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Original Research

Opening the "Black Box" in Transesophageal Echocardiography Teaching: Implementation of 3D-Printed Omniplane Simulator and Heart Models

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Introduction

Current transesophageal echocardiography (TEE) training typically involves didactic sessions, simulation practice, and supervised clinical experience.[1] Among these, simulation training holds particular significance.[2] Evidence from a meta-analysis suggests that, compared with nonsimulation training, TEE simulation training may improve both psychomotor and cognitive skills with a large effect size and result in better training satisfaction.[3] A recent multicenter randomized trial with a large sample size also indicated that clinical fellows in the TEE simulation group displayed higher theoretical test and practical test scores and achieved better self-assessments of their proficiency than those without simulation support.[4]

Most TEE simulations currently rely on mannequin-based simulators[5] designed to replicate real-life TEE procedures and present a range of cardiac pathologies. Although effective in many ways, these simulators have a key limitation: they do not emphasize the internal relationship between the probe's movement and the generation process of ultrasound images. Trainees insert the probe into a nontransparent mannequin and immediately see the resulting image. However, they often neglect how their probe positioning, orientation, or rotation affects the direction of the ultrasound beam and how it intersects the heart. This lack of visual feedback, sometimes referred to as the "black box" effect, can make it difficult for novice learners to understand why a certain image appears and how to manipulate the probe to obtain the desired view (Figure 1).

Without a clear mental model of probe-heart-beam interaction, learners often begin with random or trial-and-error movements rather than deliberate actions aimed at specific imaging goals. Instructors may also struggle to explain these spatial concepts, especially when working with 2D screen images that require learners to mentally translate movements into 3D understanding. These challenges hinder the development of spatial awareness, an essential skill for mastering TEE.

Three-dimensional printing technology has found numerous successful applications in medical education.[6,7] Many projects were primarily aimed at creating standardized models based on image data from patients for anatomy education[8,9] or procedural practice.[10] The potential effectiveness of 3D-printed models in enhancing learning may be because models with actual volume in reality can improve learners' spatial awareness compared with 2D images.[11] Recent research suggests that enhanced 3D visualization and spatial awareness may facilitate surgical planning before skin incisions in orthopedic oncology surgeries.[12] Until now, research on spatial awareness in the field of TEE education has been extremely limited despite the TEE procedure being performed entirely without direct visualization and relying heavily on spatial reasoning.

To address these gaps, we developed an instructional system using 3D-printed components to provide a more intuitive and hands-on understanding of how TEE images are generated. Building on our previous work,[13,14] we designed a teaching tool that allows learners to visualize how their probe manipulations change the orientation of the ultrasound beam and how that beam intersects the heart. In the following pilot study, we evaluated whether this instructional system could improve trainees' image interpretation, image acquisition quality, and confidence by making the internal mechanics of TEE more visible and understandable.

Materials and Methods

3D-Printed TEE Teaching System and Technical Improvements in TEE Probe Simulator (Omniplane Simulator)

This 3D-printed teaching system features a relatively inexpensive way to physically visualize the process of TEE scanning and image formation mechanism using a 3D-printed TEE probe simulator (omniplane simulator) and a set of heart models that can be segmented according to standard TEE views based on our previous work.[13] Participants can visualize the ultrasound scan plane and simulate the scanning process of multiple TEE views in reality and appreciate structures and

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orientations in real time and from various angles, which helps develop their spatial awareness and mental rotation abilities. We further modified this probe simulator by adding a battery-powered laser generator (VLM-650-28 LPT, Quarton Inc, Rowland HTS, CA). This laser generator emits a wedge-shaped laser beam, which, when illuminated on a target surface, appears as a straight line, ie, the projection of the laser scanning plane onto the target surface. This technical improvement aims to better visualize the movements of the TEE scanning plane simulated by the omniplane simulator. The modified TEE omniplane simulator is shown in Figure 2. The laser generator is attached at the center of a rotatable fan-shaped part, which represents the ultrasound scan plane. The laser beam demonstrates the same pattern as a bundle of ultrasound waves and projects a visible straight line on target surfaces. This laser scan plane can also rotate while a pointer displays the omniplane angle on the protractor (Figure 2). This omniplane simulator can be used in combination with a total of 4 types of 3D-printed segmentable heart models we developed in our previous work.[13] To give an example using the ME LAX view, when the relative probe-heart position and the omniplane angle (approximately 120°) are both correct, the laser line projected on the heart model can coincide with a gap, prompting the heart to "separate" into 2 parts along it (Figure 2B). When separated into 2 parts, the cross-sectional shape of the heart model this time is the standard TEE image of a ME LAX view. The sector (marked with "L" and "R") on the probe simulator indicates the left and right orientation of the ultrasound image (Figure 2C). This process is also shown in the Supplemental Material Video.

Study Design and Population

The Strengthening the Reporting of Observational Studies in Epidemiology checklist for research reporting was followed in this study. This pre-post study was conducted at Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, Massachusetts, from January to June 2023. An exempt type of approval from the Institutional Review Board was obtained before the beginning of this study. Anesthesiology residents in their third clinical anesthesia year (CA-3) were eligible to participate on a voluntary basis, and notification of the contents of the study was sent by email to all such residents. Upon enrollment, residents were given randomly generated identification numbers by a computer program to participate in the following process, which was conducted by an independent researcher to minimize bias in the data collection and assessment.

