Taylor & Francis
Taylor & Francis Group

The Journal of Maternal-Fetal & Neonatal Medicine

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ijmf20

Optical ultrasound simulation-based training in obstetric sonography

Lami Yeo & Roberto Romero

To cite this article: Lami Yeo & Roberto Romero (2020): Optical ultrasound simulation-based training in obstetric sonography, The Journal of Maternal-Fetal & Neonatal Medicine, DOI: 10.1080/14767058.2020.1786519

To link to this article: https://doi.org/10.1080/14767058.2020.1786519

View supplementary material

Published online: 07 Jul 2020.

Submit your article to this journal

Article views: 13

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=ijmf20

THE JOURNAL OF MATERNAL-FETAL & NEONATAL MEDICINE
https://doi.org/10.1080/14767058.2020.1786519

Taylor & Francis
Taylor & Francis Group

ORIGINAL ARTICLE

Check for updates

Optical ultrasound simulation-based training in obstetric sonography

Lami Yeo[a,b,c] and Roberto Romero[a,b,d,e,f]

[a]Perinatology Research Branch, Division of Obstetrics and Maternal-Fetal Medicine, Division of Intramural Research, Eunice Kennedy Shriver National Institute of Child Health and Human Development, National Institutes of Health, U.S. Department of Health and Human Services, Bethesda, MD and Detroit, MI, USA; [b]Detroit Medical Center, Detroit, MI, USA; [c]Department of Obstetrics and Gynecology, Wayne State University School of Medicine, Detroit, MI, USA; [d]Department of Obstetrics and Gynecology, University of Michigan, Ann Arbor, MI, USA; [e]Department of Epidemiology and Biostatistics, Michigan State University, East Lansing, MI, USA; [f]Center for Molecular Medicine and Genetics, Wayne State University, Detroit, MI, USA

ABSTRACT

Ultrasound is an imaging modality that is highly operator dependent. This article reviews the challenges in learning how to perform obstetric sonography, as well as the processes necessary to acquire expert performance skills in sonography. Simulation-based education and learning, and the value of medical simulation are also discussed. Ultrasound simulators are an effective means of teaching obstetric sonography, because it provides training, deliberate practice, and performance evaluation/feedback which allows continuous and critical self-evaluation. We review evidence that simulation can improve performance in obstetric ultrasound examination, review current simulators, and discuss the current problems/gaps in ultrasound simulation. Optical positioning ultrasound simulation is a novel high-fidelity simulation learning system, which addresses many of these problems/gaps and is introduced for the first time here.

ARTICLE HISTORY
Received 10 January 2020
Revised 27 April 2020
Accepted 19 June 2020

KEYWORDS
Education; OPUS; pregnancy; simulator; teaching

> Tell me and I forget, teach me and I may remember, involve me and I learn
>
> Attributed to Confucius in 450 B.C.

Introduction

Ultrasound imaging is integral to the practice of obstetrics, as it allows comprehensive anatomic and physiologic evaluation of the fetus and maternal pelvic organs [1]. Therefore, ultrasound examinations are recommended for all pregnant women [2–4]. Over the years, there has been an overall increase in the utilization of obstetric ultrasound in the U.S., with women receiving on average 4–5 sonographic examinations per pregnancy [5]. Yet, there is substantial variability in the sensitivity of routine sonography to detect fetal anomalies [6–8]. In a review of 36 studies that included more than 900,000 fetuses, an overall sensitivity of only approximately 40% for detecting fetal anomalies was noted [9]. Although the sensitivity of obstetric sonography depends upon gestational age at screening, type of congenital anomaly, selection of pregnant women, etc. the *level of training and expertise of the sonologist is crucial to examination performance* [10].

For the images used in this report, patients were examined at the Detroit Medical Center/Wayne State University and the Perinatology Research Branch of NICHD, NIH, DHHS. All women had been enrolled in research protocols approved by the Institutional Review Board of NICHD, NIH, and by the Human Investigation Committee of Wayne State University. All participants provided written informed consent for the use of sonographic images for research purposes.

Ultrasound is an imaging modality that is highly operator dependent

Medical imaging refers to several different technologies that view the human body in order to diagnose, monitor, or treat medical conditions [11]. Examples of imaging modalities include x-ray, magnetic resonance imaging, and computed tomography. However, for such modalities, the operator does not obtain hands-on images directly, but rather the modality itself

CONTACT Lami Yeo lyeo@med.wayne.edu; Roberto Romero prbchiefstaff@med.wayne.edu Perinatology Research Branch, NICHD, NIH, DHHS, Hutzel Women's Hospital, 3990 John R, 4 Brush, Detroit, MI 48201, USA

Supplemental data for this article can be accessed here.

