

Article

Development and Evaluation of Doppler Ultrasound Training Phantom for Human Vessel Simulation

Nagyum Kim ^{1,2}, Cheolpyo Hong ¹, Changwoo Lee ^{2,*} and Hyo-Min Cho ^{2,*}

¹ Department of Radiological Science, Daegu Catholic University, Gyeongsan-si 38430, Gyeongbuk, Republic of Korea; nagyumkim@kriss.re.kr (N.K.); chong@cu.ac.kr (C.H.)
² Medical Metrology Team, Korea Research Institute of Standards and Science (KRISS), Daejeon 34113, Chungcheong, Republic of Korea
 * Correspondence: cleee@kriss.re.kr (C.L.); chohm@kriss.re.kr (H.-M.C.)

Abstract: The purpose of this study was to create a Doppler ultrasound training phantom aimed at aiding beginners in comprehending and effectively utilizing critical parameters during the learning process. Our designed training phantom does not require the use of a water pump or an automated injector. The fabrication of the vessel-mimicking phantom was accomplished using agarose gel. We utilized LEGO blocks to introduce a height difference that simulated blood flow within the phantom. The imitation blood material was prepared using glycerin. Ultrasound images were obtained using an Accuvix V10 device. This study utilized a Doppler ultrasound training phantom to facilitate stable imaging for beginners during scanning, due to its secure fixation. Furthermore, the fabricated vessel-mimicking phantom offers the advantage of adjusting the diameter of vessels during the fabrication process. Additionally, the easy adaptability, to tailor the phantom specifically for certain conditions by modifying only the vascular components, is another notable advantage. The experimental values for parameters such as the color box, scale, and color gain were collected. The spectral Doppler was used for a rough assessment of blood flow velocity. Color Doppler images, acquired via adjusting the color box to the left and right, displayed blood flow information in blue on the left, and red on the right. At a scale setting of 4 kHz and 0.6 kHz for color Doppler imaging, aliasing was absent at 4 kHz, but appeared at 0.6 kHz. Experiments involving various gain settings (2 dB, 5 dB, 10 dB, 35 dB, 60 dB, and 100 dB) demonstrated that the blood flow information was diminished at 2 dB, and exaggerated at 100 dB.

Keywords: Doppler ultrasound training phantom; color Doppler; color box; scale; color gain



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1. Introduction

Medical Doppler ultrasonography (US) examinations play a central role in contemporary medical diagnosis, by evaluating the hemodynamics of blood flow in the body. Through a non-invasive method, ultrasonographers can assess the velocity and direction of blood flow in real time [1,2]. Furthermore, it serves as an essential diagnostic examination for cardiovascular diseases, providing visual information and quantitative information about blood flow dynamics in real time [3,4].

Color Doppler, one of the Doppler ultrasound examinations, is a diagnostic method that provides both anatomical and physiological information about blood vessels. During a color Doppler examination, a color box is placed within a grayscale image to define the area of interest. It presents information about blood flow within the color box, and it shows the direction and velocity of the blood flow, using different colors [5]. Color Doppler is essential for evaluating blood flow information, and detecting normal and abnormal flow patterns [6,7]. To obtain accurate blood flow information, it is important to optimize color Doppler imaging, by adjusting several parameters, such as the color box, scale, color gain, wall filter, and Doppler angle [7]. Among the parameters of color Doppler, the color box is one of the essential foundational parameters that beginners must become proficient in.

It allows for the visual identification of the blood flow direction, and facilitates intuitive understanding [8]. Additionally, the scale is used as a parameter to adjust an important artifact called aliasing, which occurs in Doppler ultrasound [9]. Beginners studying an ultrasound need to adjust the scale to obtain accurate blood flow information. Gain is used to control the ultrasound reception signals, and the color gain can be adjusted to modulate the blood flow signals [8]. Ultrasound examinations rely on the skill of the examiner. Therefore, in order to understand and optimize color Doppler imaging, it is necessary to achieve a certain standard of expertise and scanning skills, through training and experience.

For beginners, it is beneficial to start training under standardized conditions. However, maintaining such conditions in clinical settings may not always be possible. Therefore, the use of a training phantom to acquire standardized images becomes necessary. Learning with a training phantom provides the advantage of training, without direct patient interaction. This approach allows for the improvement of scanning techniques and the acquisition of knowledge about parameter settings, free from concerns about patient safety and time limitations. Additionally, using a training phantom provides a controlled environment, where errors associated with color Doppler can be identified and corrected. Through actively identifying and correcting errors, it is possible to improve the accuracy and diagnostic skills. However, it is worth noting that most training phantoms available are primarily designed for physician education, specifically for biopsies [10–12].

