An interactive online 3D model of the heart assists in learning standard transesophageal echocardiography views

Un modèle interactif tridimensionnel en ligne du cœur favorise l'apprentissage des coupes standard en échocardiographie transœsophagienne

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Abstract

Purpose Transesophageal echocardiography (TEE) is becoming a standard imaging tool during cardiac surgery as well as an important diagnostic tool in cardiology and in intensive care, resulting in an increasing demand for TEE training. To address the problem of limited time for learning during TEE studies, we have developed a novel online application that allows users to visualize each of the 20 standard diagnostic TEE views in conjunction with a three-dimensional (3D) heart model that can be rotated and “cut away” above the echo plane to reveal the internal cardiac structures. This study is an evaluation of the educational benefit of this application.

Methods The application was evaluated using a pre-test/post-test design assessing the improvement of subjects' test scores following three days of access to the application.

The subjects were postgraduate fellows in anesthesia, cardiology, and cardiac surgery.

Results Ten subjects showed a significant increase (31%) in their test scores after an average of 130 min of access to the application over a three-day period ($P < 0.001$, effect size = 1.9). Using five-point Likert scales, the users indicated that the application was a useful addition to their training (4.7), they would recommend the application to their colleagues (4.9), and they found the application easy to use (4.4).

Conclusion The large improvement in test scores during a short period of study and the high level of satisfaction across all of the disciplines indicates that the application is a useful adjunctive tool for learning TEE. It is now being used in TEE training worldwide.

Résumé

Objectif L'échocardiographie transœsophagienne (ÉTO) est en passe de devenir un outil d'imagerie standard pendant

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la chirurgie cardiaque ainsi qu'un outil diagnostique important en cardiologie et aux soins intensifs. Par conséquent, la demande de formation en ÉTO augmente. Afin de pallier le problème du manque de temps d'apprentissage pendant les examens d'ÉTO, nous avons mis au point une nouvelle application en ligne qui permet aux utilisateurs de visionner chacune des 20 coupes diagnostiques standard de l'ÉTO en conjonction à un modèle de cœur tridimensionnel (3D) qui peut être tourné et « découpé » au-dessus de la coupe échocardiographique pour révéler les structures internes du cœur. Notre étude a évalué les avantages éducationnels de cette application.

Méthode L'application a été évaluée à l'aide d'une méthode de test avant / après examinant l'amélioration des notes des sujets à l'examen après avoir eu accès à l'application pendant trois jours. Les participants à l'étude étaient des stagiaires post-universitaires en anesthésie, en cardiologie et en chirurgie cardiaque.

Résultats On a observé une augmentation significative (31 %) des notes à l'examen chez 10 participants après qu'ils eurent passé une moyenne de 130 minutes à accéder à l'application sur une période de trois jours ($P < 0,001$, taille de l'effet = 1,9). À l'aide d'une échelle de Likert en cinq points, les utilisateurs ont indiqué que l'application était un ajout utile à leur formation (4,7), qu'ils recommanderaient l'application à leurs collègues (4,9), et qu'ils ont trouvé que l'application était facile à utiliser (4,4).

Conclusion L'amélioration considérable des notes à l'examen en l'espace d'une courte période d'étude et le niveau élevé de satisfaction, indépendamment de la spécialité, indiquent que l'application est un outil supplémentaire utile pour apprendre l'ÉTO. Il est désormais utilisé dans la formation en ÉTO partout dans le monde.

Transesophageal echocardiography (TEE) has gained increasing popularity and widespread use during the last 30 years, particularly for the perioperative management of cardiac surgical patients and to guide treatment for hemodynamic instability in the non-cardiac surgical^{1,2} and intensive care patient population.³⁻⁵ Echocardiography is an excellent tool for diagnosing anatomical and functional abnormalities of the heart.^{6,7} It provides real-time information on a broad range of normal and abnormal cardiac conditions.^{1,8-11} The use of TEE in the operating room and intensive care is often preferred over transthoracic echocardiography due to its superior image quality and the ability to assess cardiovascular anatomy and function without surgical interruption. It is becoming a standard imaging tool intraoperatively during cardiac surgery, as it gives surgeons instantaneous feedback during the

procedure on the nature of the cardiac defect and the success of the repair.^{8-10,12,13} Recently published guidelines have recommended the use of TEE in both cardiac and non-cardiac surgery,¹⁴ which has resulted in an increasing demand for TEE training.