This work was authored as part of the Contributor's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

allows the generation of diagnostic images. For example, during a radiographic procedure, an x-ray beam is transmitted through the body, and some x-rays are absorbed or scattered by internal structures. The remaining x-ray pattern is transmitted to a detector for recording or further processing by a computer, so that images can undergo medical interpretation [12].

In contrast, real-time two-dimensional (2D) ultrasound is a challenging and highly operator dependent modality. The sonologist must continuously and actively participate throughout the examination to retrieve and display diagnostic planes from three-dimensional (3D) anatomical structures. We refer to such method of performing real-time 2D sonography (and especially obstetric sonography) as *manual navigation* [13]. This process requires extensive training and skill to assess the fetus and other structures properly. Other medical imaging modalities require the patient to be positioned in a standard manner for each examination (e.g. computed tomography). While this is also the case for obstetric sonography, there is also a second "patient", in which the fetal lie, presentation, and position differs amongst patients, affecting the configuration of diagnostic planes [13]. Moreover, during obstetric sonographic examinations, there is a need to constantly adapt to a dynamic environment. Specifically, the fetus may frequently move, and the sonologist must mentally understand how this translates to what is depicted on the monitor screen. Taken together, all these factors create a highly challenging environment for the sonologist, who must acquire a series of specific 2D planes for image display [13]. Any medical interpretation and diagnosis strictly depend upon whether such diagnostic planes have, or have not been successfully obtained.

Challenges in learning how to perform obstetric sonography

To become proficient in performing real-time obstetric sonography, extensive training and skills are required. An operator must be engaged in the simultaneous acquisition, display, and interpretation of images. This can take years to learn and may be tedious, depending upon the structure(s) of interest (e.g. fetal heart). Teaching resources and the availability of patients are also necessary. We propose that the following skill sets should be learned to be successful [13]: 1) technical skill in manipulating the transducer (i.e. *dexterity*); 2) eye-hand coordination; 3) manipulation of the console and knobs on the ultrasound machine to adjust parameters affecting the image (i.e. *knobology*); 4) mental translation of how operator movements correspond to visual images on the screen; 5) 3D reconstruction of 2D images in the sonologist's mind; 6) ability to be focused and observant (e.g. learn to differentiate amongst anatomic structures); 7) constant adaptation to a dynamic environment; 8) adequate recognition and understanding of tissue, anatomy, and organ structures, as well as their sonographic depiction; and 9) image interpretation skills. Therefore, achieving competency in sonography relies on the technical aspects of performance, image interpretation skills (cognitive performance), and the ability to integrate ultrasound examination results into patient care [14].

Of all the skill sets that should be learned, our view is that the most difficult to master and which have an extended learning curve are: 1) eye-hand coordination; 2) mental translation of how transducer movements correspond to images on the screen; and 3) 3D reconstruction of 2D sonographic images in the sonologist's mind. As will be discussed later, *simulation* is an ideal method which allows learning of such skill sets, and the following paragraphs will review the underlying concepts as specifically applied to obstetric sonography.

Eye-hand coordination without seeing the actual target

Eye-hand coordination is defined as the coordinated control of eye movement with hand movement, and the processing of visual input to guide reaching and grasping along with the use of proprioception of the hands to guide the eyes [15]. A defining characteristic of primate species is the ability to make rapid and accurate movements using extremely *dexterous hands* [16]. Such movements depend upon *visual information* about target attributes (e.g. position, size, orientation), as well as somatosensory information about where the head, eyes, and arms are at any given moment [16]. Studies on eye-hand coordination show that a saccadic eye movement usually precedes a goal-directed hand movement. Therefore, people usually direct their gaze to the "target" as they initiate hand movements, and maintain their gaze on the target until around the time the hand arrives [17]. A simple example is picking up a coffee cup from the table. The act of *looking at the target* allows the effective use of visual feedback of hand position to guide the hand to the target of interest [17,18].

Yet, when performing obstetric sonography, the "target" (i.e. fetus) can never be visualized directly by the sonologist, and the hand never arrives at the actual target itself. Instead, *via* the transducer, the invisible fetus can only be visualized indirectly on the ultrasound monitor screen, making the experience detached and arduous to understand. Moreover, imaging a fetus in the pregnant mother *via* sonography is a unique situation, in that there is a "*picture-in-picture*" environment (i.e. visualizing fetal organs within maternal organs). Therefore, mastery of eye-hand coordination in obstetric ultrasound is not intuitive and requires an extended learning curve.