Typically, a Doppler ultrasound phantom consists of a blood vessel structure, tissue-mimicking materials, and blood flow systems. For the blood vessel structure, some researchers have used the particle image velocimetry (PIV) technique, and quantitatively evaluated the velocities of an abnormal blood vessel [13,14]. There have been many attempts to manufacture abnormal blood vessels using the lost casting technique, with a silicone elastomer [15–17]. Furthermore, recent research has shown that the combination of PIV technology and 3D printing technology has been effectively utilized [18–20]. However, using silicon might result in wall echoes, which could confuse beginners with regard to understanding ultrasound signals [21]. While 3D printing technology is effective in manufacturing complicated vessel structures, it is challenging for beginners, in terms of ease of use and its cost.

To mimic human tissues, researchers have utilized several materials, including polyvinyl chloride (PVC), gelatin, and agarose. While the PVC approach resulted in a robust phantom, with excellent imaging attributes, it necessitated the use of additional materials, such as diethyl hexyl adipate, plasticizer softener, chalk powder, and mineral oil. The fabrication process was also comparatively lengthy [11]. Additionally, the acoustic impedance of the phantom range is from 1360 to 1400 m/s, which is different from the acoustic impedance of human soft tissue (i.e., 1540 m/s) [22]. Gelatin is relatively inexpensive, and provides a similar acoustic characteristic to human tissue, from 1518 to 1535 m/s [23]. However, its quality and elasticity characteristics degrade over time. To minimize biological degradation, a hydrocolloid skin dressing is applied [24]. Nonetheless, its production takes more than 12 h, making it less suitable. In contrast, agarose offers the advantages of a shorter production time and cost-effectiveness, and is simple to make, and may be shaped in a variety of ways. The acoustic impedance of agarose gel ranges from 1489 to 1600 m/s, which is closer to human soft tissue (1540 m/s) than that of PVC and gelatin [25].

In previous studies, the blood flow system used a water pump and an automatic injection [26–28]. This system offered significant advantages, such as precise velocity assessment and real-time blood flow regulation. However, due to the complexity of this system, and the requirement for technical understanding, beginners encountered difficulties in using it. Additionally, when scanning the phantoms at other sites, beginners face limitations in mobility, due to the weight of the blood flow systems.

This study proposes a method for manufacturing a Doppler ultrasound training phantom that is suitable for beginners to learn color Doppler. For beginners, we constructed a Doppler ultrasound training phantom, including normal blood vessels instead of abnor-

mal vessels. To mimic human soft tissue, we used agarose, which has a similar acoustic impedance to human soft tissue. The blood flow systems were developed using a cascaded design, with the bottom surface made of ABS in the form of LEGO blocks and LEGO bricks.

Our intention is to facilitate the comprehension and application of these essential parameters by beginners during the process of learning Doppler ultrasound. The previously mentioned color Doppler, color box, scale, and color gain are important parameters for understanding color Doppler imaging. Therefore, when designing the Doppler ultrasound training phantom, we focused on the color Doppler, color box, scale, and color gain. Furthermore, we focus on the development of a Doppler ultrasound training phantom that demonstrates significant advantages in terms of cost-effectiveness, user-friendliness, and intuitive design.

2. Materials and Methods

2.1. Vessel-Mimicking Phantom

The vessel-mimicking phantom was created using agarose gel (Sigma-Aldrich, Saint Louis, MO, USA) to simulate soft tissue. Agarose gel was chosen as the mimicking material due to its acoustic impedance, which ranges from 1489 to 1600 m/s, similar to that of human soft tissue (1540 m/s). It has a density of 1016 to 1100 kg/m³ and attenuation of 0.04 to 1.40 dB/cm [25,29].

Figure 1a is a frame design used in the making of the vessel-mimicking phantoms, made of acrylonitrile butadiene styrene (ABS). The blood vessel simulation was achieved using a 10 mm ABS rod. The trapezoidal-shaped phantom frame (Figure 1a) had dimensions of 100 mm in height, 50 mm in width, an upper side measuring 40 mm, and a lower side measuring 60 mm. The trapezoidal shape was chosen to incline the upper surface, preventing the beam direction of the probe, and the angle of blood flow, from reaching 90°. Figure 1b is a vessel-mimicking phantom created using the frame shown in Figure 1a.

