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3D PRINTED TRAINING MODEL FOR ULTRASOUND GUIDED RADIAL ARTERY APPROACH

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Abstract

Background: The transradial approach (TRA) is increasingly favored in interventional cardiology and radiology due to its reduced complication rates; however, mastering this technique requires specialized training that is often hindered by the lack of accessible, high-fidelity simulation models. Methods: This study presents the development of a 3D-printed hand phantom designed for TRA education, utilizing a detailed 3D scan and incorporating materials such as Agar-Agar and flexible resin to replicate human anatomy and ultrasound characteristics. Results: The implementation of the 3D-printed hand phantom for transradial approach training significantly improved participant performance, with pre-workshop mean scores averaging 2.6, while post-workshop scores increased to an average of 4.5 across various assessment metrics, reflecting a 73% enhancement in confidence and proficiency. Furthermore, the statistical analysis revealed a mean intensity value of 109.863 for Soft Tissues, compared to 27.189 and 26.947 for Ballistic Block (10%) and (20%), respectively, demonstrating the phantom's effectiveness in mimicking human tissue properties for ultrasound-guided procedures.Conclusion: The 3D-printed hand phantom serves as a cost-effective and anatomically accurate training tool, enhancing the educational experience for healthcare professionals in mastering the transradial approach.

Keywords: 3D Printing; Healthcare Education; Transradial Approach; 3D-Printed Phantom; Medical Education.

1. Introduction

The transradial approach (TRA) has become increasingly recommended in interventional cardiology and radiology due to its reduced complication rates and enhanced patient comfort compared to the traditional transfemoral approach [1], [2]. Despite these benefits, the TRA technique requires specialized training to master the fine anatomical differences and the associated procedural skills. The inability to access the transradial artery accounts for 57% of all failures in transradial percutaneous coronary interventions (PCI) [3]. The radial artery, measuring between 2.4 and 2.6 mm in diameter [4], approaches the 2- to 4-mm threshold of two-point discrimination detectable by fingertip palpation. High-fidelity simulation models are essential tools in medical education, allowing trainees to practice and refine their skills in a risk-free environment [5], [6]. However, commercially available models are often prohibitively expensive or lack the anatomical accuracy required for effective training. Real-time ultrasound (US) guidance has been shown to improve the safety and efficiency of vascular access in central veins and the femoral artery [7], [8]. To address these challenges, Three-

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dimensional printing (3DP) technology has emerged as a promising solution, enabling the creation of cost-effective, anatomically accurate models tailored to specific educational needs [9].

Additive manufacturing (AM), commonly known as 3D printing, has gained significant attention in recent years due to its ability to produce complex, customized, and anatomically accurate structures directly from digital 3D models. By 3D printing objects layer-by-layer, AM technologies enable rapid prototyping, reduced material waste, cost-effective production, and a high degree of design freedom compared to conventional manufacturing methods. Among various AM technologies, material extrusion processes such as Fused Deposition Modeling (FDM) is particularly attractive because of their accessibility, relatively low equipment costs, and wide range of available materials, including rigid polymers, engineering thermoplastics, and flexible elastomeric materials suitable for medical applications. The flexibility of AM technologies has facilitated their adoption in numerous medical fields, including surgical planning, medical education, personalized implants, prosthetics, and the development of patient-specific anatomical phantoms. Recent studies have demonstrated that 3D-printed phantoms can successfully replicate anatomical structures and tissue characteristics while providing a low-cost alternative to commercially available training models. Furthermore, advances in material development, process optimization, and post-processing techniques continue to improve the mechanical performance, dimensional accuracy, and functional properties of 3D-printed components, further expanding their applicability in healthcare and medical simulation environments [10], [11], [12], [13].

This study focuses on the development of a 3D printed hand phantom designed for educational purposes in the context of the TRA. Our approach demonstrates the feasibility of using 3D printing combined with different materials such to create realistic, cost-effective phantoms for medical training. This paper presents the design, fabrication process, and initial validation of the phantom, with a focus on its application in medical education.

2. Materials and Methods

The creation of the 3D-printed hand phantom for TRA training involved several key steps, starting with the selection and preparation of materials. The first step in the process was obtaining a highly detailed 3D scan of a human hand, which served as the foundation for the model (Fig. 1). The hand used for the scan was chosen to represent average adult anatomy, ensuring broad applicability in educational settings. The 3D scan was performed using the Artec Eva 3D scanner, to capture intricate surface details with a resolution of 0.1 mm. This scanner utilizes structured light technology, which allows for precise imaging of complex surfaces such as the human hand.