The technical and cognitive skills necessary to perform TEE successfully are usually acquired during fellowship level training¹⁵⁻¹⁸ where, traditionally, learning has been confined to the use of textbooks combined with supervised practical experience. Novices face a steep initial learning curve where basic image acquisition is dependent on simultaneously acquiring probe manipulation skills and an understanding of the 20 standard diagnostic TEE views.¹⁹ An appreciation of basic cardiac anatomy and the identification of cardiac structures in three-dimensional (3D) space is important for acquiring proficiency in probe manipulation. Basic TEE training often takes place in a brief timeframe. For instance, there is limited time to practise acquiring basic views during patient exams while the awake patient is experiencing discomfort in the cardiology echo laboratory or during surgical procedures in the operating room where there is the need for prompt diagnosis. Recognizing the 20 standard diagnostic TEE views and the cardiac structures within must be mastered prior to any assessment of cardiac pathology. To aid the novice practitioner in overcoming these challenges, we have developed a novel online application that allows users to visualize each of the 20 standard TEE views in conjunction with a 3D heart model that can be rotated and “cut away” above the echo plane revealing the internal cardiac structures. The tool was designed to relate anatomic structures of the 3D heart model to the standard echo plane images, providing a time-efficient learning option to supplement current teaching practice. This study was designed to assess the educational utility of this new application among a multidisciplinary group of trainees who were in the early stages of their TEE training.

Methods

Construction of the 3D model

We constructed an accurate heart model using 3D reconstruction from serial CT scan slices of a heart using Osirix (Osirix, Geneva, Switzerland). This volume-based model was then traced in three dimensions using Cinema 4D Version 10.0 (Maxon Computer Inc, Newbury Park, CA, USA) to create a simplified polygon-based model that removed imperfections and smoothed the surfaces for easier manipulation in an interactive teaching application. Surface colour and texture were then applied to the model to produce a realistic rendering of the heart exterior.

Heart rotation around a vertical or horizontal axis was then created by rendering 30 images at 12° increments around each axis. These images were combined into a Web application using Flash (Adobe, San Jose, CA, USA), allowing the user to rotate the heart by clicking on buttons or dragging the mouse over the heart. A 3D model of the TEE probe and the echo plane was combined with the heart model exterior (Fig. 1). Heart model sections were rendered along the echo plane for each of the 20 standard TEE views, allowing the user to see the internal heart structures corresponding to the TEE image (Fig. 2). The TEE image, which is also displayed with the reference point of the probe at the top of the screen, corresponds to the section showing the “cut away” 3D heart model, which is labelled to identify the important cardiac structures (Fig. 3).

The content of the application was reviewed and validated by three experienced cardiac anesthesiologists, a cardiologist who performs weekly TEE studies, and a cardiac surgeon who regularly reviews TEE images in the operating room. Following the assessment of face and content validity, the usability of the application was assessed by observing five subjects attempt to exercise all functions of the application. If the subjects did not exercise all of the features spontaneously, they were prompted to find out if they could accomplish certain tasks, such as

rotating the 3D model. Adjustments were then made to the user interface by adding a Help function and by making the application's features more obvious and intuitive.

Study design

There were two parts to the study, i.e., the validation of the performance tests and the assessment of educational benefit. To determine whether this online application was a useful adjunct to the educational experience of trainees learning TEE, we measured the improvement in their performance on multiple-choice tests using a pre-test/post-test design before and after three days of access to the 20 standard TEE views module. We created two 20-question multiple-choice tests designed to assess the recognition of the standard views and their anatomical structures. Each question showed a video clip of a standard view followed by a question with five possible answers, only one of which was correct. Thus, an individual's test score could range from 0 (0%) to 20 (100%). Following completion of the study, the two tests were made available on our website for trainees to use as self-tests.²⁰ The two tests were validated by assessing their ability to discriminate between novice and experienced echocardiographers. Both tests were administered to five anesthesia fellows with no formal TEE

Fig. 1 The three dimensional (3D) model of the heart is on the left and the transesophageal echocardiography (TEE) image is on the right for the *Mid-esophageal Two Chamber* view. The echo probe (A) and the echo plane (B) can be seen in the 3D model. The 3D model can be rotated around the vertical axis either by using the two buttons with arrow icons below the model or by dragging the mouse over the

model. Each of the 20 standard TEE views can be selected from the drop-down menu or from the forward and back buttons at the top of the screen. The TEE video clip can be played or stopped using the controls below the TEE image. The red and green lines in the TEE clip correspond to the red and green edges of the echo plane in the 3D model

Fig. 2 Clicking on the “View slice” button removes the portion of the heart above the echo plane. The heart can then be rotated around the vertical axis as before

Fig. 3 Clicking on the button with the red and green icon of the echo plane in Fig. 2 rotates the model to position the probe at the top of the screen so that the orientation of the three dimensional model

corresponds to the transesophageal echocardiography image. Clicking on the button with the rotation icon returns to the display in Fig. 2

training and five anesthesiologists who perform TEE studies regularly. The tests were administered online, and the subjects were assigned pairs of eight-digit random numbers that acted as user identification and passwords to login to the test. These pairs of numbers were distributed in sealed envelopes to preserve anonymity of the test results.

