EchoComTEE – a simulator for transoesophageal echocardiography

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Summary
Transoesophageal echocardiography (TOE) requires extensive hands-on training, and it is for this purpose we have designed EchoComTEE, a simulator for TOE. It consists of a manikin and dummy probe; according to the position of the dummy probe (tracked by an electromagnetic sensor), two-dimensional (2D) images are calculated from three-dimensional (3D) data sets. Echocardiographic images are presented side-by-side with a virtual scene consisting of a 3D heart, probe tip and image plane. In this way the trainee is provided with visual feed-back of the relationship between echocardiogram and image plane position. We evaluated the simulator using a standardised questionnaire. Twenty-five experts and 31 novice users participated in the study. Most experts graded the simulator as realistic and all recommended its use for training. Most novice users felt the simulator supported spatial orientation during TOE and, as anaesthetists often do not have training in transthoracic echocardiography, in this group the TOE simulator might be particularly useful.

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Echocardiography is a user-dependent image modality that requires extensive training [1]. For the beginner, steering the probe and spatial orientation are two of the most difficult tasks. Due to the semi-invasive nature of transoesophageal echocardiography (TOE) the availability of hands-on training is limited. However, the demand for TOE is increasing [2]. Simulators are used increasingly in medicine to train doctors in procedures or emergency situations [3, 4]. TOE is especially suitable for simulation because the feedback from the simulator comprises images and not complex reactions of biological systems [5]. We have developed a TOE simulator based on our previously reported simulator for transthoracic echocardiography (TTE), which was evaluated positively [6]. We hypothesised that the advantages and acceptance of simulator training we found with the TTE simulator would be even greater with the TOE simulator.

Methods

Simulator
The simulator consists of a manikin within an electromagnetic field, in which a dummy TOE probe can be inserted (Fig. 1). This probe has the same mechanical properties as a real TOE probe. A 3D electromagnetic tracking system (Patriot^{TM} digital tracker, Polhemus, Colchester, VT) attached to the tip transmits its position data to EchoComTEE, which is installed on a standard PC (Fig. 2). All probe manoeuvres such as advancing, withdrawing, turning, ante- and retroflexion, flexion to the right and left are tracked, transmitted to the PC and visualised on the screen. The functionality of the tracking system is described in detail by Martin et al. [7].

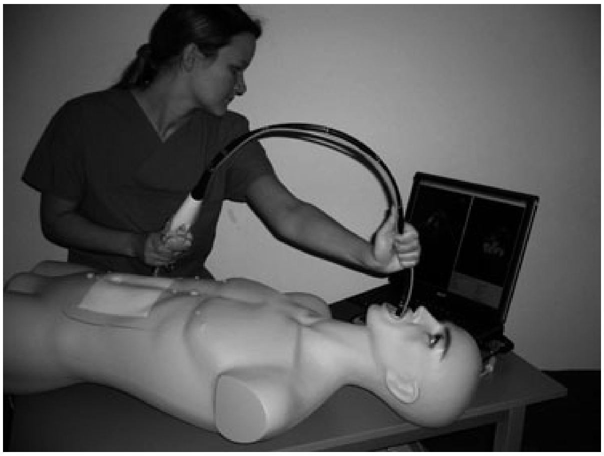

Figure 1 Setting of the TOE simulator.

3D echocardiographic data sets

Echocardiographic data sets were obtained from a Vingmed System V scanner (Vingmed Sound A/S, Horton, Norway) attached to a workstation with dedicated software for 3D reconstruction (4D EchoScan, TomTec GmbH, Munich, Germany). The technique of 3D echocardiography is described in detail by Nosir et al. [8], and Vogel et al. [9]. Theoretically, every 3D data set, regardless of the acquisition mode, can be integrated. Data sets were recorded by stepwise rotation with the transducer placed on the apex. Because of the transducer position the data sets do not contain supracardiac structures (for example, the aortic arch) or the right ventricular free wall.