TEE Simulation Training Session with 3D-Printed Models

All residents underwent a TEE simulation training session of approximately 1.5 hours following the same process as shown in Figure 3. The setup of the equipment is displayed in Supplemental Material Figure 1. Assessments of trainees' TEE skill levels were conducted before and after simulation training and from 3 perspectives:

1. Subjectively reported level of confidence in TEE knowledge and image acquisition
2. Objectively evaluated basic knowledge related to TEE views
3. Objectively assessed image quality of 12 basic TEE views acquired on a mannequin-based TEE simulator (CAE Vimedix, Quebec, Canada)

Twelve basic TEE views were selected based on guideline recommendations[15,16] and our experience with views that are of clinical importance and beginner-friendly, including mid esophageal (ME) 4-chamber, ME 2-chamber, ME long axis (LAX), ME bicaval, ME right ventricular (RV) inflow-outflow, ME aortic valve short axis (AV SAX), ME ascending aorta SAX, ME ascending aorta LAX, transgastric (TG) basal SAX, TG mid papillary SAX, TG apical SAX, and deep transgastric (DTG) 5-chamber.

After the presession evaluation, one instructor described the use of this 3D-printed TEE training system and demonstrated how these models can be utilized to obtain those 12 basic TEE views above (Supplemental Material Video, which demonstrates obtaining the ME LAX view from this model. The sample video also shows how the model is rotated in reality to align the orientation with the left and right sides of the ultrasound image). Participants were then given 20 minutes of free learning time with these models, followed by postsession evaluations.

Data Acquisition

Presession and postsession TEE basic knowledge was assessed by 2 basic questions (4 in total) for each of the 12 TEE views selected, including the name, the possible omniplane angle to obtain this view, and the important anatomical structures within. The 4 questions for presession and postsession assessments were similar in difficulty but not identical in content (sample questions shown in Supplemental Material Figure 2).

As for the presession and postsession TEE image quality assessment, we adopted a validated assessment system developed by Ferrero et al.[17] Three independent TEE-qualified researchers scored all images separately, and these researchers were blinded to the participants being evaluated and whether the images were from pre or post sessions. The total image quality score (IQS) for each view consisted of 3 portions (Supplemental Material Table 1): angle score (AS), anatomical structure score (SS), and overall impression score (IS). The majority of views had 3 important structures that must be clearly shown to get full marks (Supplemental Material Table 2). If the structure was recognizable but of poor quality, only 1 mark was given; if the structure was missing from the image, 0 marks were scored.

The 5-point Likert questionnaire obtained confidence in TEE knowledge and image acquisition before and after the session.

All trainees' identifiers were removed from all data for confidentiality as well as blinding for evaluations and scoring processes.

Statistical Analysis

The results of the knowledge assessment score were normalized to a maximum of 100 to facilitate display. The IQS of each view was calculated by the following formulas:

$$IQS_{final} = \frac{IQS_1 + IQS_2 + IQS_3}{3},$$

$$IQS_n = AS_n + SS_{n1} + SS_{n2} + SS_{n3} + IS_n,$$

where IQS_n was from each single evaluator and $SS_{1\text{-}3}$ were the scores for structures 1

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to 3. The maximum value of IQS_{final} is 10. Exceptionally, in ME ascending aorta LAX, only 2 structures were required; hence, all the SS_3 equaled 2 in the formula.

A divergent stacked bar chart was adopted to visualize the Likert questionnaire results. Each option was converted to numerical form for statistical analysis (*extremely not confident* = -2, *somewhat not confident* = -1, *neutral* = 0, *somewhat confident* = 1, *extremely confident* = 2). All analyses were performed with GraphPad Prism version 9.1.0 (GraphPad Software). The Shapiro-Wilk test was used to check the normal distribution of the difference between presession and postsession data: if a normal distribution was detected, a paired Student *t* test was used; otherwise, a paired Wilcoxon signed-rank test was adopted. Data were presented as mean ± SD or median (interquartile range), and a two-tailed *P* value less than .05 was considered statistically significant.

Results

A total of 10 CA-3 residents participated in this study. Demographic information is presented in Supplemental Material Table 3. Most (90%) of the participants had 3–5 months of prior anesthesia rotation experience with TEE.

Presession and Postsession TEE View-Related Knowledge Assessment Score

The presession and postsession TEE view-related knowledge assessment score results are presented in Figure 4A and Supplemental Material Table 4. The average score significantly improved after the simulation training session with 3D-printed models [56.0 ± 22.60 vs 93.5 ± 6.26, $P < .001$, mean difference (MD) = 37.50].

Presession and Postsession Image Quality Score

Figure 4B and Supplemental Material Table 4 summarize the IQS before and after the simulation session with 3D-printed TEE training models. Scores of 8 out of 12 required views obtained from a mannequin-based simulator were significantly improved after the session, including ME 4-chamber, ME bicaval, ME RV inflow-outflow, ME ascending aorta SAX, ME ascending aorta LAX, TG basal SAX, TG apical SAX, and DTG 5-chamber (7.27 vs 8.40, 1.70 vs 7.43, 2.30 vs 7.27, 4.70 vs 7.60, 3.03 vs 7.77, 4.77 vs 7.47, 4.33 vs 7.73, 2.30 vs 7.20, respectively; average MD = 3.81). Positive MDs were also observed in all the results of the other views, but statistical significance was not achieved.

Presession and Postsession Self-Assessment Results

Figure 5 illustrates the 5-point Likert questionnaire results. The first question assessed the trainee's confidence in understanding and memorizing omniplane angles and corresponding TEE views. This result was significantly improved after training with 3D-printed models [1.00 (0.75, 1.25) vs 0.00 (-1.00, 1.00), $P < .01$]. The second question aimed to evaluate the confidence in understanding and interpreting different orientations in TEE views. The postsession confidence level was also elevated [1.00 (1.00, 2.00) vs 0.00 (-1.00, 1.00), $P < .01$].

