Efficiency of ultrasound training simulators: Method for assessing image realism

Running title: Assessing realism in ultrasound simulators

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Abstract

Although ultrasound has become an important imaging modality within several medical professions, the benefit of ultrasound depends to some degree on the skills of the person operating the probe and interpreting the image. For some applications, the possibility to educate operators in a clinical setting is limited, and the use of training simulators is considered an alternative approach for learning basic skills. To ensure the quality of simulator based training, it is important to produce simulated ultrasound images that resemble true images to a sufficient degree. This article describes a method that allows corresponding true and simulated ultrasound images to be generated and displayed side by side in real time, thus facilitating an interactive evaluation of ultrasound simulators in terms of image resemblance, real-time characteristics and man-machine interaction. The proposed method could be used to study the realism of ultrasound simulators and how this realism affects quality of training, as well as being a valuable tool in the development of simulation algorithms.

Keywords: ultrasound, simulation, training simulator, technology enhanced learning

Introduction

Ultrasound imaging is used in numerous medical applications. It is a real-time modality, it does not involve ionising radiation, and the equipment is portable and relatively inexpensive. A challenge with ultrasound is, however, that it is operator-dependent, and it therefore requires training to fully exploit its potential (1). Skills are needed both for optimal handling of the probe to obtain the best possible image, and for interpreting the images correctly. For some applications, such as image-guided interventions, detection of internal haemorrhage in blunt trauma or for rare diseases or injuries, there are limited possibilities for training in clinical situations. The use of simulators may provide a means for obtaining the basic skills necessary for these applications as well as a possibility for training on patient specific cases.

Training simulators have been developed e.g. for different surgical procedures (2), endoscopy (3), diagnostic ultrasound imaging (4) and ultrasound-guided needle insertion (5). Typically, an ultrasound training simulator consists of a computer running the simulation software, a mannequin representing the exterior of the patient's body, a dummy ultrasound probe and a positioning system reading the position of the probe relative to the mannequin. The internal anatomy of the virtual patient may be represented by pre-acquired three-dimensional images from computed tomography (CT), magnetic resonance imaging (MRI), ultrasound or anatomical atlases. The simulated ultrasound images can then be generated in real time by cross-sectioning these three-dimensional images and adding ultrasound-specific features to the cross sections depending on the direction of view (6-9).

Investigations have indicated the usefulness of simulators in the teaching of clinical ultrasound (1, 4). These investigations have mostly been concerned with the overall learning outcome of simulator training. However, a premise for the efficiency of such training is that the simulator resembles reality to a sufficient degree. In this article we describe a method in which corresponding true and simulated ultrasound images are generated and displayed side by side in real time, i.e. continuously while the ultrasound probe is being moved, thus facilitating an evaluation of ultrasound simulators in terms of image resemblance, real-time characteristics and man-machine interaction.