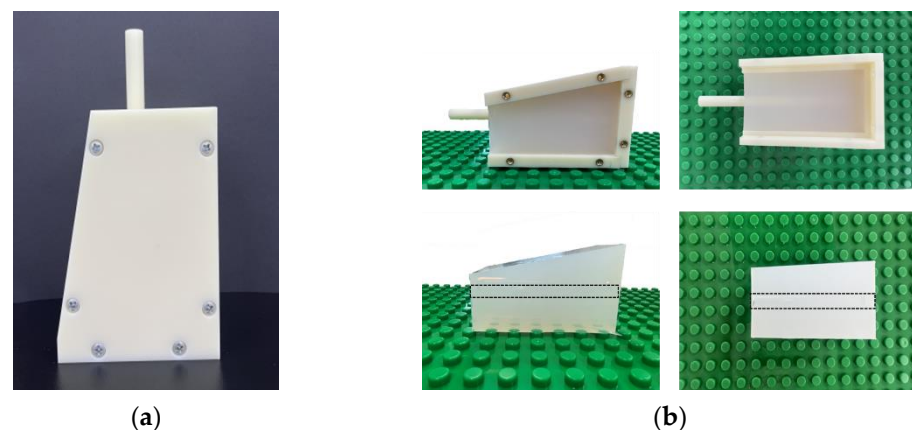


Figure 1. (a) The vessel-mimicking phantom frame. (b) The vessel-mimicking phantom made of agarose gel, photographed from the left and top. The dashed lines represent the simulated vessel.

The production process of the vessel-mimicking phantom is as follows: 2% weight/volume (w/v) agarose gel was added into 300 g of deionized water, and the mixture was stirred using a magnetic stirrer (PC-420D, Corning, NY, USA) at a speed of 260 rpm at 280 °C for 30 min. Observations revealed that the initially opaque mixture began transitioning into transparency after approximately 17 min. After a total of 30 min, the mixture became completely transparent. To remove ultrasound image artifacts caused by air bubbles, a degassing process was carried out for 10 min, using a vacuum degas system (GAST; Model DOA-P704-AA, Benton Harbor, MI, USA), after the completion of stirring. Given the agarose gel's tendency to solidify rapidly, care was taken not to exceed an appropriate duration for the degassing process. Subsequently, the degassed mixture was poured into the trapezoidal frame, as shown in Figure 1a, and left to solidify for 4 h.

2.2. Doppler Ultrasound Training Phantom

The ultrasound training phantom was ingeniously designed to reduce costs by avoiding the need for water pumps or automated injectors. Instead, it takes inspiration from a staircase, mimicking blood flow. Crafted from LEGO bricks and ABS material, the Doppler ultrasound training phantom boasts a unique LEGO shape on its lower ABS surface. Moreover, the LEGO plates provided stable fixation for the phantom, enabling beginners to perform scans with unwavering stability [30]. The design adheres to a LEGO module format, meticulously factoring in the significance of portability and user-friendliness.

Figure 2a illustrates the schematic diagram of the Doppler ultrasound phantom. The schematic diagram of the phantom was created in a top view. It shows the movement of the blood-mimicking fluid from point A (right) to point C (left). The detailed process of conducting the experiment will be explained in the following sentence. The red arrows in Figure 2b represent the flow of the blood-mimicking fluid. The experiment is conducted as follows. Firstly, A is filled with a blood-mimicking fluid made of glycerin, and the valve at A is closed. The vessel-mimicking phantom, shown in Figure 1b, is then inserted in the middle of B. During the examination, the valve at A is kept open, allowing the blood-mimicking fluid from A to flow through the vessel-mimicking phantom, and transfer to C. The experiment continues until the blood-mimicking fluid has completely transferred and filled C. Once the blood-mimicking fluid has been fully transferred to C, the valve is closed. Finally, the blood-mimicking fluid in C is poured back into A.

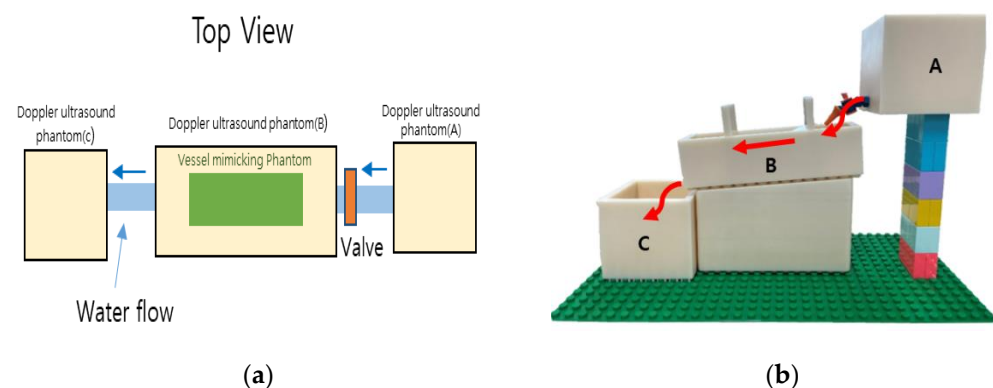


Figure 2. The Doppler ultrasound training phantom. (a) A schematic diagram of the Doppler ultrasound training phantom. The blue arrows indicate the blood flow direction. (b) A picture of the Doppler ultrasound training phantom. A and C phantoms are for filling with water. B phantom is designed for inserting a vessel-mimicking phantom. The red arrows indicate the blood flow direction.

