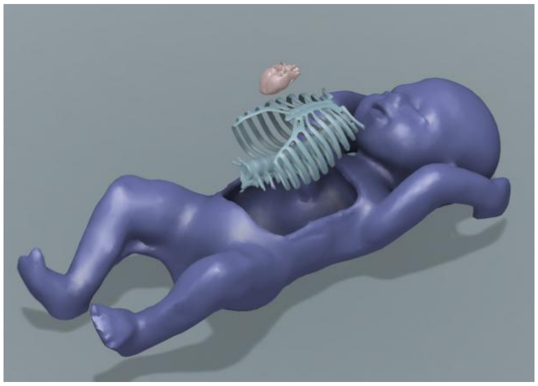

Figure 9: Full 3D Model of our Manikin
Here is a digital 3D diagram of our model.

In completing this model in full, we reached the end of our first specific aim, which was to design an ultrasound-compatible and anatomically correct neonatal manikin. A simulation of our model is shown in Figure 9. Our original specifications were met, as our neonatal body was a biologically relevant size, and all internal structures matched that size. The skin material chosen allowed the ability to be refilled and drained as well as resistance to puncture holes. The model can thus be used repeatedly without compromising the structural integrity, although the skin material does not allow infinite uses.

We then moved on to the validation of our model, which was completed in our second specific aim. We hoped to show the validated neonatal manikin's ability to simulate neonatal pericardiocentesis, thoracentesis, and paracentesis. This required the filling of the replicated pleural space, peritoneal cavity, and pericardium with saline or water and the re-insertion of all of these structures into the structure we created. We did this portion with our advisor, Dr. Jaclyn Wiggins, who is an experienced neonatal surgeon who has completed these surgeries countless times. She practiced inserting the needle into the peritoneal cavity as well as the pericardium and determined that our model was a good representation of an anatomically accurate simulation of neonatal TAPP procedures. Our validation techniques are described in our results section. Overall, Dr. Wiggins agreed that our model would allow physicians to practice real-time, ultrasound-guided fluid removal, simulating conditions during actual TAPP procedures.

End Matter

Author Contributions and Notes

A.E.H, G.I.G, and M.J.P designed research, A.E.H, G.I.G, and M.J.P performed research, A.E.H, G.I.G, and M.J.P built and tested model, A.E.H, G.I.G, and M.J.P analyzed the data; and A.E.H, G.I.G, and M.J.P wrote the paper. The authors declare no conflict of interest.

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