Materials and methods

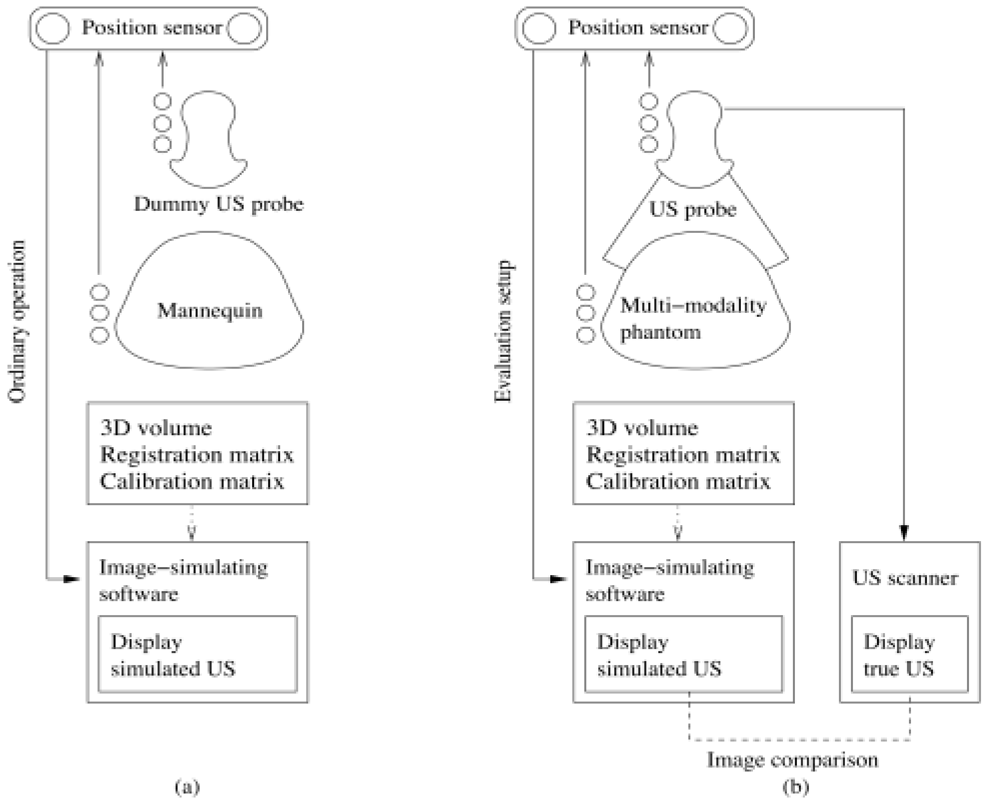
Ultrasound simulator

The ultrasound simulator that was used for demonstrating the evaluation method consisted of a mannequin, a dummy ultrasound probe and the optical positioning system Polaris Spectra from Northern Digital Inc. (Waterloo, Canada). The Polaris system consists of reflective positioning frames, which are attached to the objects that are to be traced, and an infrared camera to read the position of these frames. The simulator software was written in the technical computing language MATLAB (MathWorks, Natick, MA, USA) and run on a standard laptop computer.

The internal anatomy of the virtual patient was represented by a three-dimensional image volume, which was pre-acquired from a patient and given as input to the simulator. The volume could be from either ultrasound or CT, and it was aligned with the mannequin through a point-based registration method using fiducials (10). Both the probe and the mannequin were equipped with positioning frames allowing their position and orientation to be continuously measured and passed to the computer in real time. Based on these measurements, the simulator software then extracted the appropriate cross section from the image volume. In the case of ultrasound data, the cross sections were displayed directly, whereas the CT data were processed to include ultrasound-specific characteristics prior to display (8). The data flow of the simulator is shown in Figure 1 (a), and the equipment is shown in Figure 2 (a).

Evaluation setup

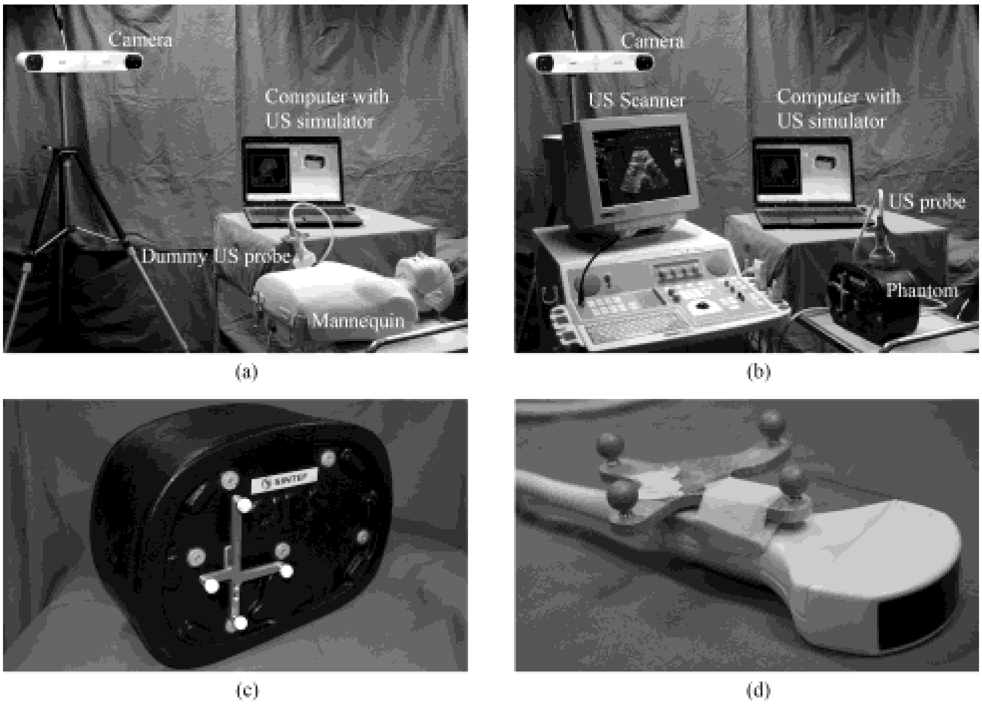
To facilitate an evaluation of the simulator, the dummy probe was replaced by a true ultrasound probe (3.5MHz curved linear array) connected to a System FiVe ultrasound scanner (GE Vingmed Ultrasound, Horten, Norway) and the mannequin was replaced by a multi-modality imaging phantom (Interventional 3D Abdominal Phantom (model 057), CIRS, Norfolk, VA, USA). The phantom is made to resemble a human abdomen when imaged by CT, MRI or ultrasound, and it contains structures mimicking liver, kidneys, vertebra and ribs, as well as muscle, fat and interstitial tissues. Both the probe and the phantom were equipped with positioning frames, allowing them to be tracked by the positioning system. The data flow of the setup is shown in Figure 1 (b), and the equipment is shown in Figure 2 (b)–(d).