Discussion

TEE plays an increasingly important role in perioperative patient management,[15,16] and the effectiveness of TEE education directly impacts the widespread application of this technology. The exploration of TEE teaching methods based on 2D images has been relatively comprehensive so far, including online learning tools exhibiting rotatable and segmented cardiac anatomy and corresponding TEE images (examples include the online virtual transesophageal echocardiography website developed by the Toronto General Hospital Department of Anesthesia, https://pie.med.utoronto.ca/tee/index) as well as the simulated cardiac anatomy diagrams that come with traditional mannequin-based TEE simulators. Therefore, we have shifted our focus to increasing trainees' 3D spatial awareness, anatomical appreciation, and reducing the "black box" effect in TEE training utilizing 3D printing.

In this current study, we attempted to address this "black box" effect by filling in the gaps of the educational contents that are missing from the current mannequin-based TEE simulators with these innovative 3D-printed models (Figure 6). Notable improvements were observed in all 3 aspects after the training session with 3D-printed models: TEE view-related knowledge, image quality in basic TEE views, and confidence in understanding TEE mechanisms.

The knowledge tests examined the trainee's ability to recognize 12 basic TEE views and the important structures within. By using 3D-printed models, 2D TEE images can be extended into real-time 3D structures, facilitating the identification of anatomy from various angles in real time. This may be the reason for a significant increase in presession and postsession knowledge assessment scores.

Regarding the improvement in image quality after the training session, because the model simulates the real scanning process and probe movements, we wanted to make this type of simulation lean more toward target-oriented ability training. We define target-oriented ability as the ability of learners to understand how hand movements affect image planes and how probe manipulations slice through the 3D heart model to generate desired views deliberately. For example, before training with 3D-printed models, when the trainees planned to transition from the ME LAX view to the ME bicaval view, many were aware only of adjusting the omniplane angle. However, the actual probe-heart position and image-generation process can be simulated by the 3D-printed models, which demonstrates that the ME bicaval view requires a probe rotation to the right for proper visualization of the right-heart structures. The improvement in image quality after the training session may indicate that this model can guide a target-oriented simulation-based teaching approach.

This teaching system can also enhance trainees' confidence. The explanation may be that it is difficult to imagine complex spatial relationships and anatomical structures from a 2D plane as in traditional video-based learning tools. However, displaying them in 3D space as models with actual volume and haptic feedback makes it easier to understand and remember. This is reflected in surveys assessing confidence in recognizing anatomy, obtaining views, and identifying orientation.

This study has some limitations. The study

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was a pre-post design from a single institute with a small sample size, which may limit the generalizability of the conclusions. The lack of a control group prevents us from more objectively evaluating the absolute improvement in TEE training effectiveness of this teaching system. Although we implemented a blind method, we may still be unable to avoid possible bias from its nonrandomized nature. The reason for recruiting only CA-3 residents was that they had some basic knowledge of TEE and, therefore, did not need additional lectures on the basics of ultrasound (which was also not the focus of this study), but this may also have led to the possibility that the effect of the training session may have been confounded by the impact from the previous TEE training they had received. The lack of follow-up of the trainees' TEE performance in the clinical environment is another limitation of this study. Future randomized controlled educational studies in novice trainees, along with long-term follow-up, will be necessary to further investigate the effectiveness of this 3D-printed TEE teaching system.

Conclusion

We developed and improved a set of 3D-printed TEE training models that can provide educational content that current mannequin-based simulators struggle to deliver intuitively. This study conducted among CA-3 residents showed significant effects of this set of models in improving TEE view-related knowledge, image quality, and learners' confidence. Future larger scale and randomized educational trials will be needed to further investigate its application in TEE simulation training.

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Abstract

Introduction: Simulation training is an essential component of transesophageal echocardiography (TEE) education, particularly for novice learners. However, a critical limitation of current mannequin-based TEE simulators is their inability to emphasize the spatial relationship between the probe's position and the resulting ultrasound images. This limitation, referred to as the "black box" effect, can make it difficult to understand how probe manipulation affects image acquisition, including probe orientation, beam trajectory, and the intersection of the ultrasound beam with cardiac structures. As a result, educators may struggle to convey these critical spatial concepts using existing simulation tools.

Methods: A set of 3D-printed TEE training models was first developed to simulate the steps involved in TEE scanning procedures. They also provide beginners with an intuitive visual representation and a mental rotation process, enhancing their spatial awareness. Then, a pre-post pilot study was conducted among third-year clinical anesthesia (CA-3) residents. Three aspects of teaching quality were evaluated before and after the simulation training with 3D-printed models: TEE view-related knowledge, image quality on a mannequin-based simulator, and learners' confidence.

Results: A total of 10 residents were included in this study. The knowledge assessment score significantly improved after the session (56.0 ± 22.60 vs 93.5 ± 6.26, $P < .001$). Image quality scores of 8 out of 12 required TEE views were also improved. Using the models positively influenced trainees' confidence in understanding and memorizing basic TEE principles: omniplane angles and corresponding TEE views [1.00 (0.75, 1.25) vs 0.00 (-1.00, 1.00), $P < .01$]; orientation interpretation [1.00 (1.00, 2.00) vs 0.00 (-1.00, 1.00), $P < .01$].

Conclusions: A simulation training session with a set of 3D-printed TEE teaching models significantly improved TEE view-related knowledge, image quality, and learners' confidence among CA-3 residents.