Augmented reality scene EchoComTEE

EchoComTEE is based on the concept of augmented reality. Augmented reality couples virtual with real data (in particular, 3D image data). In contrast to virtual reality environments, in which the real world is totally replaced, in augmented reality applications the user remains in the real world and interacts with real image data. The purpose of the added virtual data is to increase the information content of the real image data, not to replace it [10, 11]. In EchoComTEE an animated, beating virtual heart is registered with 3D echocardiographic data sets to achieve spatial and temporal congruence. In addition to the heart, the scene consists of a virtual image plane and probe tip. Based on the data of the position sensor attached to the dummy probe, 2D echocardiographic images are calculated from the model and from 3D echocardiographic data sets. The echocardiographic images and the position of the probe are represented side-by-side on the computer screen to support visual understanding of the relationship between probe position, heart anatomy and 2D image. To increase ease of use and acceptance, we designed EchoComTEE as a simple 'Windows' interface (Fig. 2). Rotation of the image plane (forward and backward rotation from 0° to 180°) happens without probe movement. Thus the 3D tracking systems would not detect it. We have attached buttons at the probe handle simulating electronically controlled rotation. By

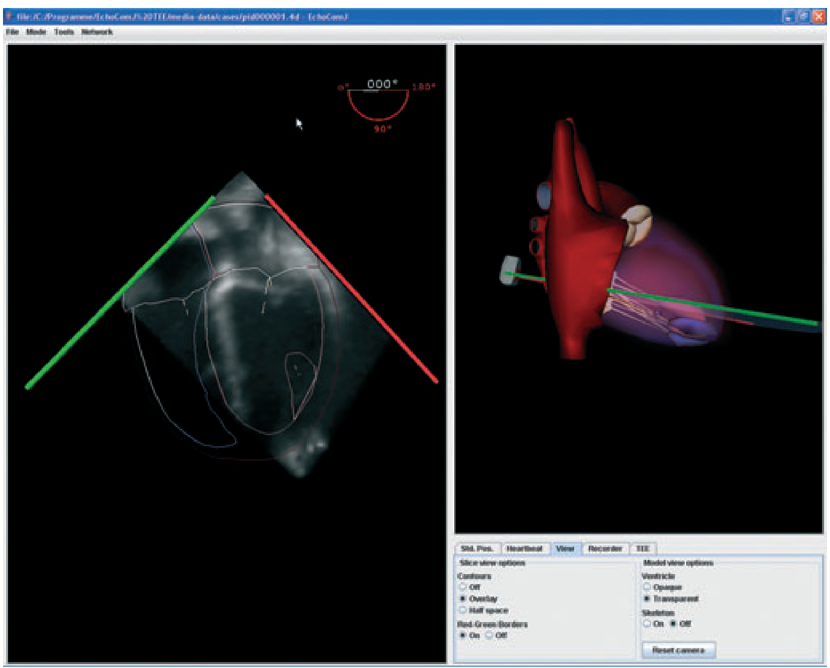

Figure 2 Screenshot of EchoComTEE. Visualised in the virtual scene (right window) are the heart, image plane and probe in a lateral projection. Visualised in the left window is the corresponding echocardiographic image, in this example a four chamber view. The contours of the heart model that are intersected by the virtual scan plane are optionally projected upon the echocardiogram to simplify identification of the structures. At the top the degree of rotation of the image plane is indicated. On the bottom right is a control panel with different menus, e.g. to control the heart rate or for different visualisation modes. The heart can be tilted, rotated or zoomed.

pressing the buttons the image plane is rotated by 1° steps as in real TOE (Fig. 3). Commands are transferred to the PC via USB. The echocardiographic images are then calculated from the image plane position in the usual fashion [12]. As the 2D images are derived in real time they are not restricted by prerecorded views and the beginner can interactively explore the heart by manipulating the dummy probe. There are multiple options to interact with the 3D scene to explore this spatial relation, e.g. rotating, tilting, zooming and shifting the heart. It is possible to add a virtual thorax and to visualise the ventricles transparent to view the valves. The technical details of the system are described in detail elsewhere [12].