Figur 1: Description of data flow of the simulator (a) and the evaluation setup (b). Solid lines denote real-time flows, the dotted line indicates off-line input to the simulator and the perforated line is the image comparison. The setup was devised to scan a phantom with an ultrasound scanner while measuring the position of the ultrasound probe relative to a fixed positioning frame attached to the phantom. Two-dimensional slices were selected from the pre-recorded CT or ultrasound images of the phantom according to the position of the ultrasound probe, and given as input to the simulator. This allowed corresponding true and simulated ultrasound images to be generated and displayed side by side in real time.

The position and orientation of the ultrasound scan sector relative to the positioning frame on the probe were determined using the membrane technique described by Mercier et al. (11), an operation commonly referred to as probe calibration. The resulting calibration transform was combined with the tracking information from the Polaris system before it was passed to the simulator software.

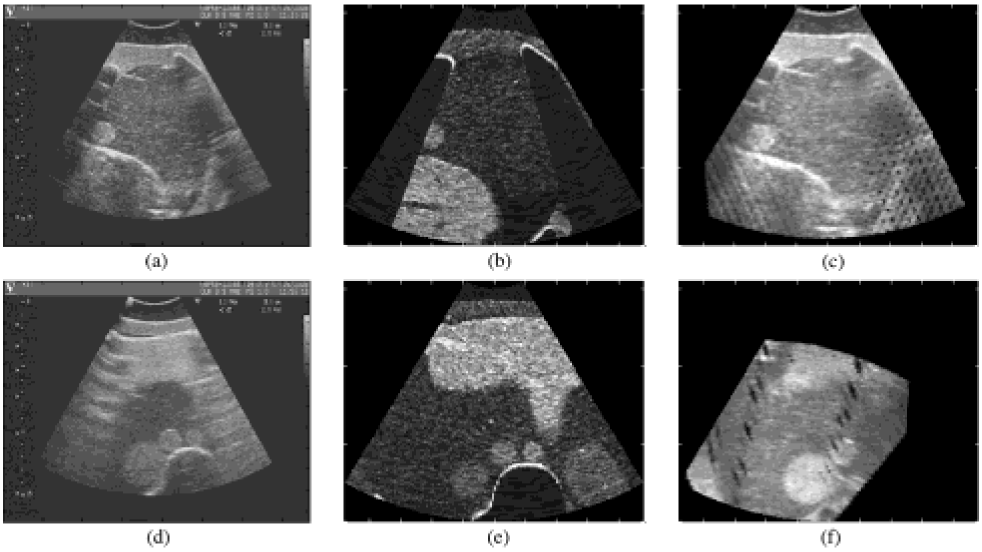
Three-dimensional image volumes of the phantom were acquired using both CT and ultrasound, and these volumes were used as anatomical representations in the simulator. The CT volume was recorded by a SOMATOM Sensation 64 scanner from Siemens (Munich, Germany), whereas the ultrasound images were acquired with a System FiVe ultrasound scanner from GE Vingmed Ultrasound (Horten, Norway) and reconstructed to a three-dimensional volume using the Pixel Nearest Neighbour algorithm as described by Solberg et al. (12).



Figur 2: Ultrasound simulator (a) and laboratory setup for the evaluation of the simulator (b). The camera tracks the position of the probe relative to the phantom. A simulated image corresponding to the image on the display of the ultrasound scanner is generated based on this position. The phantom with fiducials and positioning frame is shown close up in (c), and the ultrasound probe with positioning frame in (d).