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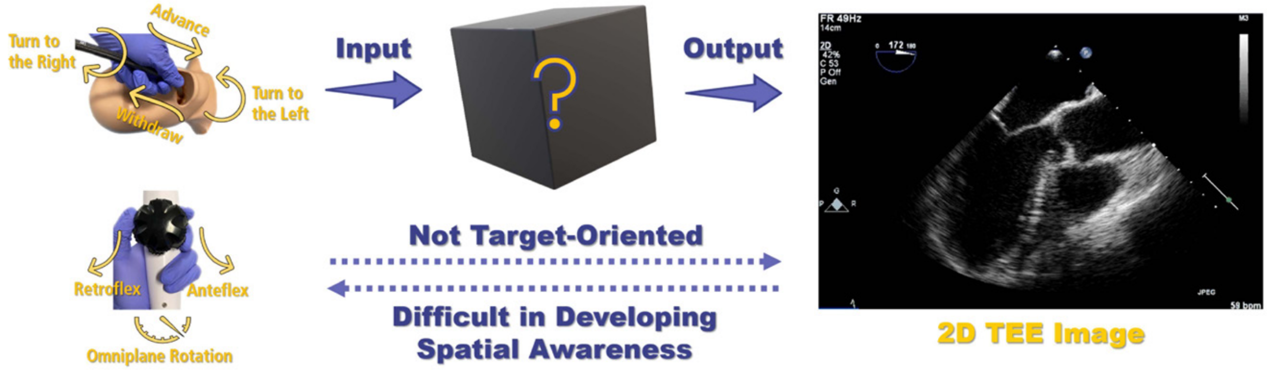
Figures

Figure 1. *The "black box" effect in current TEE simulation training. Hand movements (multidirectional, complex probe manipulations) were input by the trainee into a mannequin-based simulator, which directly output the TEE images. Several critical steps in TEE image formation are hidden from the trainee between input and output, making it challenging to train target-oriented probe manipulations, and it is also difficult to establish spatial awareness for the trainee from the 2D TEE image on the screen. Abbreviation: TEE, transesophageal echocardiography.*



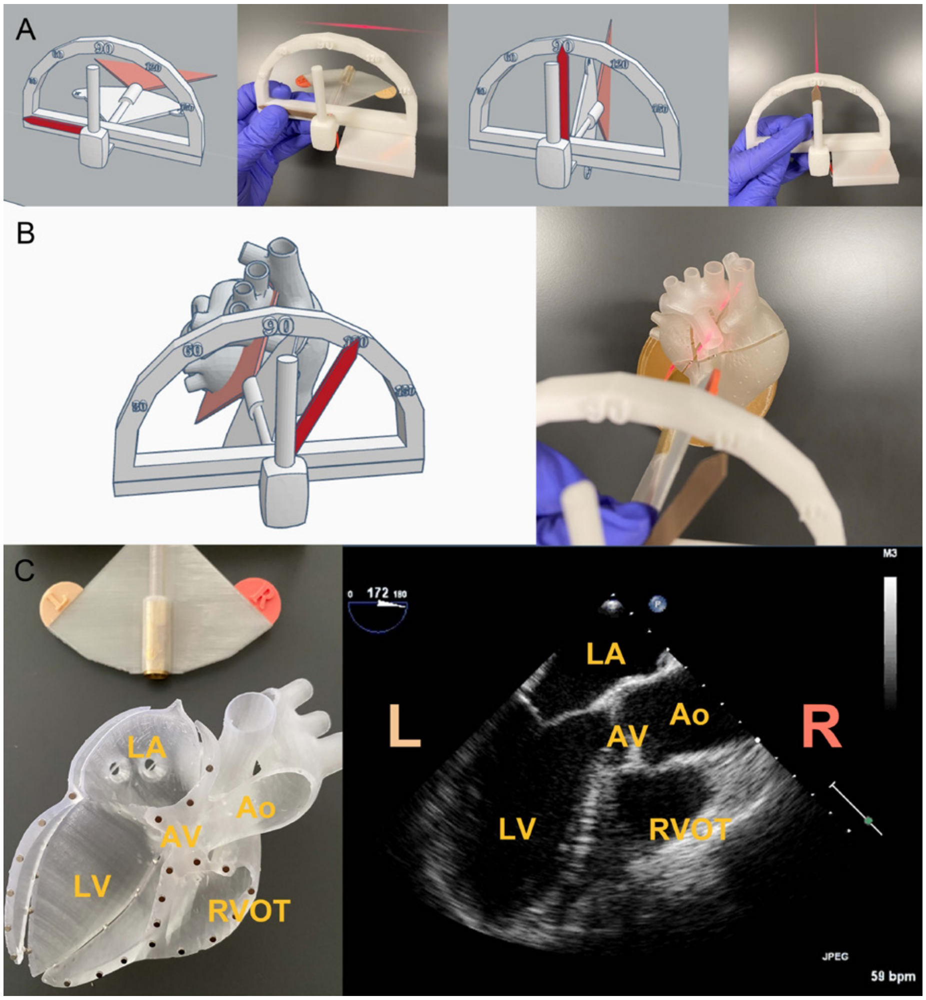


Figure 2. *Improvements in a TEE probe simulator. (A) Based on our previous work, a battery-powered laser generator was equipped with this new type of TEE probe simulator. This laser generator emits a wedge-shaped beam of laser light in the same pattern as an ultrasound probe emits ultrasound waves. This laser beam projects a straight line on the target plane, which is the projection of the laser scanning plane onto that target plane. Finally, this laser scan plane can be rotated along with the sector representing the ultrasound scanning plane on the simulator, whereas the omniplane angle is displayed on the protractor by a pointer. (B) The probe simulator can be used in combination with a 3D-printed segmentable heart model. When the relative probe-heart position and the omniplane angle are both correct, the laser line projected on the heart model can coincide with a gap, prompting the heart to be separated into two parts along this gap. (C) The cross-sectional shape of the separated heart model is the standard TEE image generated when the probe-heart position and omniplane angle are appropriate. The sector (marked with L and R) on the probe simulator indicates the left and right orientation in the ultrasound image. Abbreviations: Ao, aorta; AV, aortic valve; L, left side of the TEE view; LA, left atrium; LV, left ventricle; R, right side of the TEE view; RVOT, right ventricular outflow tract; TEE, transesophageal echocardiography.*