Evaluation

We evaluated the simulator within board-certified courses in TOE for anaesthetists (German Society of Anaesthesiology) that were conducted at our institution and during a national meeting of cardiothoracic anaesthetists. We hypothesised that experts graded the simulator as realistic and would find it useful for education. Beginners without experience in TOE could not judge the realism of the simulator and cannot comment on its usefulness for TOE training. However, they can comment on specific skills they have to acquire. We hypothesised that the simulator supported novices, learning probe handling, spatial orientation and standard plane adjustment. As motivation is an important aspect in education they were asked whether the simulator was easy to use and fun to use. Following written informed consent, the simulator was introduced to the participants in small groups of four or five. Groups consisted either of experts in TOE (defined as having done > 100 examinations) or beginners (defined as having done < 10 examinations). Each group had 30–60 min in which to use the simulator. Experts received a short introduction to the simulator functionality and explored the simulator afterwards intuitively. Beginners were asked to adjust standard planes according to the recommendations of the American Society of Echocardiography and the Society of Cardiovascular Anaesthesiologists [13]. The main focus was on midoesophageal views and transgastric views of the left ventricle. Right ventricular structures such as the free wall and the pulmonary valve were not within the 3D echocardiographic data sets. However, these structures are visualised by the contours of the heart model. Right ventricular standard views were trained using these contours. At the end of the session each participant completed a questionnaire with statements based on a rating scale of 1–5 and yes/no questions. Rating scales were analysed using the proportional distribution.

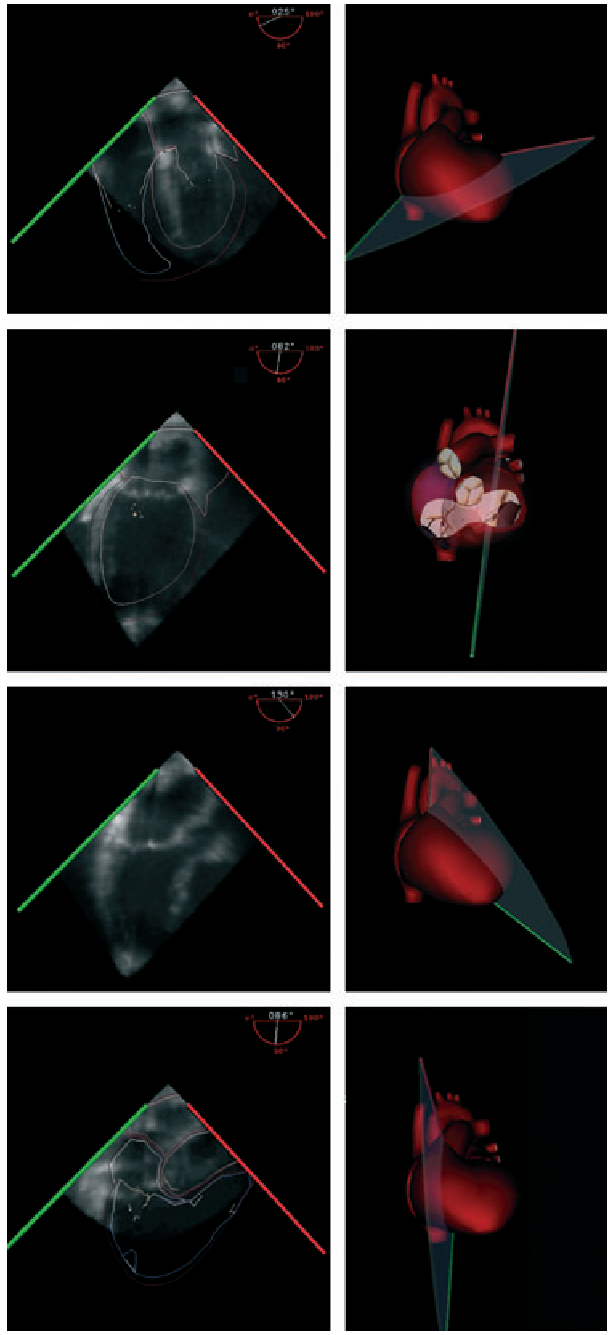

Figure 3 Rotation of the image plane from 25° to 130° (first three pictures). The virtual heart is oriented in an antero–posterior projection. In the second picture the chambers are visualised transparent. In the third picture the contours of the virtual heart are not visualised in the echocardiographic image. The lower right picture shows a rotation of the probe to the right to visualise the right side (right ventricular inflow-outflow view). Since the RV free wall is not included in the echocardiographic data set, only the contours of the heart model are visualised.