2.3. Blood-Mimicking Fluid

The blood-mimicking fluid was made using glycerin. To prepare the fluid, 50 g of 99% glycerin was mixed with 500 g of deionized water, and stirred at 650 rpm for 30 min, using a stirrer. Glycerin was chosen due to its ability to adjust acoustic properties based on concentration, providing flexibility in controlling the characteristics of the fluid. A glycerin concentration of 10% was selected, to create a blood-mimicking fluid with similar acoustic properties, while minimizing the influence of backscattering [31,32].

2.4. Acquisition of Ultrasound Image and Analysis

The experiments were performed using the ultrasound equipment Accuvix V10 (Samsung Medison, Seoul, Republic of Korea), and a linear transducer (L5-13IS) with a frequency range of 6–12 MHz and a width of 48 mm. Different settings were applied to the color box, scale, and color gain, and we explore the characteristics of the ultrasound images based on the settings of each parameter. Additionally, spectral Doppler imaging was acquired, to provide assessment of the blood flow velocities. I have organized the parameter settings in Table 1.

Table 1. The experimental setup and parameter settings.

	Color Box		Scale		Gain	
	2D	Color	2D	Color	2D	Color
Depth (mm)	45	-	45	-	45	-
Gain (dB)	73	35	73	35	73	2, 5, 10, 35, 60, 100
Dynamic range (dB)	105	-	105	-	105	-
Frame average	10	4	10	4	10	4
Power (W)	90	-	90	-	90	-
Scale (kHz)	-	4	-	0.6, 4	-	4
Wall filter	-	0	-	0	-	0

The first experiment aimed to investigate the characteristics based on the direction of the color box. The color box was steered to the left and right, and the images were acquired accordingly. In the 2D mode, the image settings were configured with a depth of 45 mm, with the focus set at the midpoint of the vessel, at 17 mm. The gain was set to 73 dB, the dynamic range to 105 dB, the frame average to 10, and the power to 90 W. The color Doppler imaging was performed using the following settings: a frame average of 4, a wall filter of 0, a color gain of 35 dB, and a scale of 45 kHz.

The second experiment aimed to investigate the image characteristics based on the scale setting. The scale was adjusted to 4 kHz and 0.6 kHz, and the images were acquired accordingly. Adjusting the scale helps reduce the aliasing artifacts that occur in color Doppler imaging. Aliasing is an artifact in which the blood flow appears to reverse direction because the maximum frequency shift is more than half of the pulse repetition frequency (PRF). To reduce aliasing, the PRF can be increased, ensuring that the blood flow velocities fall within the Nyquist limit ($PRF/2$) [33,34]. In practical ultrasound equipment, increasing the scale setting leads to an increase in the PRF, facilitating the control of aliasing [35]. For the second experiment, the imaging settings in the 2D mode remained the same as in the previous experiment. The color imaging was performed using the following settings, a frame average of 4, a wall filter of 0, a color gain of 35 dB, and a scale adjusted to 4 kHz and 0.6 kHz.

Lastly, in order to examine the ultrasound characteristics associated with the color gain parameter, the color gain was adjusted to 2 dB, 5 dB, 10 dB, 35 dB, 60 dB, and 100 dB. The gain is a parameter that amplifies the ultrasonic signal returning to the transducer [8]. In B-mode imaging, the gain affects the brightness of the image, while in color Doppler mode, the gain impacts the blood flow signals. In color Doppler mode, it is important to adjust the gain appropriately. Increasing the gain allows for a better recognition of low blood flow velocities. However, excessively increasing the gain can lead to the appearance of “bleeding” artifacts, which may obscure the visualization of the vessel surface [36]. In addition, reducing the gain can help reduce artifacts such as “bleeding” [37]. However, caution should be exercised, as lower gain settings may result in the loss of blood flow information. For the third experiment, the imaging settings in the 2D mode remained consistent with the previous experiments. In the color imaging settings, a frame average of 4, a wall filter of 0, a scale of 4 kHz, and gains of 2 dB, 5 dB, 10 dB, 35 dB, 60 dB, and 100 dB were adjusted for image acquisition.