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Figure 3. *Flowchart of the transesophageal echocardiography (TEE) training session with 3D-printed TEE training models.*

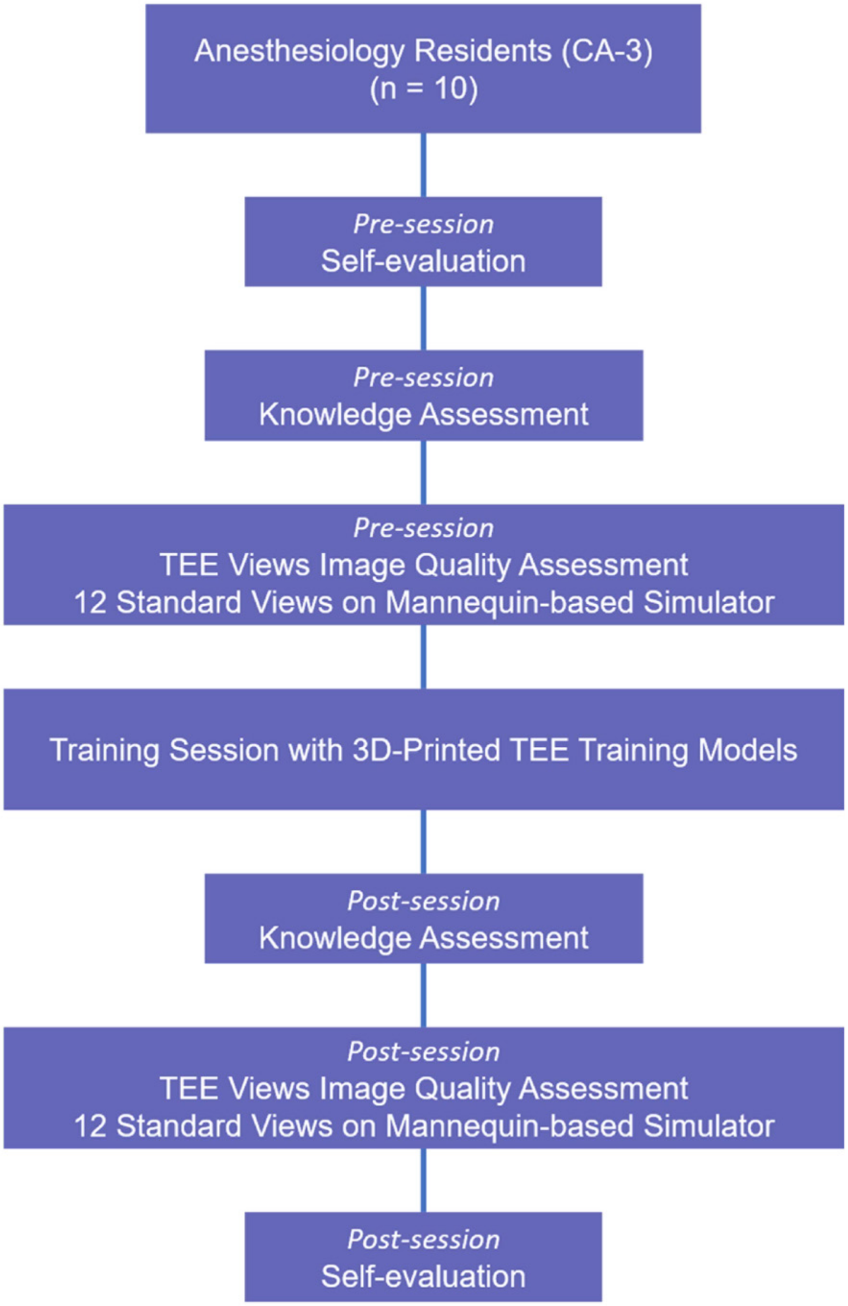

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Figure 4. *Results of the knowledge assessment and image quality score. (A) The knowledge assessment score obtained after the simulation session with 3D-printed TEE training models was improved versus the score obtained before the session. (B) The image quality scores of 12 official TEE views were also evaluated before and after the simulation session with 3D-printed TEE training models. Scores of 8 views were significantly improved after the session, including ME – 4C, ME – Bicaval, ME – RV In – Out, ME – Asc Ao SAX, ME – Asc Ao LAX, TG – Basal, TG – Apical, and DTG – 5C. **P < .01, ***P < .001. Abbreviations: 2C, two chamber; 4C, four chamber; 5C, five chamber; Asc Ao, ascending aorta; AV, aortic valve; DTG, deep transgastric; LAX, long axis; ME, middle esophageal; RV In – Out, right ventricular inflow – outflow; SAX, short axis; TEE, transesophageal echocardiography; TG, transgastric.*