Fig. 1. Hand scanned (left) and processed scan into“mesh” file (right)

Once the scan was completed, the data was imported to Solidworks software (Dassault Systems, Solidworks Corps, USA), for analysis, for refining and optimizing 3D models. In Solidworks data was refined to enhance the anatomical accuracy of the model, ensuring that it would replicate the physical dimensions and surface textures of a real hand (Fig. 2).

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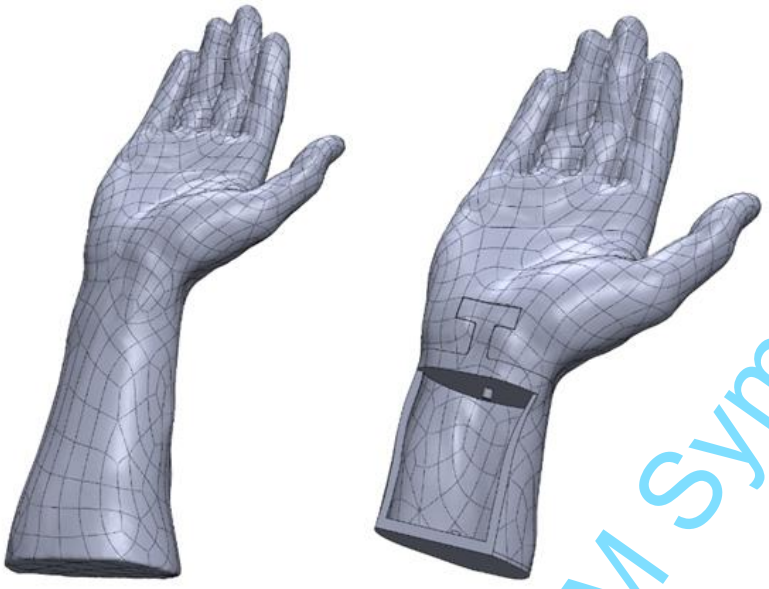

Fig. 2. Importing the hand pattern in "solidbody" format (left) and designing in SolidWorks the final iteration of the usable model (right)

For the soft tissue mimicking we inspected Ballistic Block 10%, Ballistic Block 20 and agar-agar For the simulation of soft tissues, agar-agar was selected as the material due to its favourable ultrasound properties. Agar-agar, a polysaccharide derived from seaweed, is commonly used in medical phantoms because it closely mimics the acoustic properties of human soft tissues, particularly in terms of sound speed and attenuation. The agar-agar used in this study was food-grade, with a concentration of approximately 900 grams per cubic meter (g/m3). This concentration was chosen based on previous studies that demonstrated its effectiveness in replicating soft tissue characteristics under ultrasound imaging. The agar-agar was prepared by dissolving the powder in distilled water, heating the solution to 90°C to ensure complete dissolution, and then allowing it to cool to approximately 40°C before use. To avoid air bubbles, which could interfere with ultrasound imaging, the agar-agar was introduced into the model in a series of slow, controlled pours. The filled hand model was then allowed to set at room temperature for 24 hours, ensuring the agar-agar fully gelled and adhered to the inner surfaces of the printed shell.

Fig. 3. Medical simulation setup using an Ultrasound on a 3D-printed hand model, designed for training purposes

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To replicate the radial artery within the hand model, flexible resin (Flex 80A Resin) was used. Flex Resin is essential for accurately simulating the behaviour of arteries under physiological conditions. The flexible resin was printed using the Formlabs Form 3B (Formlabs, Somerville, MA, USA) stereolithography (SLA) 3D printer. This printer was selected for its high precision and ability to produce complex geometries with fine detail, which is critical when creating structures such as the radial artery. Once the agar-agar had set, the radial artery was carefully inserted into the pre-designed channel within the hand model. The artery was positioned precisely to replicate its anatomical course through the wrist and forearm, aligning with the surface landmarks that are palpated during the TRA.

Finally, the completed hand phantom was tested in a simulated clinical environment, where medical trainees practiced the TRA (Fig. 3). Evaluation was collected from participants regarding the realism of the model, its ease of use, and its educational value. This feedback was used to assess the overall success of the phantom in fulfilling its intended educational purpose.