Results

A total of 25 experts and 31 beginners participated in the study. All participants were anaesthetists (either certified or in training).

Experts

Of the experts, 52% had done between 100 and 1000 examinations and 48% more than 1000. The results of the questionnaire are depicted in Fig. 4a. The dummy torso was judged realistic or very realistic by 82%, and the probe handling as realistic or very realistic by 68%. Sixty-six per cent found the 2D echocardiograms comparable to real 2D images. All thought that the simulator effectively demonstrated the spatial relation between the heart/probe and resulting echocardiographic image. Almost all thought that the simulator prepared well for real TOE examinations and that proficiency in TOE might be accomplished more quickly with it. All would recommend the use of the simulator for training.

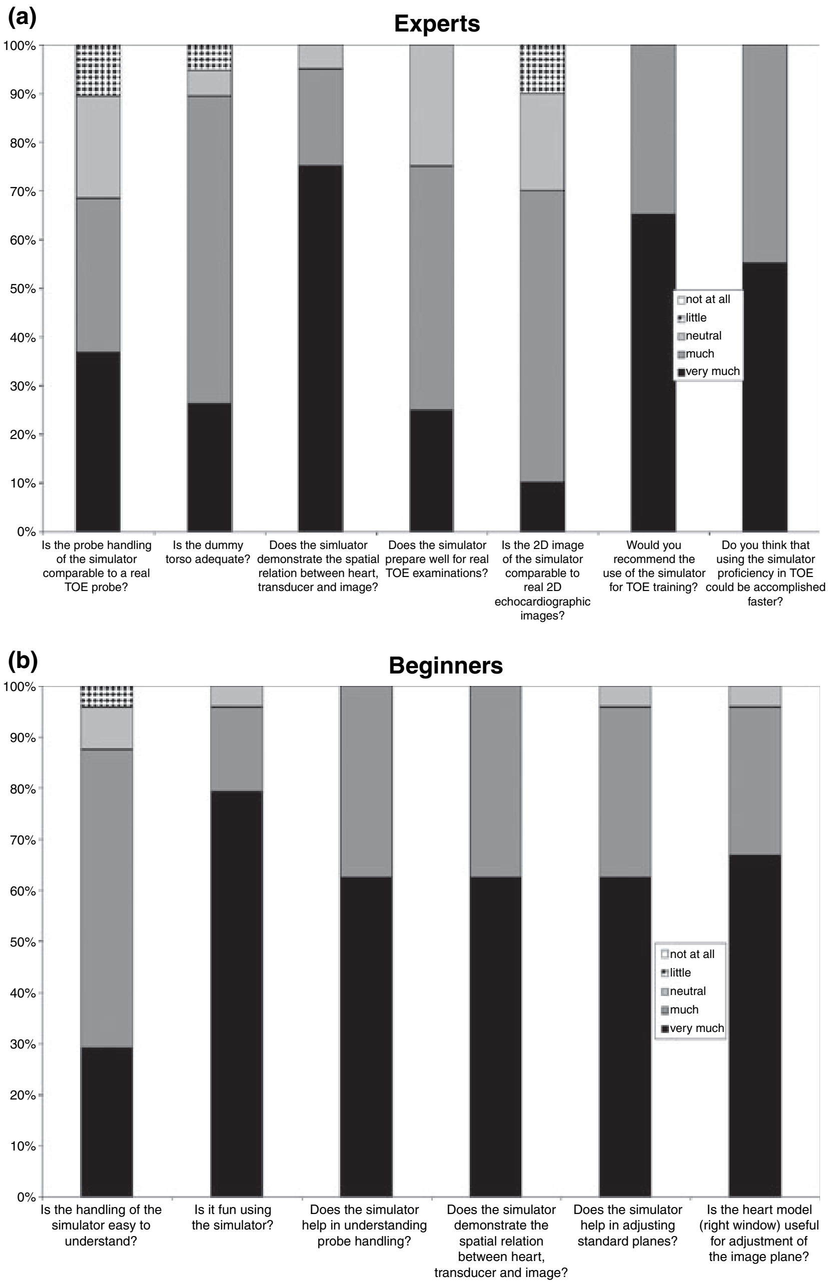

Figure 4 (a) Results of the experts' questionnaire. (b) Results of the beginners' questionnaire.

Beginners

Fifty-two per cent of the beginners had never performed TOE themselves, and 48% had done fewer than 10 examinations. The results are shown in Fig. 4b. For 87% of the beginners the simulator was easy to use and all thought it was fun using it. The two main skills, probe handling and spatial orientation, were demonstrated and supported effectively by the simulator in the trainees' opinion. More than 90% found the virtual heart model useful for image adjustment.

Discussion

Echocardiography is a user-dependent image modality. Necessary skills for performing echocardiograms are probe steering and spatial orientation. Without proficiency in these, diagnostic interpretation of the images will fail. Spatial orientation not only refers to knowledge of probe position, but also the ability mentally to reconstruct the scanned heart from multiple 2D images. These skills have to be acquired before such cognitive skills as diagnostic knowledge can be applied. Unfortunately, they are inadequately addressed by currently available learning media, for example, textbooks or atlases. Hands-on training supervised by an experienced echocardiographer is therefore necessary.