A disconnect exists between transducer movements and resulting sonographic images

In the game of billiards, players use a cue (long stick) to strike a visible ball on the table in order to move it in a certain direction. This is a tactile sport, because the ball can be seen, and there is physical contact between the cue and ball, leading to a *connection* in the mind of how cue movements translate into resultant actions.

In obstetric ultrasound, the novice may initially think that this is a straightforward modality – one places the transducer on the maternal abdomen, images appear on the monitor screen, pictures are captured, and then they are interpreted to make a diagnosis. However, we propose that for the beginner sonologist, there is an initial *disconnect* in the mind between transducer movement(s) and resultant sonographic images on the monitor screen. In other words, it is difficult to comprehend what the transducer is actually "doing". To make this process even more complicated, the configuration of a standard diagnostic plane (e.g. left ventricular outflow tract) depends upon the fetal lie, presentation, and position [13]. Therefore, the sonologist cannot simply learn and memorize a standard set of transducer movements to obtain a desired image each time. Instead, to successfully obtain an anatomic structure, one should manipulate the transducer differently, depending upon whether the fetus has a longitudinal/transverse/oblique lie, or is in a vertex/breech/transverse presentation.

A simple example is that when a fetus is in vertex presentation, the sonologist must move the transducer on the maternal abdomen toward her head to obtain the fetal stomach. However, if the fetus is in breech presentation, one must move the transducer in the opposite direction to obtain the same structure. While this "rule" may be easy to learn for some organs (e.g. fetal stomach), this is not the case for locating anatomical structures (e.g. right ventricular outflow tract) of complex and asymmetrical organs, such as the fetal heart. In such cases, there is a stronger disconnect in the mind between transducer movements and resultant sonographic images, thus requiring a much higher degree of mental dexterity and comprehension.

3D reconstruction of 2D sonographic images in one's mind

Finally, to gain mastery in translation of transducer movements into the desired sonographic image, one must possess the ability to perform a *3D reconstruction* of the 2D sonographic images in one's mind.

The sonologist should also learn how to intentionally "target" a structure using the transducer (i.e. *targeted behavior*) so that the image is displayed appropriately on the ultrasound monitor screen. Expert sonologists can accomplish this easily, rather than scanning in a random manner, or waiting for the fetal structure(s) to come into the field of view (i.e. *passive behavior*).

Simulation-based education and learning

Simulation is defined as a technique that creates a situation or environment to allow persons to experience a representation of a real event for the purpose of practice, learning, evaluation, testing, or to gain understanding of systems or human actions [19]. Simulation-based training strategies, techniques, and tools can be applied to design structured learning experiences, and can also be used as a measurement tool linked to targeted competencies and learning objectives [20]. Simulation-based learning has been applied to many different disciplines (e.g. aviation, military), as well as trainees [20], and is a pervasive method of training. Its value lies in the ability to improve errors and maintain a culture of safety, especially in industries where there is zero tolerance for deviations from set standards [20].

Historically, perhaps one of the most important simulators ever developed was a flight simulator widely used during World War II [21]. The "Link Trainer" (also known as the "Blue box" or "Pilot Trainer") was invented by Edwin A. Link, and allowed pilots to train in realistic conditions without comprising their safety. Prior to its invention, student pilots learned how to fly from other pilots; however, this was expensive, dangerous, and time consuming. Initially, there was slow interest in the Link Trainer; however, this changed in

1934 when use of the trainer for instrument flight training captured the attention of the U.S. Army Air Corps [21]. At that time, there were several highly publicized crashes because pilots could not fly using instruments at night or in bad weather. During World War II, over 10,000 Link Trainers were used to improve safety and shorten the training time for more than 500,000 pilots [21]. Even today, flight simulators are an important and integral component of commercial, military, and space flight training.

Value of medical simulation

K. Anders Ericsson, a recognized researcher in the psychological nature of expertise and human performance, describes an *expert performance approach* which identifies the final goal of training, which is reproducibly superior objective performance (i.e. superior patient outcomes) for medical individuals [22]. He describes that when correct resources are provided to support such an expert performance approach, this allows medical individuals to become self-regulated learners and possess the tools to improve their own performance throughout a career [22].