3. Results

3.1. Vessel-Mimicking Phantom

In this study, color Doppler imaging was utilized to assess the ultrasound characteristics with parameter adjustments. Figure 3a shows the 10 mm vessel-mimicking phantom. The yellow arrow indicates the direction of the ultrasound beam, while the red arrow shows the direction of blood flow. Due to the proximity of the left vessel to the transducer compared to the right vessel, it is expected that the ultrasound beam will reach the left vessel faster than the right vessel.

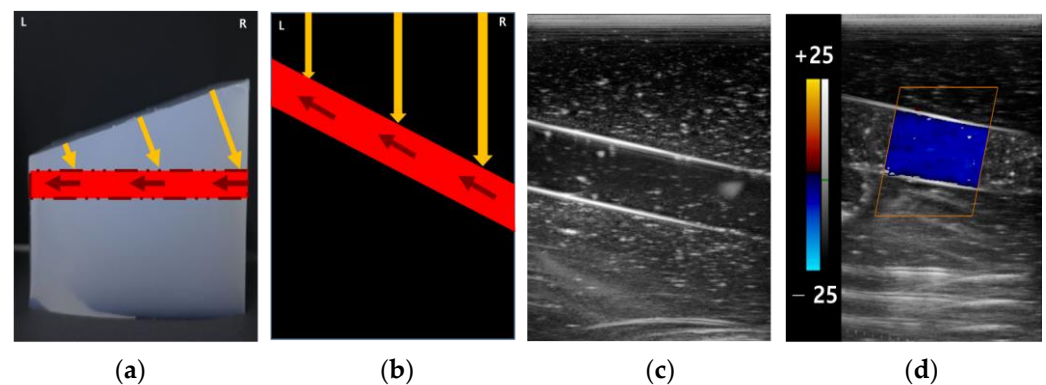


Figure 3. The direction of blood flow and the ultrasound beam. (a) A representation of the direction of blood flow, and the ultrasound beam direction, within the phantom. (b) An image formed via visualizing the information in panel (a), using B-mode imaging. (c) A B-mode image of the vessel-mimicking phantom. (d) A color Doppler image of the vessel-mimicking phantom.

Figure 3b illustrates the visualization of the information regarding the direction of blood flow and the ultrasound beam shown in Figure 3a, using ultrasound B-mode imaging. The ultrasound image is displayed from top to bottom, with the upper part of the image representing structures closer to the transducer, and the lower part representing structures that are further away. Therefore, as observed in the phantom's B-mode image shown in Figure 3c, the vessels closer to the probe appear at the top, while the vessels that are farther away are displayed at the bottom.

Figure 3d displays the color Doppler, the visualization of the direction of blood flow. The blood flow appears as blue, indicating a flow moving away from the transducer. Thus, the color Doppler image provides evidence that the blood flow within the phantom is flowing from right to left.

3.2. The Color Doppler Results

3.2.1. Color Box

Color Doppler acquires blood flow information within the color box, by setting the color box. The direction of blood flow in color Doppler is determined by the color map. In Figure 4a,b, the color map is displayed on the left side. The color map indicates the directions of blood flow. The color at the top (red) represents a blood flow toward the transducer. On the other hand, the color at the bottom (blue) represents a blood flow away from the transducer.

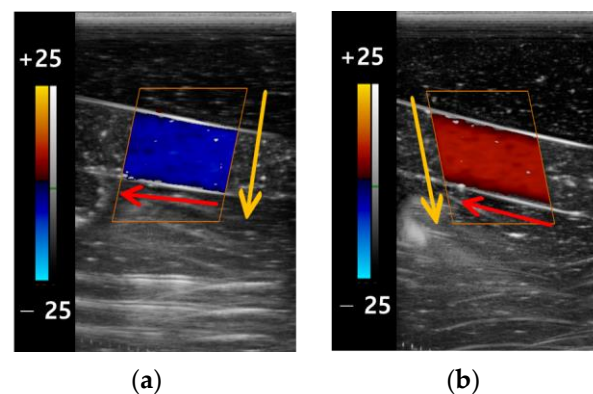


Figure 4. Color Doppler imaging of the color box steer. (a) The color box is steered to the left, (b) the color box is steered to the right. The red arrows represent the direction of blood flow, while the yellow arrows represent the direction of the ultrasound beam.

The blood flow information varies depending on the steer setting of the color box. In Figure 4a,b, the red arrows represent the direction of blood flow, while the yellow arrows represent the direction of the ultrasound beam. Figure 4a shows an image with the color box steered to the left. In this image, the blood flow appears in blue, indicating that the blood flow is moving away from the ultrasound beam [38,39]. In contrast, Figure 4b shows an image with the color box steered to the right. In this image, the blood flow appears in red, indicating that the blood flow is moving toward the direction of the ultrasound beam [38,39]. This experiment demonstrates that the blood flow information appears differently in Figure 4a,b.