3. Results

Ultrasound intensity measurements were obtained from various materials used within the phantom, aiming to identify a material that could replicate the imaging properties of human soft tissues effectively. The materials tested included Ballistic Bloc at two different concentrations (10% and 20%), Agar-Agar, and actual soft tissues, with the latter serving as the reference standard. The results offer insight into the intensity values, variability, and overall suitability of each material for educational purposes.

A quantitative assessment was conducted to determine the ultrasound intensity values for each material. The analysis involved calculating the mean, minimum, maximum, and standard deviation of intensity values. These values reflect each material's acoustic properties, providing information on their likeness to human soft tissues, a crucial factor in simulating realistic ultrasound imaging experiences in medical education. Figure 4. provides a boxplot comparing intensity distributions across materials.

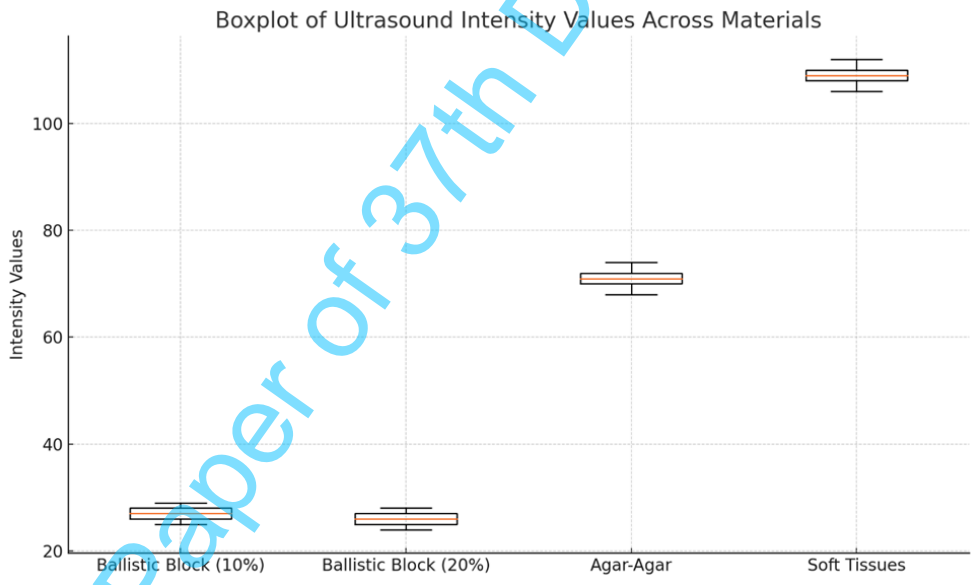

Fig. 4. Illustrates the distribution of ultrasound intensity values across four materials: Ballistic Block (10%), Ballistic Block (20%), Agar-Agar, and Soft Tissues. Each box represents the interquartile range (IQR) of the intensity values, with the central line indicating the median; the whiskers extend to the minimum and maximum values within 1.5 times the IQR, highlighting the spread and variability of the data. The plot clearly demonstrates that both types of Ballistic Block exhibit lower median intensity values compared to Agar-Agar and Soft Tissues, which show greater intensity ranges and median values, indicating their potential effectiveness as ultrasound imaging phantoms.

Figure 5. shows evaluation of the performance for each material to illustrate the mean intensity values alongside their corresponding standard deviations. This plot provides insight into the variability associated with each material and highlights the consistency of ultrasound imaging responses.

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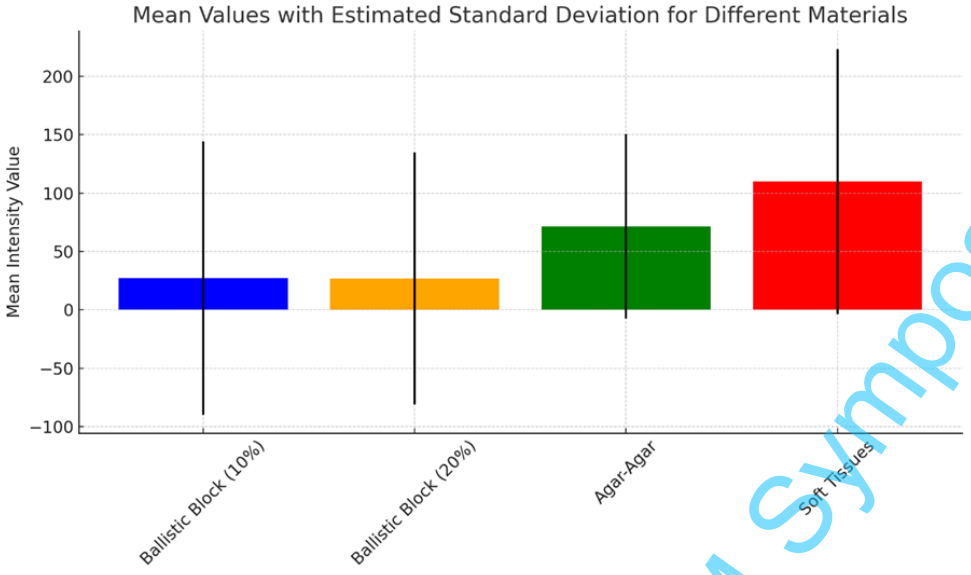