The American College of Cardiology and the American Heart Association recommend performing a minimum of 50 TOE examinations on the basis of having level 2 competence in TTE to achieve proficiency [14]. Probably all cardiologists learning TOE have experience in TTE. The concept of mental modelling of the heart from 2D images therefore is not new to them. A formal training in TTE for anaesthetists would perhaps also be useful, as compared to TOE it is less risky and uncomfortable for the patient. However, due to the additional resources required, this is impractical for anaesthetists performing peri-operative TOE, simply because they do not use TTE on a daily basis. Therefore a large number of anaesthetists do not have training in TTE before starting their training in TOE. This is endorsed by the recommendations of the American Society of Echocardiography and the Society of Cardiovascular Anaesthesiologists, who recommend that 150 examinations be interpreted and 50 examinations performed for a basic peri-operative TOE training for anaesthetists without prior TTE training [15]. The semi-invasive nature of TOE limits the opportunities for beginners to have enough hands-on training. However, the use of peri-operative TOE is increasing, and therefore there is a growing requirement for training [2]. Simulator training is used quite extensively in anaesthesia for training and assessment [16]. The high number of publications and editorials in peer group journals indicates a high level of acceptance and interest in simulation technology [17, 18]. Advantages include the risk-free setting, the possibility to tailor the training according to the trainee's needs and standardised presentation of the data. Simulator training is not only promoted by trainees and medical societies but by public interest [19, 20]. The positive rating of the experts in our evaluation not only reflects the usefulness of our application for TOE but also the attitude of anaesthetists towards these new technologies. To be accepted, simulators have to have a realistic look and feel. The results of our questionnaire show that important aspects have been taken into account, that is, a realistic scenario (realistic manikin), probe handling and adequate images. We have not tried to simulate probe insertion. Experiences with manikins used for intubation showed that the necessary biological behaviour of the material is very hard to simulate. The necessary costs would have exaggerated the training benefit for our purposes. Also, probe insertion is a minor problem for most anaesthetists who are trained in intubation.