Subject selection

Following Research Ethics Board approval, potential subjects were contacted by the study coordinator who obtained consent from those who volunteered to participate in the study. The trainees who were used to evaluate the

educational value of the application were volunteers from a pool of 20 fellows with little or no formal TEE training from the Department of Anesthesia, the Department of Cardiology, and the Division of Cardiovascular Surgery at Toronto General Hospital. Although cardiovascular surgical trainees are not required to conduct TEE examinations, they often consult with the anesthesiologist and interpret the TEE images that are obtained during the surgical procedure. They thus require a good understanding of the structures that are shown in the TEE images.

Assessment of educational benefit

After test validation, we measured the improvement in the test scores of four anesthesiology, three cardiology, and three cardiac surgical fellows following three days of unlimited online access to the 20 standard views module. On initial login, the subjects were required to complete the pre-test. After completing the pre-test, the subjects could then access the 20 standard views module as often as they wished for a three-day period by logging in from any web-enabled computer. Whenever they felt they had mastered the 20 standard views, or after three days, the subjects could then take the online post-test. They could not view the application while they were taking the tests. To balance for possible difficulty between the two tests, the subjects were randomly assigned one of the two tests as a pre-test and the other as a post-test. We subtracted each subject's test results and averaged the difference in scores. We used the Related-Samples Wilcoxon Signed Ranks Test to test the hypothesis that the median improvement in the number of correctly answered questions differed from zero. A P value < 0.05 was considered significant.

Assessment of satisfaction

On completion of the post-test, each subject was asked to complete a brief online questionnaire identifying their specialty, years of postgraduate training, and TEE experience. Satisfaction was measured using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) by asking the subjects to rate the ease of use of the application, whether they thought the application was valuable for their training, and whether they would recommend the application to their colleagues.

Tracking the utilization of the application

The application automatically recorded the date and time of login and each action the user took while using the module. The time per session was calculated by subtracting the login time from the time of the last action. The following actions were tracked: selecting a standard view, clicking on a button to rotate the heart, dragging the mouse

to rotate the heart, clicking on a button to reveal the internal heart structures, and changing the orientation of the opened view to match the orientation of the TEE image.

Results

In the test validation, the TEE experts scored an average of 91% on test 1 and 92% on test 2, while the novices scored 55% on test 1 and 47% on test 2 with no overlap between the scores of experts and novices. The average scores of the TEE experts ($91.5\% \pm 7.2\%$) on both tests were significantly higher than the average scores of the novices ($51\% \pm 13.5\%$) $P < 0.001$. Hence, the multiple-choice tests discriminated between novices and experts.

In the evaluation of educational benefit, the majority of candidates had more than seven years of postgraduate experience, with transthoracic and TEE experience largely confined to participating in echo reading sessions and assessing case studies (Table 1). During the three days in which the subjects had access to the application, the subjects used it for a median of 105.5 min in an average of 3.9 sessions. There was an 31% improvement (95% confidence interval 21–41%) between the mean pre-test score ($51\% \pm 12\%$) and the mean post-test score ($82\% \pm 15\%$) (Table 2) and there was a significant improvement in the median number of questions answered correctly ($P = 0.005$ using the Related-Samples Wilcoxon Signed Ranks Test). Six of the ten subjects achieved a post-test score $\geq 90\%$ (the same performance as the experts). There was no relationship between the time spent using the application and the improvement in score. All users, except one, used all of the features of the program. One user did not rotate the heart model by dragging with the mouse. The satisfaction scores (Table 3) indicated that the users considered the application a useful addition to their training (4.7); they would recommend the application to their colleagues (4.9), and they found the application easy to use (4.4).

Discussion

Current training in TEE involves reading standard textbooks and attending echo reading sessions, continuing

Table 1 Previous echocardiography experience of trainees ($n = 10$)

Number of studies performed	None	Case studies*	1 – 25	> 25
Transthoracic echocardiography	5	4		1
Transesophageal echocardiography	6	4		

* Candidates have participated in echo reading sessions and assessment of case studies

Table 2 Pre- and post-test scores and time spent using the application

Subject Number	Pre-Test (%)	Post-Test (%)	Test Score Difference (%)	Difference in correct answers	Time on site (min)	Sessions
1	45	65	20	4	110	4
2	35	95	60	12	53	2
3	45	60	15	3	104	3
4	60	90	30	6	116	3
5	60	70	10	2	70	4
6	70	95	25	5	131	5
7	45	95	50	10	435	5
8	50	95	45	9	81	3
9	35	65	30	6	94	7
10	65	90	25	5	107	3
Mean	51	82	31	5.5 (median)	105.5 (median)	3.9