Fig. 5. Displays the mean intensity values along with the estimated standard deviations for four materials: Ballistic Block (10%), Ballistic Block (20%), Agar-Agar, and Soft Tissues. The blue and orange bars represent the mean intensity values for the two types of Ballistic Blocks, both of which exhibit lower intensity values compared to Agar-Agar and Soft Tissues, which are represented by green and red bars, respectively. The inclusion of error bars indicating standard deviation highlights the variability within the intensity measurements, suggesting that Soft Tissues exhibit greater consistency in ultrasound intensity compared to the other materials.

The soft tissue sample shows a high mean intensity with a moderate standard deviation, indicating reliable imaging quality and consistency under ultrasound. Agar-Agar displays a similar mean intensity, though with slightly greater variability, as reflected by the longer error bars. This suggests that while Agar-Agar can approximate the imaging properties of soft tissues, it may present a slightly less stable ultrasound response. Both concentrations of Ballistic Bloc, however, exhibit low mean intensities with considerable variability, indicating they are less suited for replicating soft tissue characteristics in ultrasound imaging.

The large standard deviations observed with Ballistic Bloc materials may be attributed to the heterogeneous nature of these substances, which can result in variable ultrasound reflectivity across samples. This variability, along with lower mean intensity values, renders Ballistic Bloc a less effective choice for transradial educational models where accurate tissue mimicry under ultrasound is necessary.

The effectiveness of the 3DP hand phantom was evaluated through a survey of workshop participants before and after training. Figure 6. compares the pre- and post-workshop scores for various aspects of transradial approach familiarity and confidence in practical skills. The survey assessed participants' understanding of transradial anatomy, confidence in identifying anatomical landmarks, skill in cannulation, comfort with ultrasound use, and their perceived value of the 3D-printed hand model in a clinical setting.

The bar chart in Figure 6. illustrates a significant improvement in mean scores across all categories following the workshop. Pre-workshop scores are represented in blue, indicating an initial baseline of familiarity and confidence, whereas post-workshop scores are represented in green, showing marked enhancement in knowledge and skills after using the 3D-printed phantom.

The most substantial improvements are observed in areas directly related to transradial anatomy and cannulation skills, underscoring the utility of the 3D-printed hand model in practical training. Notably, post-workshop scores in categories like 'Confidence in Identifying Radial Artery Role' and 'Skill in Cannulation' reached near-maximal levels, reflecting participants' increased proficiency and readiness to apply these skills in clinical scenarios. Participants also rated the value of the 3D-printed hand model highly, indicating it as an effective and impactful tool for procedural training.

The findings from this study demonstrate that Agar-Agar closely approximates the ultrasound imaging characteristics of human soft tissue, making it a viable option for educational phantom models intended for ultrasound-guided procedures. The 3D-printed hand phantom, incorporating Agar-Agar, proved beneficial in a workshop setting, enhancing both theoretical knowledge and practical skills among medical students. Given its cost-effectiveness and suitability for ultrasound simulation, this model presents a promising solution for educational institutions with limited resources.