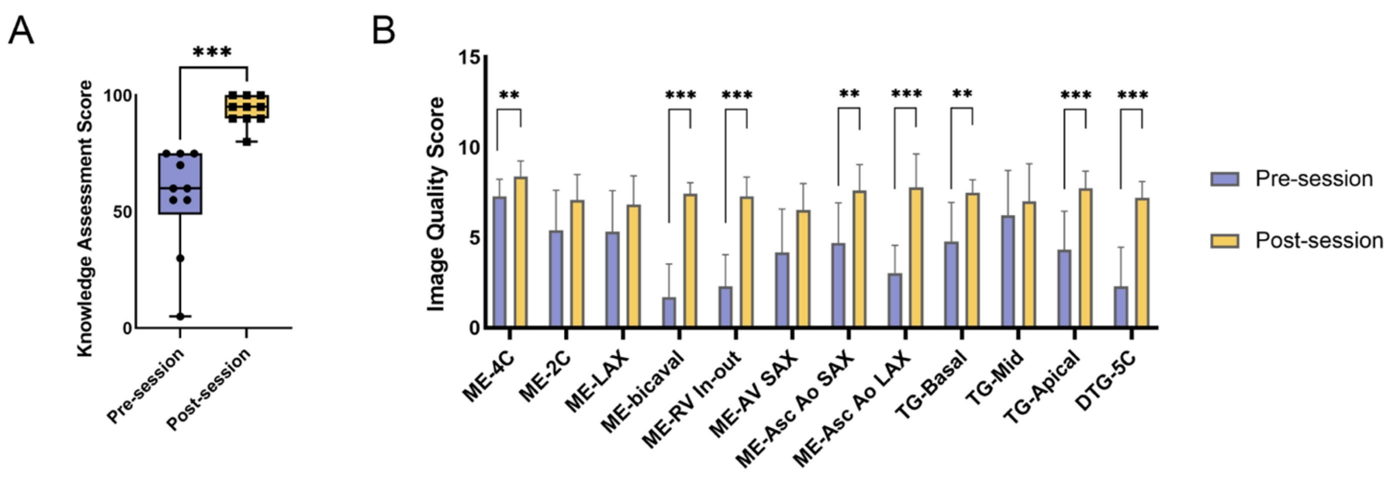

Figure 5. *Results of the self-evaluation questionnaire. Confidence in understanding and memorizing omniplane angles and corresponding TEE views and confidence in understanding and interpreting different orientations in TEE views both improved after the training session with 3D-printed TEE training models. **P < .01. Abbreviation: TEE, transesophageal echocardiography.*