Table 3 Assessment of satisfaction: frequency of responses and average response

	Strongly Disagree				Strongly Agree	Mean
	1	2	3	4	5	
Useful for training			1	1	8	4.7
Recommend to colleagues				1	9	4.9
Easy to use		1	1	1	7	4.4

medical education courses, and heart dissection wet labs. Hands-on experience during TEE studies comes from teaching that is supervised by an advanced echocardiographer. Within our institution, cardiac anesthesia fellows receive one month of dedicated echo training during which time they are expected to become proficient in probe manipulation, acquisition of the 20 standard TEE views, and assessment of basic cardiac function and pathology. Since teaching during TEE studies is limited by time constraints that restrict the trainee learning experience, the increasing demand for learning and introducing TEE services within various practices requires novel teaching tools to assist with accelerated and time-efficient learning.^{5,18}

The online learning module introduces the basic knowledge of the 20 standard views required for conducting a TEE study. It can be used both as a teaching aid in the classroom and by trainees for self-study before participating in training sessions with patients. This approach should reduce the time spent learning the 20 standard TEE views during patient exams, allowing instructors and trainees to concentrate on learning to manipulate the probe. It will free up time to learn, diagnose, and assess pathological lesions, to manipulate the probe to perform off-axis views, and to understand how to obtain images in complex cardiac lesions.

Our study found a significant improvement in the subjects' knowledge of the cardiac structures shown in the 20 standard TEE views, with a mean increase in test scores of 31% following review of the application for about two hours over a three-day period. The majority of candidates found the application simple to use; they would recommend it to their colleagues, and they felt it was a useful training tool. The large improvement in test scores during a short period of study and the high level of satisfaction across all of the disciplines indicates that the application is a useful adjunctive tool for learning TEE. This tool could be useful as a study aid in fulfilling some of the basic and advanced objectives as required by the National Board of Echocardiography.

There are a number of limitations to our study. The small sample size may limit generalizing the results to a larger population. The increase in test scores may be attributable, in part, to candidates becoming familiar with the testing process during the pre-testing phase. However, during the test validation, the novices completed both tests in sequence, and their scores on the second test did not show improvement. Our application does not provide the "hands-on" experience of probe manipulation. These skills can be learned outside the operating room or clinic using mannequin simulators, e.g., HeartWorks, (Inventive Medical Ltd., London, UK) or by performing examinations on anesthetized animal models.^{19,21} These settings provide a low stress environment for trainees to practise probe manipulation and image acquisition before encountering patients; however, this educational technology is expensive and has limited availability. Our study did not use a control group, so we did not test whether this technology was better than learning from traditional sources. However, in a recent review of E-learning,²² Cook contends that such comparisons are not worth studying, particularly when the E-learning material is intended as a supplement rather than

as a replacement for traditional learning resources. The post-test was administered immediately following the last use of the module, so there was no measurement of long-term retention of the educational benefit.

On completion of this study, the password protection was removed and the application was made freely available on the Virtual TEE website (<http://pie.med.utoronto.ca/tee>). This accessibility provides a cost-effective tool for institutions to use in teaching the fundamentals of TEE and relating the TEE images to cardiac anatomy. It offers remote centres a good e-learning resource to supplement their TEE training programs. The pre-tests and post-tests used in this study are available on this website for trainees to use as self-tests. Unsolicited E-mails from trainees and medical educators around the world confirm the high regard placed on this application as a resource for teaching and learning TEE. The enthusiasm has been such that clinicians have volunteered to translate the application into Chinese, French, German, Italian, Japanese, Russian, Polish, and Spanish, making it accessible to educators and trainees around the world. We have since added a Guide Sheet to the website and have developed a new interactive online application, Virtual TEE, based on this Guide Sheet to assist trainees in learning to navigate amongst the 20 standard TEE views. We have also added a module providing colour Doppler TEE images for each of the 20 standard views and a section covering spectral Doppler. The application is having a worldwide impact on teaching TEE, with the site attracting approximately 6,000 visits per month from more than 80 countries. Future development will include a TEE simulation allowing users to move a virtual probe to any arbitrary position and display the resulting simulated TEE image.

In conclusion, the large improvement in test scores during a short period of study and the high level of satisfaction across all of the disciplines indicates that the application is a useful adjunctive tool for learning TEE. It is now being used in TEE training around the world.

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Conflicts of interests None declared.

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