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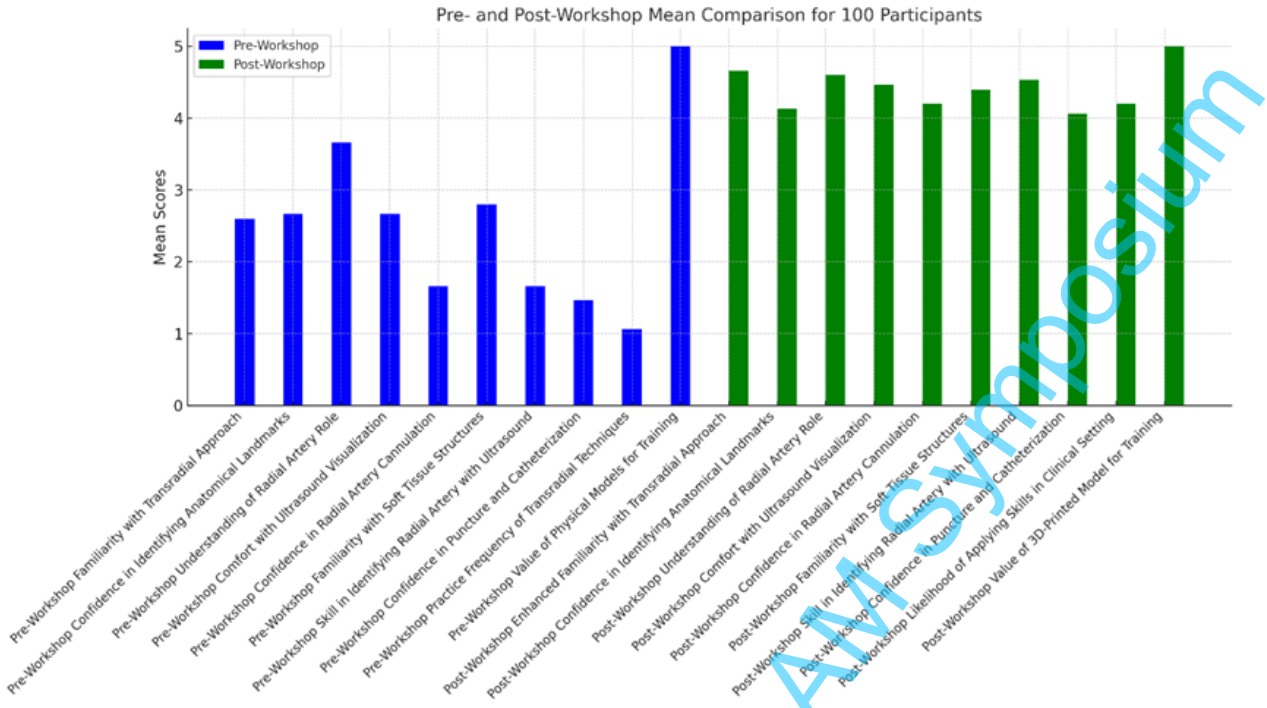

Fig. 6. Comparative analysis of pre- and post-workshop mean scores from participants regarding their familiarity and confidence in performing transradial access procedures. The blue bars denote pre-workshop scores, while the green bars indicate post-workshop scores across various assessment categories, including identification of anatomical landmarks, understanding the role of the radial artery, and proficiency in ultrasound visualization. The marked increase in post-workshop scores across all metrics underscores the efficacy of the workshop intervention, demonstrating significant improvements in participants knowledge, confidence, and practical skills associated with Ultrasound-guided procedures.

These results support the adoption of 3D-printed educational models in clinical training programs, particularly for procedures requiring ultrasound guidance, such as the TRA. Future research could explore additional materials and modifications to further refine the phantom's imaging properties and expand its application across various training scenarios.

4. Discussion

In this study, we developed a 3DP hand phantom to facilitate the TRA for vascular access training. The materials show marked differences in ultrasound intensity, with Agar-Agar and soft tissues presenting relatively high mean values, indicating stronger ultrasound signal return. In contrast, both Ballistic Block concentrations had lower mean values, suggesting lower signal intensity and, thus, less visibility under ultrasound imaging conditions.

The Figure 3. visually represents the intensity value distribution for each material, displaying the median, interquartile range, and variability within the data. Agar-Agar exhibits a higher intensity value compared to both concentrations of Ballistic Block, with the range of values approaching that of actual soft tissues. This proximity suggests that Agar-Agar could be a viable substitute in simulating soft tissue characteristics for educational models. The boxplot reveals a distinct clustering of lower intensity values for Ballistic Bloc materials, indicating reduced ultrasound reflectivity, making them less suitable for applications requiring high contrast and visibility under ultrasound. Previous findings suggest that the concentration of Ballistic Gelatin (BG) for phantoms designed to simulate human muscle tissue should not exceed 10% by weight to achieve optimal biomechanical properties (14). The phantom structures can be molded into various shapes due to its liquid form during the preparation process, offering flexibility for different anatomical models.