Results

A setup for evaluating ultrasound simulators consisting of the equipment and methods described in the previous section was assembled. Comparable true and simulated ultrasound images, based on the same two-dimensional region within the phantom, were generated and displayed side by side in real time, i.e. continuously while the ultrasound probe was being moved. Some examples of typical sets of comparable images are shown in Figure 3 (a)–(f).



Figur 3: A true ultrasound image (a) was recorded at the same position as two simulated images based on pre-acquired, three-dimensional image volumes acquired with CT (b) and ultrasound (c) respectively. They were subsequently displayed side by side for easy comparison. Comparable images from another position are shown in (d)–(f). This last position differs considerably from the positions used to record the pre-acquired ultrasound volume, and essential data is therefore missing.

The setup made it easy to immediately recognise strengths and weaknesses of the different prototype simulators. For example, in the images based on pre-acquired CT data, the anatomical structures were clearly visible. However, these images lacked the reverberation effects of ultrasound imaging, and they also differed from the true ultrasound images in resolution and at interfaces between different organs. The simulated images based on pre-acquired ultrasound data clearly resembled the true ultrasound images when taken from the same direction as the data were originally acquired (Figure 3 (c)), but due to weaknesses in the reconstruction of the pre-acquired data it was blurred and contained empty areas. When taken from a different direction (Figure 3 (f)), several organs, such as the blood vessel and the kidney at the lower right corner, were concealed by shadows, whereas the kidney to the left of the backbone was more clearly visible than in the true image. The clarity of the discrepancies between the simulated and true ultrasound images demonstrates the potential of the setup for evaluating the realism of simulated images.

Since the setup did not involve any extra work for either the simulator or the ultrasound scanner, they were able to operate simultaneously and in real time without any time lag. The real-time characteristics of the simulations, such as frame rate and transition between images, were therefore easily compared to those of the ultrasound scanner. The same was true for the man-machine interaction, i.e. the response of the images to the handling of the ultrasound probe.

Discussion

Which properties a training simulator should have depends on which skills it is meant to train. This is also what determines the degree of realism required for the different aspects of the simulator. In the case of clinical ultrasound, there may be skills that could be trained by a simulator with poor image realism, or even using an abstract environment. One example is the understanding of the relation between the positioning of the probe and the anatomical cross section that is displayed. Other skills, such as diagnosing a given condition based on the displayed images, are likely to require a higher degree of image realism, but then only when it comes to image properties that are relevant to the diagnosis in question. In order to study this relationship between image realism and training efficiency, it is important to have methods that allow a systematic and thorough evaluation of the realism of the simulated images.

Ultrasound simulators have previously been evaluated off-line against true ultrasound (9), and expert ultrasound users have evaluated the image realism and quality of simulators based on their experience (4). The main advantage of the proposed setup over these evaluation methods is that it, by producing comparable true and synthetic ultrasound images in real time, enables an interactive exploration of the properties of the simulator while at the same time presenting an objective basis for comparison. This makes it possible to explore a large number of different images taken from various positions without having to record large amounts of data. Moreover, it allows for an evaluation of the realism of the man-machine interaction by comparing the response of the two images to the handling of the ultrasound probe.

The image realism is evaluated in terms of similarity to true ultrasound images. In this context, similarity is the degree to which the user recognises the images as true images. This is most easily evaluated through a subjective assessment by a user. With the proposed setup, the assessment is made more objective since it does not rely exclusively on the experience and memory of the user, but also allows the images to be directly compared to corresponding true images. In addition, similarity metrics can be applied to the produced images, which would provide an even more objective measure. However, the development of a metric measuring the human perception of the similarity between ultrasound images is complicated and requires considerably more research.

In order for the setup to achieve its purpose, it is essential that the spatial correspondence between the sector imaged by the ultrasound scanner and the image slice extracted by the simulator is satisfactory. This correspondence depends mainly on the joint accuracy of three separate operations: the registration of the image volume to the phantom, the probe calibration and the tracking of the phantom and the probe. This accuracy has previously been analyzed in the context of a navigation system for neurosurgery, which included all of these operations (13). The analysis indicated that the overall error was less than 2 mm, which should provide sufficient correspondence between the produced images for the purpose of comparison.