The learning curve for spatial orientation and image acquisition is rather flat. During traditional training a supervisor either adjusts the image plane himself or verbally directs a trainee steering the probe in the desired direction. The problem is that getting from one image plane to another is not a predetermined and consciously planned task. Echocardiographers tend to approach the desired plane in small steps based on the interaction of probe movements, resulting image and mental heart model. The complexity of this process and the fact that it is at least partially subconscious make verbal explanations rather imprecise and ineffective. Image acquisition can best be learned if the trainee gets a visual demonstration of the probe and image plane alterations and the resulting echocardiogram.

Ultrasound simulators for abdominal or gynaecological sonography are commercially available [21, 22]. These simulators provide a realistic scenario. What they lack, however, is an intuitive 3D model to support spatial orientation. We think that orientation in echocardiography is more difficult than in abdominal ultrasound due to the complex geometry of the heart. We have therefore used the concept of augmented reality that couples virtual and real image data. The interface of our simulator not only shows the echocardiogram in real time. Within a virtual scene it demonstrates the probe position in respect to the heart and how the image plane dissects the heart. Using red and green lines for the image plane borders further helps orientation. For example, in a midoesophageal four-chamber view even the beginner would know that when scanning a normal heart the left ventricle is visualised on the right side of the ultrasound screen. However, the reason why it 'moves' to the left side when the image plane is rotated was not understood by most beginners whom we interviewed. As depicted in Fig. 3, EchoComTEE not only shows how the image plane rotates, but why the left ventricle is on the right side (red border) of the screen at 0° but 'moves' to the left (green border) at 130°. Our evaluation confirmed our assumption that the simulator effectively imparted this spatial understanding. Most beginners appreciated the heart model when they tried to adjust image planes.

Limitations of the simulator

EchoComTEE is a prototype of an ongoing research project and not a commercially available product. There are several limitations that have to be overcome in the future. The echocardiographic data sets were recorded by apical rotational scans. Therefore, the data do not include the complete cardiac structures and great vessels. Important views like the upper oesophageal views or imaging the descending aorta therefore cannot be simulated. However, once the beginner understands the principles of image acquisition and image orientation, he or she should be able to transfer this knowledge to other views when scanning a real patient. An advantage of the simulator is that adjustment of standard views is not learned simply by memorising probe depth or degree of image plane rotation, but by understanding what happens when the image plane and probe are manipulated. It should be easier for the novice to transfer this knowledge to previously unknown views, although this is has not been proved. Also, for basic perioperative TOE the midoesophageal and transgastral views are the most important.The number of available 3D data sets and the quality of the data we used for the evaluation were limited due to the stepwise rotational acquisition mode. Also, they were obtained by transthoracic scanning and the structures that are in the far field in TTE with lower resolution are therefore in the near field in TOE and vice versa. Recently, we were able to obtain 3D real time data (Philips Sonos 7500 and iE 33, Philips Medical Systems, Bothell, WA, USA) using TomTec software for data conversion. We hope that the quality of the 2D echocardiographic images will improve. In the future we are planning to build up a data base of a wide variety of pathological data sets, including congenital heart defects. This will hopefully extend the group of users who benefit from the simulator training to more experienced echocardiographers. Simulator training will not replace traditional learning methods or the process of life-long learning. However, it may be possible to speed up the process of becoming acquainted with TOE. Evaluation of new education methods is difficult, as learning is a complex task that is influenced by multiple factors [23, 24]. Echocardiography cannot be learned in short periods, but requires several months [14], and limiting this due to access to a simulator is less than ideal. In addition, it is not easy to measure skills such as spatial orientation or probe handling. Most publications concerning the effectiveness of simulator training have evaluated whether simulator learning improves knowledge but have not measured the impact of simulators within a training program. Most studies have not compared simulator training with traditional methods, or evaluated the impact on patient outcome [23, 25]. Our preliminary evaluation did not prove the efficacy of EchoComTEE in terms of training effect to achieve a certain level of expertise. However, it has demonstrated the acceptability of our simulator amongst both experts and beginners. Taking into account the costs of simulator training, a more extended evaluation is necessary before simulators will be widely accepted and used more extensively.

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