The soft tissues, serving as the baseline, demonstrate the expected high intensity, confirming their natural suitability for ultrasound visualization. Agar-Agar follows closely, reflecting an ability to mimic the ultrasound properties of human tissue effectively. These observations suggest that Agar-Agar might serve as a preferable choice in 3DP phantom models aimed at ultrasound-based transradial training.

The development and implementation of a 3DP hand phantom for the educational training of the TRA marks a significant advancement in medical simulation technology. The utilization of 3D scanning and printing techniques,

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combined with materials that mimic the acoustic properties of human tissues, has enabled the creation of a highly realistic and functional model.

One of the primary goals of this study was to create a hand phantom that not only replicates the external anatomy of the human hand but also simulates the internal structures critical to the TRA. The use of a high-resolution 3D scan as the basis for the model ensured that the phantom closely matches the anatomical dimensions and surface features of a real hand. The incorporation of the radial artery within the model, using Flex Resin, provided a flexible, realistic simulation of the artery, which is essential for practicing cannulation techniques under ultrasound guidance (15).

The choice of Agar-Agar as a soft tissue mimicking material was particularly successful, as evidenced by the quality of ultrasound imaging achieved with the phantom. Agar-agar's acoustic properties, which closely resemble those of human soft tissues, allowed for clear visualization of the radial artery and surrounding structures during ultrasound examination. This feature is crucial for training, as it enables trainees to practice identifying and navigating the artery in a manner that closely mirrors real-life scenarios (16).

The feedback from trainees who used the phantom in a simulated clinical environment was overwhelmingly positive. Participants reported that the phantom provided a realistic and challenging experience, allowing them to develop their skills in a controlled, risk-free setting. The ability to repeatedly practice the TRA on a model that accurately simulates both the feel and ultrasound characteristics of a real hand is a significant benefit for medical education. This hands-on practice is particularly valuable for novices, who may require numerous repetitions to achieve proficiency (17).

The ability to produce customized, anatomically accurate models at a fraction of the cost of commercial simulators makes this approach highly accessible for educational institutions, particularly those with limited resources. The adaptability of the 3DP process also allows for the creation of phantoms tailored to specific educational needs, such as variations in anatomy or pathological conditions, further enhancing the educational utility of this technology.

5. Limitations

Despite the successes of this research, several limitations should be acknowledged. First, while the Flex Resin used for the radial artery provided adequate flexibility and durability, it does not perfectly replicate the biomechanical properties of human arterial tissue. Future research could explore alternative materials or composite structures that more closely mimic the elasticity and compliance of real arteries under physiological conditions.

Second, the Agar-Agar gel, while effective for simulating soft tissue in terms of ultrasound properties, is susceptible to degradation over time, particularly in warm or humid environments. This limits the shelf life of the phantom and may require careful storage or periodic replacement of the soft tissue component. Exploring other gel-like substances or composites that offer improved longevity without sacrificing ultrasound fidelity could address this issue.

6. Future Directions

The promising results of this research open several avenues for future research and development. One potential direction is the creation of a full-arm phantom, extending the current hand model to include the forearm and upper arm. Such a model would provide a more comprehensive tool for training in the TRA, allowing practitioners to simulate the entire procedure from access to catheterization.

Additionally, the integration of sensors within the 3DP phantom could provide real-time feedback during training sessions, such as detecting excessive force or incorrect needle angles. This would further enhance the educational value of the phantom by providing objective metrics for assessing trainee performance.

Another area for exploration is the application of this technology to other areas of medical training, such as peripheral intravenous access or arterial line placement in other anatomical sites. The versatility of 3DP technology, combined with materials like agar-agar and Flex Resin, suggests that similar phantoms could be developed for a wide range of procedural training needs.

7. Conclusion

The transradial approach (TRA) is widely used in interventional procedures, but effective training requires realistic and accessible simulation models. This study presents the development of a 3D-printed hand phantom for ultrasound-guided TRA training. A 3D scan of a human hand was used to create the model, while Agar-Agar and flexible resin were used to simulate soft tissue and the radial artery. Ultrasound measurements showed that Agar-Agar provided imaging characteristics closer to human soft tissue than the tested ballistic block materials. The phantom was also evaluated during a training workshop, where participants showed improved scores in anatomical understanding, ultrasound use, and

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cannulation skills after training. The results indicate that the developed phantom can provide a simple, low-cost and realistic platform for TRA training and further development of 3D-printed medical simulation models.

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