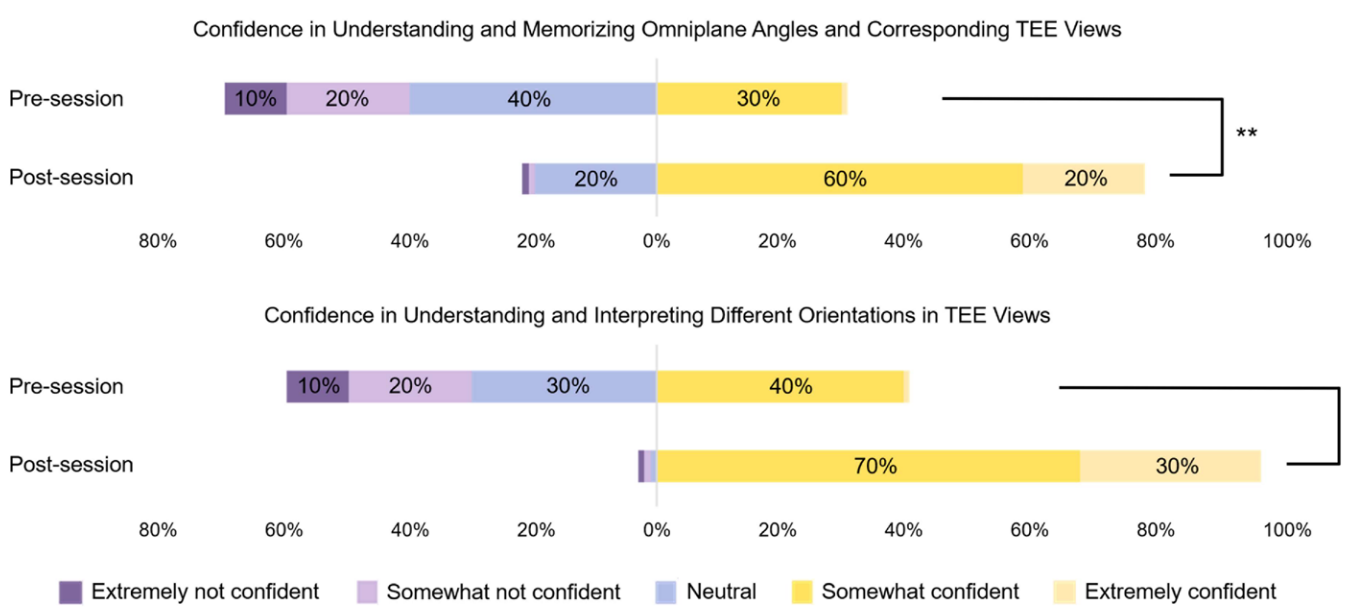

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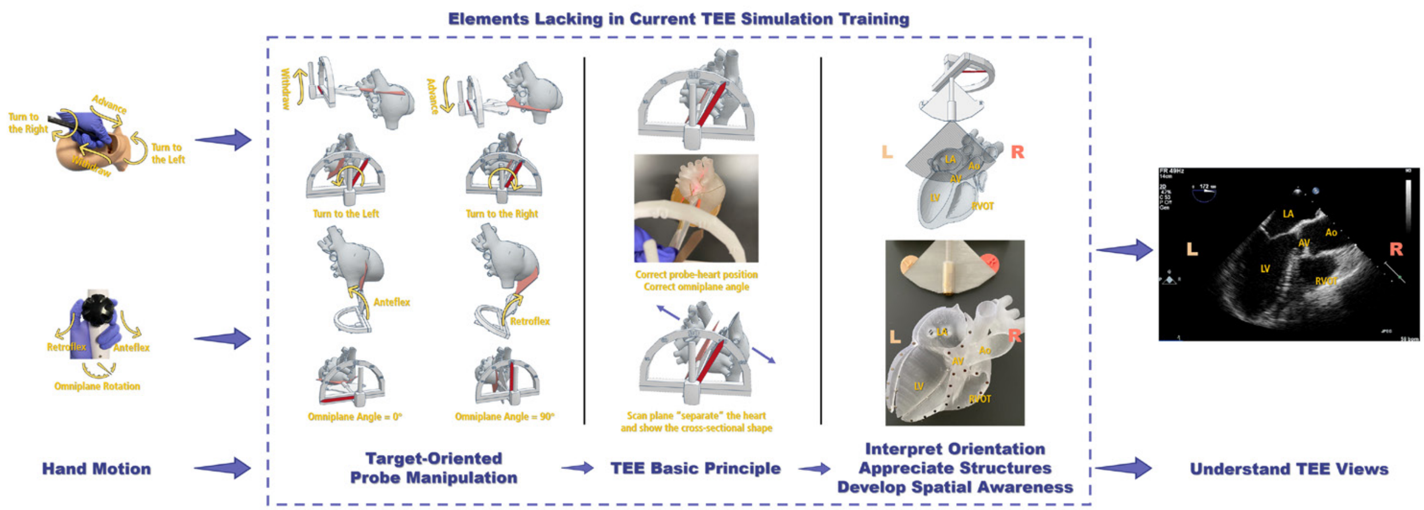
Figure 6. *Three-dimensional printed TEE training models provide essential educational contents lacking in current TEE simulation training, which intuitively bridges the gap between different hand motions and TEE views. Abbreviations: Ao, aorta; AV, aortic valve; L, left side of the TEE view; LA, left atrium; LV, left ventricle; R, right side of the TEE view; RVOT, right ventricular outflow tract; TEE, transesophageal echocardiography.*



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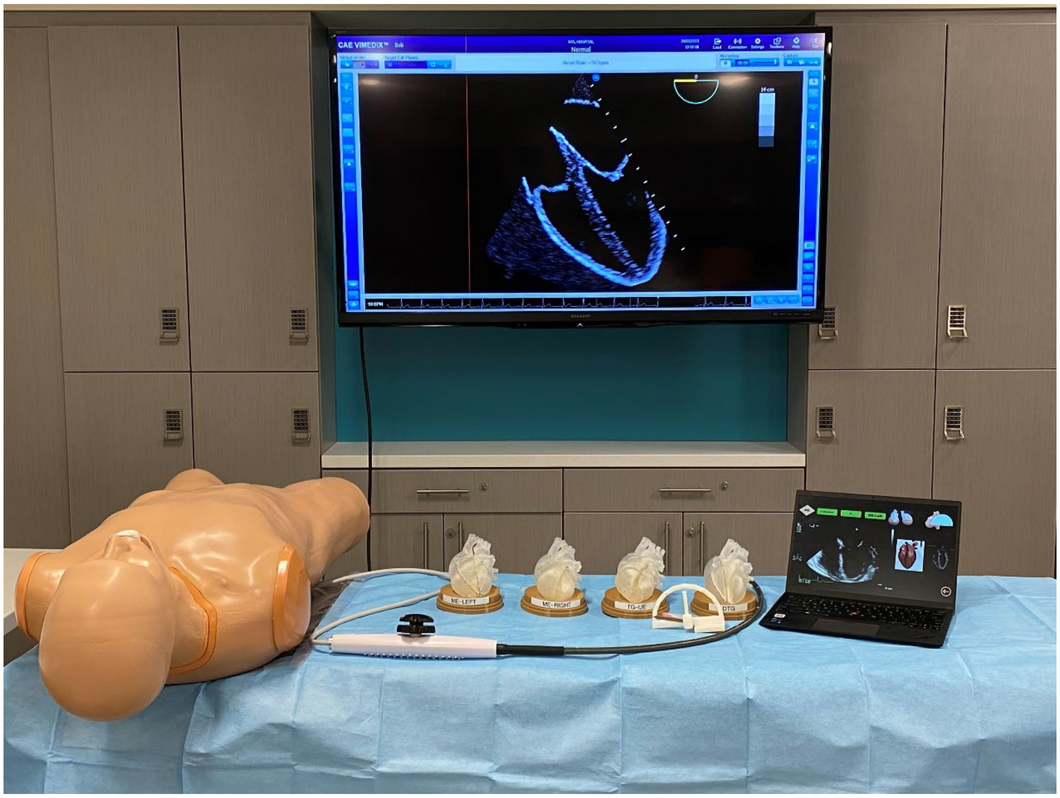
Supplemental Online Material

Supplemental Material Figure. 1. TEE Training Session Setup



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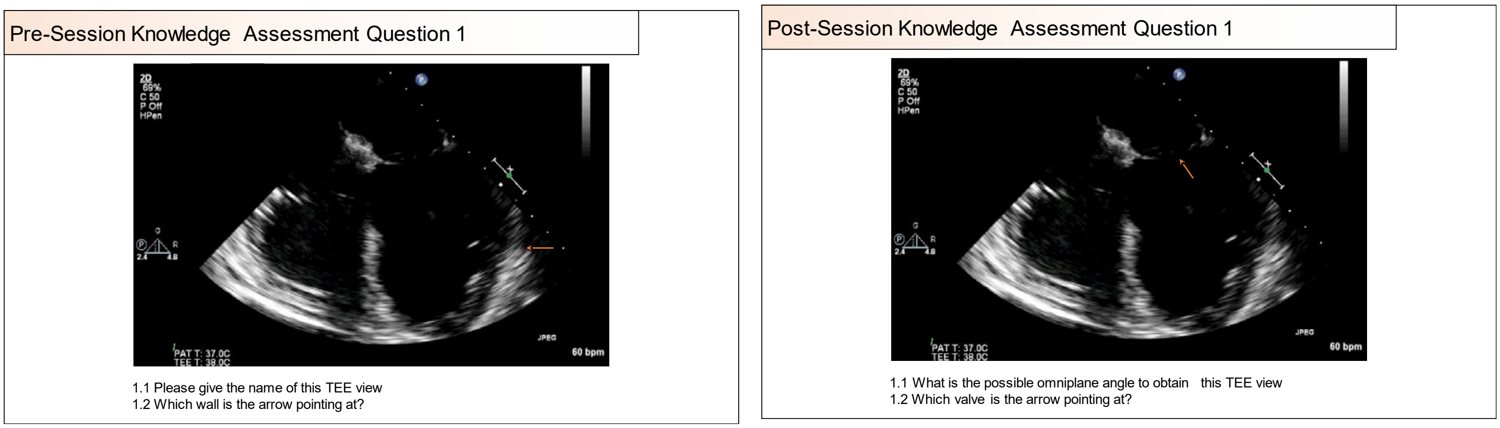
Supplemental Online Material *continued*