Traditionally, medical training has focused on learning theoretical knowledge first, and then gaining actual experiences in the real world, where performance has an impact on patient care. Years ago, before the existence of medical schools, the traditional method of medical training was to learn as an on-the-job apprentice, in which one trained under the hand of a local, experienced and respectable practitioner. The quality of training was entirely dependent upon the skills of the teacher. This has been exemplified by the traditional adage about learning and performing medical procedures by trainees – "*See one, do one, teach one*" [22]. After observing a procedure once, trainees are expected to be able to perform such procedure, followed by being able to teach another trainee how to do the same procedure. Yet, many have argued that "*learning by doing*" has become less acceptable and patient safety is at risk, especially when invasive procedures and high-risk care are required [23]. An example of this practice is learning how to perform abdominal hysterectomy, in which the medical teacher ligates ligaments and anatomical structures on one side, while the trainee imitates the actions on the contralateral side.

Perhaps the most optimal method of "practicing" in a safe environment is through medical simulation. Indeed, the 2019 Accreditation Council for Graduate Medical Education (ACGME) Program Requirements for Graduate Medical Education in General Surgery state that resources for resident education should include simulation and skills laboratories.

Simulation in health care is defined as an instructional process that substitutes real patient encounters with artificial models, live actors, or virtual reality patients that replicate the clinical scenario [24,25]. Simulation has been shown to be a reliable tool to assess learners, and is effective in teaching teamwork and communication, basic science and clinical knowledge, as well as procedural skills [24,26]. Therefore, simulation has now become accepted in medical education due to the reproducibility of content, safety of the environment, ease of simulating critical events, and the ability to demonstrate multiple patient problems [24,27]. Learning activities are standardized, reproducible, consistent, predictable, and safe [24]. Moreover, there is a growing body of evidence that simulator training improves healthcare education [28] and practice, as well as patient safety [24]. The opportunity to develop skills is done through trial and error, without placing patients at risk or requiring them to be available. Indeed, studies have shown that stress is reduced for trainees when learning by simulation [29], and has therefore been associated with a beneficial effect on subsequent performance [30]. Evidence also suggests that the clinical skills acquired in medical simulation settings transfer directly to both improved patient care practices and patient outcomes [31–33].

Taken together, simulation in medical training has led to the following: 1) improvements in medical knowledge; 2) comfort in procedures; 3) improved performance during re-testing in simulated scenarios; and 4) improved patient care practices/outcomes [24,31]. Examples of improved patient care practices linked directly to simulation-based medical education include shoulder dystocia [34], laparoscopic surgery [35], and bronchoscopy [36]. Improved patient outcomes linked directly to simulation-based medical education have been reported in studies that address reductions in catheter-related bloodstream infections [37], brachial plexus injury [34], and neonatal hypoxic-ischemic encephalopathy [38].

The importance of simulation in medicine is reflected by organizations (e.g. AIMS: Advanced Initiatives in Medical Simulation), Journals (e.g. Journal of Simulation, Simulation in Healthcare), and conferences (IMSH: International Meeting on Simulation in Healthcare) which focus on this topic. AIMS is a coalition comprised of hospitals, universities, organizations, and individuals committed to promoting medical simulation as a way to improve the quality of health

care and patient safety by reducing medical errors, ensuring provider competency, providing adequate training for health care professionals, and reducing the overall cost of health care. Moreover, an increasing number of both medical schools and health care institutions are using simulation-based learning [20].

Three factors have been identified that lead to a maximum benefit of simulation-based medical education: 1) repetitive, active, and standardized educational experiences (to prevent trainees from being "passive bystanders"); 2) educational feedback; and 3) embedding training into the standard curriculum [39]. In simulation-based education and motor skills training, a dose-response relationship exists, with an increasing number of repetitions leading to an increasingly superior performance until a performance plateau is reached [40,41]. In a prospective randomized study, Bosse *et al.* studied the influence of high (vs. low) frequency expert feedback on the learning curve of medical students' clinical procedural skills (i.e. inserting a nasogastric tube into a simulation mannequin). The authors found that *deliberate practice* (see below for definition) with both high and low frequency intermittent feedback results in a strong improvement of students' early acquisition of procedural skills [40]. However, high frequency intermittent feedback led to an even better and smoother performance. Issenberg *et al.* analyzed the learning outcomes of simulation-based training to assess which specific training conditions were transferable (i.e. associated with improved performance of procedures outside simulation) [39]. The most important element to achieve effective and transferable learning was linked to having explicit performance goals. Other vital elements included receiving immediate, accurate feedback, as well as repeatedly performing the assigned task.