The Polaris tracking system was easily adapted to the given setup as both the infrared camera and the positioning frames were external to the rest of the simulator. This made the substitution of the mannequin and the probe straightforward. For simulators where the tracking system is integrated in either the mannequin or the probe, the setup may require a separate tracking system, which can be adapted to the phantom and to the true ultrasound probe. Ideally, this should be identical to the one used in the simulator. If another system is used, it is important to take into consideration the change in spatial accuracy and temporal performance that this may introduce, e.g. due to differences in update rate or communication rate. This change may affect the possibility to evaluate the real-time characteristics of the simulator.

The described setup utilises an imaging phantom, which has the advantage of allowing easy and repeated access to the setup in the laboratory. However, a training simulator will most often use image data from humans. The phantom presented here emulates human anatomy to a certain degree, but it is of obvious interest to test the simulator also on clinical data. The proposed setup allows for this by replacing the phantom with a patient. In the case of CT data, this requires that the person is equipped with fiducial markers prior to scanning to facilitate an accurate registration, but otherwise the adaption is straightforward. Thus, the setup can be applied to a number of both normal and pathological cases.

Conclusion

By replacing the simulator mannequin and the dummy ultrasound probe with a multi-modality phantom and a true ultrasound probe, and combining this with an accurate registration and probe calibration, an evaluation setup with a high degree of spatial accuracy was achieved. The setup made it possible to evaluate image resemblance, real-time characteristics and man-machine interaction in real time. The proposed method may have an important role in assessing the efficiency of ultrasound training simulators, as well as being a valuable tool in the development of simulation algorithms of sufficient quality.

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References

1. Weidenbach M, Wild F, Scheer K, Muth G, Kreutter S, Grunst G, et al. Computer-based training in two-dimensional echocardiography using an echocardiography simulator. J Am Soc Echocardiogr. 2005;8:362–6.
2. Satava RM. Accomplishments and challenges of surgical simulation. Surg Endosc. 2001;15(3):232–41.
3. Vining DJ, Stelts DR, Ahn DK, Hemler PF, Ge Y, Hunt GW, et al. FreeFlight: A virtual endoscopy system. In: Troccaz J, Grimson E, Mösges R, editors. First Joint Conference Computer Vision, Virtual Reality and Robotics in Medicine and Medical Robotics and Computer-Assisted Surgery – CVRMed-MRCAS'97; Grenoble, France1997. p. 413–6.
4. Maul H, Scharf A, Baier P, Wuestemann M, Guenter H, Gebauer G, et al. Ultrasound simulators: experience with the SonoTrainer and comparative review of other training systems. Ultrasound Obstet Gynecol. 2004;24(5):581–5.
5. Magee D, Zhu Y, Ratnalingam R, Gardner P, Kessel D. An augmented reality simulator for ultrasound guided needle placement training. Med Biol Eng Comput. 2007;45(10):957–67.
6. Aiger D, Cohen-Or D. Real-Time Ultrasound Imaging Simulation. Real-Time Imaging. 1998;4(4):263–74.
7. Ehricke H-H. SONOSim3D: a multimedia system for sonography simulation and education with an extensible case database. Eur J Ultrasound. 1998;7(3):225–30.
8. Hostettler A, Forest C, Forgione A, Soler L, Marescaux J. Real-time ultrasonography simulator based on 3D CT-scan images. Stud Health Technol Inform. 2005;111:191–3.

9. Bommersheim S, Tiede U, Burmester E, Riemer M, Handels H. Simulation von Ultraschallbildern für ein virtuelles Trainingssystem für endoskopische Longitudinal-Ultraschalluntersuchungen. In: Meinzer H-P, Handels H, Horsch A, Tolxdoff T, editors. Bildverarbeitung für die Medizin 2005. Berlin, Germany: Springer 2005. p. 450–4.

10. Horn BKP. Closed-form solution of absolute orientation using unit quaternions. J Opt Soc Am A Opt Image Sci Vis. 1987;4(4):629–42.

11. Mercier L, Langø T, Lindseth F, Collins DL. A review of calibration techniques for freehand 3-D ultrasound systems. Ultrasound Med Biol. 2005;31(4):449–71.

12. Solberg OV, Lindseth F, Torp H, Blake RE, Hernes TAN. Freehand 3D ultrasound reconstruction algorithms – a review. Ultrasound Med Biol. 2007;33(7):991–1009.

13. Lindseth F, Langø T, Bang J, Hernes TAN. Accuracy evaluation of a 3D ultrasound-based neuronavigation system. Comput Aided Surg. 2002;7(4):197–222.