3.2.2. Scale

The scale is a parameter that controls the range of velocity displayed in the image. In this experiment, color Doppler imaging was performed with scale settings of 4 kHz and 0.6 kHz. Figure 5a,c display the images obtained with a scale setting of 4 kHz. Figure 5a represents the image with the color box set to the left, while Figure 5c represents the image with the color box set to the right. The Nyquist limit for the scale setting of 4 kHz in Figure 5a,c was 25. As the maximum velocity of the blood flow did not exceed this Nyquist limit, no aliasing artifacts were observed.

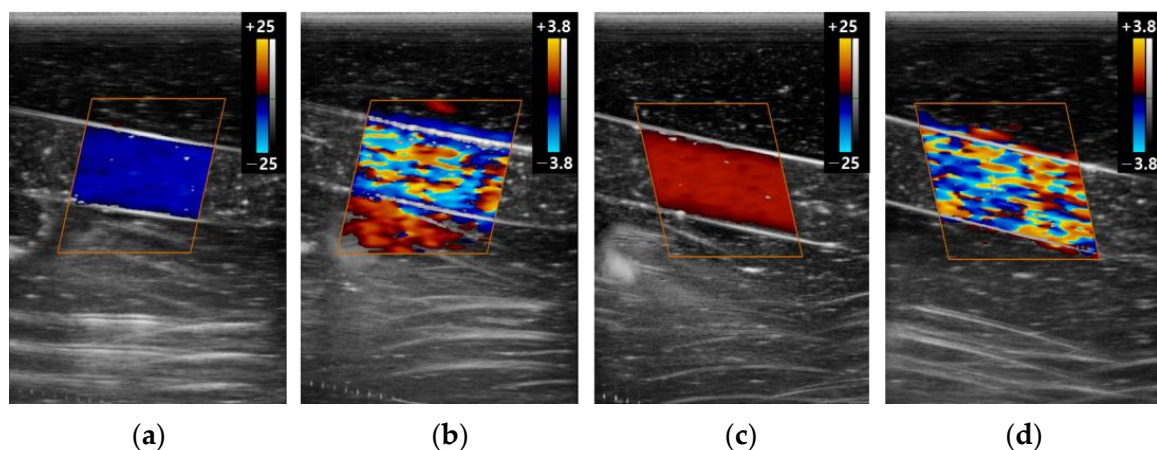


Figure 5. Color Doppler images based on scale settings. (a) Color Doppler with a scale setting of 4 kHz and leftward steer of the color box. (b) Color Doppler with a scale setting of 0.6 kHz and leftward steer of the color box. (c) Color Doppler with a scale setting of 4 kHz and rightward steer of the color box. (d) Color Doppler with a scale setting of 0.6 kHz and rightward steer of the color box.

Figure 5b,d show the images obtained with a scale setting of 0.6 kHz. Figure 5b represents the image with the color box steered to the left, while Figure 5d represents the image with the color box steered to the right. The Nyquist limit corresponding to a scale of 0.6 kHz was 3.8. As the maximum velocity of the blood flow exceeded the Nyquist limit of 3.8, aliasing artifacts were observed. These aliasing artifacts resulted in the appearance of various colors within the vessels, affecting the visualization of the blood flow information.

3.2.3. Gain

In this experiment, color Doppler imaging was performed with gain settings of 2 dB, 5 dB, 10 dB, 35 dB, 60 dB, and 100 dB. Additionally, color Doppler images were acquired via steering the color box to the left and right. Figures 6 and 7 display the resulting images obtained through adjusting the gain to 2 dB, 5 dB, 10 dB, 35 dB, 60 dB, and 100 dB, with the color box steered to the left and right, respectively.

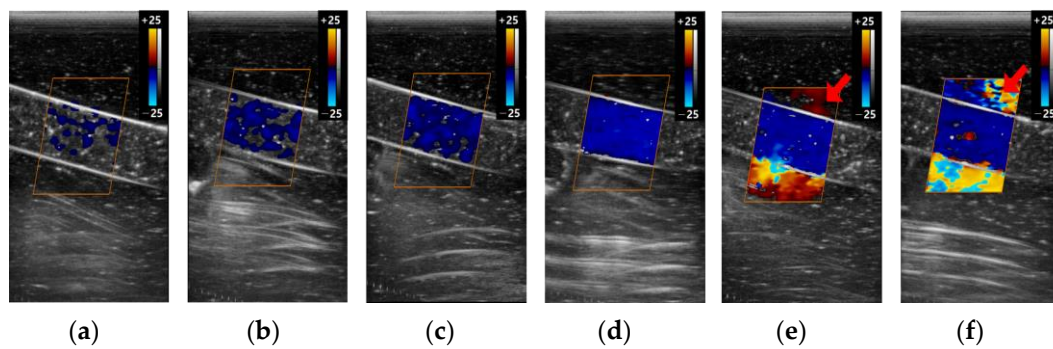


Figure 6. Color Doppler imaging with varying gain settings, using leftward steer of the color box. Color Doppler with a gain of (a) 2 dB, (b) 5 dB, (c) 10 dB, (d) 35 dB, (e) 60 dB, and (f) 100 dB. The arrows in (e,f) indicate the presence of bleeding artifacts.