Supplemental Material Figure. 2. Sample Questions from the Pre- and Post-Session Knowledge Assessment Tests



Supplemental Material Table 1. Image Quality Scoring System

	Anatomical Structure Scores			
Angle Score	Structure 1	Structure 2	Structure 3	Overall Impression Score
Out of range = 0	Not visible = 0	Not visible = 0	Not visible = 0	Poor = 0
Within range = 2	Visible, fair quality = 1	Visible, fair quality = 1	Visible, fair quality = 1	Acceptable = 1
	Visible, good quality = 2	Visible, good quality = 2	Visible, good quality = 2	Good = 2

Anatomical structures with scores are presented in **Supplemental Material Table 2**.

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Supplemental Online Material *continued*

Supplemental Material Table 2. Anatomical Structures with Scores

Standard TEE Views Required	Anatomical Structures with Scores		
	Structure 1	Structure 2	Structure 3
ME four-chamber	LA	LV	RV
ME two-chamber	LA	LV	MV
ME long-axis	LV	LVOT	AV
ME bicaval	RA	SVC	LA
ME right ventricular inflow-outflow	TV	PV	RV
ME aortic valve short-axis	LCC	RCC	NCC
ME ascending aorta short-axis	Ao	MPA	RPA
ME ascending aorta long-axis	Ao	RPA	/
TG basal short-axis	Ant Leaflet	Pos Leaflet	LV
TG mid papillary short-axis	Ant Pap	Pos Pap	LV
TG apical short-axis	LV apex	RV apex	IVS
DTG five-chamber	LV	MV	AV

ME = middle esophageal; TG = transgastric; DTG = deep transgastric; LA = left atrium; LV = left ventricle; RV = right ventricle; MV = mitral valve; LVOT = left ventricular outflow tract; RA = right atrium; SVC = superior vena cava; TV = tricuspid valve; PV = pulmonary valve; LCC = left coronary cusp; RCC = right coronary cusp; NCC = non-coronary cusp; Ao = aorta; MPA = main pulmonary artery; RPA = right pulmonary artery; Ant = anterior; Pos = posterior; Pap = papillary muscle; IVS = interventricular septum.

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Supplemental Online Material *continued*

Supplemental Material Table 3. Demographic Information

	CA-3 Resident Participant N = 10 (%)
Gender	
Male	4 (40%)
Female	6 (60%)
Other	0 (0%)
Prior Rotation with TEE Experience	
0 - 2 month	0 (0%)
3 - 5 months	9 (90%)
> 5 months	1 (10%)

Supplemental Material Table 4. Results of the Knowledge Assessment and Image Quality Score

	Pre-Session (n = 10)	Post-Session (n = 10)	Mean Difference (post- minus pre-session mean)	*P* Value
Knowledge Assessment Score	56.00 ± 22.6	93.5 ± 6.26	37.50	**< 0.001**
Image Quality Score				
ME four-chamber	7.27 ± 0.97	8.40 ± 0.84	1.13	**< 0.01**
ME two-chamber	5.40 ± 2.22	7.07 ± 1.43	1.67	0.094
ME long-axis	5.33 ± 2.27	6.83 ± 1.59	1.50	0.095
ME bicaval	1.70 ± 1.83	7.43 ± 0.61	5.73	**< 0.001**
ME right ventricular inflow-outflow	2.30 ± 1.76	7.27 ± 1.09	4.97	**< 0.001**
ME aortic valve short-axis	4.17 ± 2.42	6.53 ± 1.46	2.37	0.057
ME ascending aorta short-axis	4.70 ± 2.21	7.60 ± 1.44	2.90	**< 0.01**
ME ascending aorta long-axis	3.03 ± 1.54	7.77 ± 1.86	4.73	**< 0.001**
TG basal short-axis	4.77 ± 2.17	7.47 ± 0.74	2.70	**< 0.01**
TG mid papillary short-axis	6.23 ± 2.49	7.00 ± 2.09	0.77	0.050
TG apical short-axis	4.33 ± 2.13	7.73 ± 0.95	3.40	**< 0.001**
DTG five-chamber	2.30 ± 2.16	7.20 ± 0.91	4.90	**< 0.001**

Data are presented as mean ± standard deviation (SD). ME = middle esophageal; TG = transgastric; DTG = deep transgastric.

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Supplemental Online Material *continued*

Supplemental Material Video Link

https://www.dropbox.com/scl/fi/9ofl2h0a3k8gsoiuy1mv4/Supplemental-Digital-Content-Video.mkv?rlkey=64s4gg3begv5a6zpxoj1fijsa&st=h3v0efam&dl=0
This video demonstrates how to obtain the ME LAX view from this model. It also shows the model rotation in reality to align the orientation with the left and right sides of the actual ultrasound image.