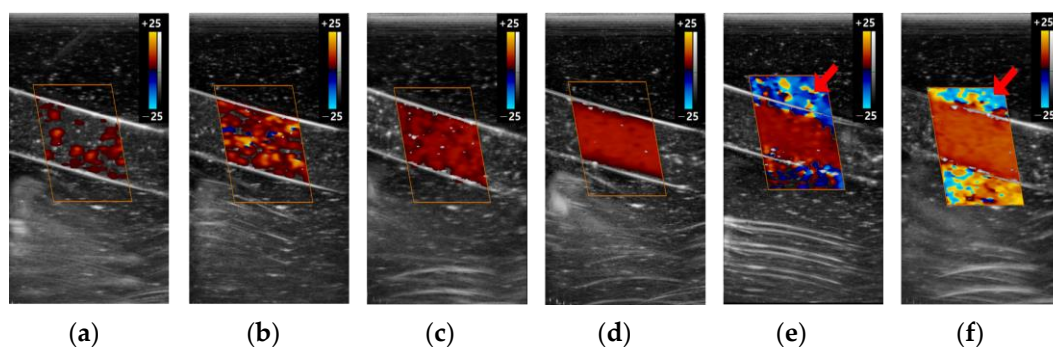


Figure 7. Color Doppler imaging with varying gain settings, using rightward steer of the color box. Color Doppler with a gain of (a) 2 dB, (b) 5 dB, (c) 10 dB, (d) 35 dB, (e) 60 dB, and (f) 100 dB. The arrows in (e,f) indicate the presence of bleeding artifacts.

Figure 6a represents the image obtained with a gain setting of 2 dB, showing a significant loss in blood flow information. On the other hand, Figure 6f displays the image acquired with a gain of 100 dB, indicating an overestimation of blood flow, as indicated by the arrow. As the gain increases, blood flow appears excessively, and becomes difficult to evaluate accurately, due to artifacts such as bleeding, as indicated by red arrows in Figure 6e,f. Conversely, as the gain decreases, blood flow information becomes attenuated, making it challenging to assess properly. Similar observations were made in Figure 7, where the color box was set in the reverse direction. Among the tested gain settings, 35 dB appeared to be the most suitable, as shown in Figures 6d and 7d. To adjust the gain appropriately, it was increased until artifacts appeared, and then decreased until the artifacts disappeared, indicating the optimal Doppler gain [40].

4. Discussion

The main purpose of this work was to introduce methods for manufacturing the Doppler training phantom, and to provide insights into various aspects related to blood flow information. The Doppler ultrasound training phantom was designed to aid beginners in learning color Doppler, and to optimize and evaluate ultrasound images with various parameters. These include the impact of the color box steering direction on blood flow information, the control of aliasing through scale adjustment, and the changes in blood flow information resulting from color gain adjustments. Beginners can use the Doppler ultrasound training phantom to learn how these parameters affect blood flow ultrasound images.

We utilized a gel-based phantom to investigate the effects of the color box, scale, and color gain settings. The linear probe was positioned parallel to the vessels in the phantom, and ultrasound images were acquired with consistent time gain compensation (TGC) settings. When comparing the scale images with the spectral Doppler images, we observed

the absence of aliasing artifacts when the scale image had a Nyquist limit of 25 m/s. This indicates that the maximum blood flow velocity did not exceed 25 m/s. Additionally, the spectral Doppler analysis revealed a maximum velocity of 25 m/s, and an average velocity of 15 m/s. These experimental results demonstrate the consistent measurements of blood flow velocity provided by the Doppler ultrasound training phantom, and indicate its potential for ultrasound education and training purposes.

In the manufacture of the vessel-mimicking phantom, the upper surface was inclined, to prevent the Doppler angle from reaching 90° . The Doppler angle is determined via measuring the angle between the direction of the ultrasound beam and the direction of blood flow. The Doppler angle can be determined using $\cos \theta$. In this context, θ represents the angle between the direction of blood flow and the ultrasound beam. It is important to note that the value of θ and $\cos \theta$ are inversely proportional, with $\cos 0^\circ$ being 1, $\cos 60^\circ$ being 0.5, and $\cos 90^\circ$ being 0. When $\cos \theta$ is 0, it becomes impossible to obtain information about the blood flow [41]. For this reason, in the manufacturing of a vessel-mimicking phantom, a slope is applied to the upper surface. This ensures that the angle formed by the ultrasound beam and the direction of blood flow does not reach 90° .

The tissue-mimicking material for the phantom was manufactured using 2% agarose gel [42–44]. Agarose gel was chosen due to its ease of manufacture and cost-effectiveness [45]. Alternative materials, such as Vyta Flex and gelatin, were considered but, ultimately, excluded. While Vyta Flex offered long-term usability, it had the weakness of poor background visualization. Even with the addition of the 30% scattering agent hydroxyapatite according to weight, the ultrasound images lacked a clear background and well-defined reflection from objects. To address these issues, further research is planned, to explore new additives to enhance the material's characteristics. Gelatin, while only entailing a simple manufacturing process, required approximately 12 h to fully solidify, and the defoaming process was not satisfactory, leading to its exclusion. The agarose gel used in this study also has limitations, such as being prone to easy fragmentation and mold growth due to microbial invasion, resulting in a limited lifespan. However, these issues were resolved through securely fixing the agarose gel within the Doppler ultrasound training phantom frame, to prevent easy breakage. During the experiments, direct contact with the phantom was minimized, and the phantom maintained stability for up to one month via refrigerated storage.

In this study, the design of the training phantom for beginners prioritized efficiency and portability. The Doppler ultrasound training phantom was created using LEGO bricks and ABS material, in a modular LEGO format. The lower ABS surface of the component was deliberately designed to resemble the shape of LEGO blocks. The choice of utilizing LEGO for this purpose stemmed from several key reasons. Firstly, the LEGO plates provided a robust and secure fixation for the Doppler ultrasound training phantom, enabling novice users to carry out scans with stability. Moreover, LEGO offered notable advantages in terms of accessibility, affordability, and user-friendliness. Its flexibility allowed for the formation of various shapes tailored to user preferences. Secondly, through the combination of 12 small LEGO pieces (each sized $4\text{ cm} \times 3\text{ cm} \times 1.5\text{ cm}$), the phantom (Figure 2b of A) was effectively supported, offering the added benefits of reduced weight and enhanced portability compared to the previously designed ABS phantom holder. Additionally, it is easy to assemble and disassemble, and has a high level of reproducibility [46–48]. The Doppler ultrasound training phantom was manufactured in a LEGO format to facilitate portability and user-friendliness, making it intuitive even for beginners. The decision to adopt a staircase-like design was motivated by the goal of avoiding the need for a water pump or automated injector, ultimately minimizing costs. Furthermore, the Doppler ultrasound training phantom, fabricated in LEGO format, enables probe fixation using LEGO pieces, and allows for versatile modifications in various shapes [30,46,47]. We plan to leverage these aspects to enhance the diversity of LEGO-based phantoms. However, it should be noted that the Doppler ultrasound training phantom, which utilizes height differences, may not completely reproduce a continuous flow of blood within the phantom. However, this design choice was made to prioritize portability and ease of use for beginner

training purposes. Despite this limitation, as the Doppler ultrasound training phantom was able to reproduce the flow of blood to some extent, there were no issues with learning the various parameters. If necessary, the water pump can be used to reproduce a continuous flow of blood.

The vessel-mimicking phantom offers the advantage of adjusting the vessel diameter and customization based on user requirements. However, it should be noted that the manufactured phantom does not reproduce the anatomical structure of the arterial wall layers, including the intima, media, and adventitia. Our focus in developing the vessel-mimicking phantom was on assisting beginners in understanding and acquiring fundamental knowledge about blood flow direction and parameters. Therefore, an exact reproduction of the actual structure was not necessary. However, our phantom offers easy customization and optimization for specific target conditions, such as arterial sclerosis and cerebrovascular diseases. By making modifications specifically to the vascular component, it is relatively easy to create phantoms that are optimized for specific target conditions, such as arterial sclerosis and cerebrovascular diseases. This allows for advanced and diversified phantom development.

5. Conclusions

In conclusion, this study aimed to manufacture an affordable educational Doppler ultrasound phantom specifically designed for beginners. The goal was to use this phantom as a tool to enhance the learning process and comprehension of image variations based on different parameter settings. In contrast to traditional methods of creating phantoms, this research adopted a LEGO-based design, eliminating the need for water pumps or automated injectors. Additionally, the accuracy of replicating ultrasound characteristics within the phantom was verified through features such as color boxes, scale variations, and color gain adjustments. Through the Doppler ultrasound training phantom, beginners would be able to visually understand the effect of parameters on ultrasound imaging.

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