Areas of medical simulation

In general, medical simulation is divided into four areas depending upon the educational tool: 1) *standardized patient*; 2) *computer-based simulation* or *virtual-reality simulation*, in which the user interacts with a computer and the display demonstrates a realistic setting (e.g. fiber-optic bronchoscopy); 3) *partial-task trainer* devices that represent a single part of the human body (e.g. limb), and are designed to allow the practice of procedures, such as venipuncture. Such models simulate a subset of physiologic functions to include normal and abnormal anatomy [42]. Other examples include airway models and virtual reality endoscopic devices; and 4) *integrated simulation*, which uses computer-enhanced human mannequins. Such technology can vary in *fidelity* (see below) and are applicable to a variety of medical fields [24,43,44].

Standardized patients are actors who have been trained to portray a specific patient role, assess a trainee's clinical skills, and provide feedback. Simulation *fidelity* describes the accuracy of simulation and how closely it imitates the real-life counterpart [45]. Fidelity can be classified broadly into three categories: 1) *low* (the minimum simulation required for a system to respond to accept inputs and provide outputs); 2) *medium* (responds automatically to stimuli, with limited accuracy); and 3) *high* (nearly indistinguishable, or as close as possible to the real system) [29]. High-fidelity mannequin simulators (a component of *full environment simulation*) are now available, which simulate physical exam findings (e.g. normal and abnormal heart sounds, cyanosis) and physiological changes (e.g. changes in blood pressure, pulse, and breathing) [43]. Full-environment simulation includes: 1) a patient (i.e. high-fidelity mannequin simulator); 2) other healthcare professionals; and 3) ancillary equipment and supplies designed to replicate the clinical environment [24]. As such, learners can practice procedures in a realistic environment in which human behaviors and interactions occur.

Acquisition of expert performance in sonography

In our view, three processes must occur to acquire expert performance skills in sonography: 1) extensive training; 2) deliberate practice; and 3) performance evaluation/feedback. As will be described later, ultrasound simulation provides the opportunity to learn all such skills.

Extensive training involves years of learning repetitive skills and evaluating a variety and large number of patients, as well as normal and abnormal fetal cases. Yet, this may not be possible, depending upon the practice type (e.g. tertiary referral center for ultrasound) and location. This can lead to a prolonged training phase for sonologists.

Deliberate practice is defined as engagement in structured activities created specifically to improve performance in a domain [46,47]. The achievement of expert performance is thought to be the result of an individual's prolonged effort to improve performance, while negotiating motivational and external constraints [46]. Therefore, some investigators have proposed that individual differences in the performance of several domains (e.g. music, games, sports) largely

reflects individual differences in the amount of deliberate practice [46,47].

Our view is that there are elements of deliberate practice which are relevant to learning sonography, including: 1) well-defined learning objectives or tasks; 2) focused, repetitive practice; 3) informative feedback from educational sources (e.g. teachers, simulators) that promote monitoring, error correction, and more deliberate practice; and 4) evaluation and performance that may reach a mastery standard where learning time may vary, but expected minimal outcomes are identical [31,48]. The power of deliberate practice is demonstrated in a quantitative meta-analysis spanning 20 years, in which the authors reported that simulated-based medical education with deliberate practice is superior to traditional clinical medical education (i.e. classroom instruction and supervised performance in clinics) in achieving specific clinical skill acquisition goals [31].

Performance evaluation/feedback is also an integral part of continuous learning, and helps health care professionals understand how well they are performing [49]. This certainly applies to the discipline of ultrasound. Ideally, learning how to perform a specific domain should occur through teachers who can evaluate and provide immediate and informative feedback, rather than *autodidacticism*. The latter is defined as independent self-directed learning without the guidance of masters (e.g. teachers) or institutions (e.g. schools) [50]. Yet, our view is that while teachers are very important for learning, a formal evaluation of sonographic skills *via* empirical data offers additional value.

Why use simulation to improve performance in obstetric ultrasound examinations?

Ultrasound simulators provide training, deliberate practice, and for some systems, performance evaluation/feedback which allows continuous and critical self-evaluation. There is broad consensus on the utility of integrating simulation into ultrasound education and training programs [44]. Simulation shifts the perspective of education from the conventional *patient*-centered approach to a more innovative *learner*-centered approach [51]. This is relevant, since learning how to perform sonography on pregnant women uses an opportunistic approach, and depends upon patient availability. Moreover, some women are physically and psychologically uncomfortable with this process. The U.S. Food and Drug Administration (FDA) has recommendations to limit non-clinical obstetric ultrasound scanning due to concerns about ultrasound bioeffects on the developing fetus.

Chalouhi *et al.* reported that an obstetric ultrasound simulator is as effective as volunteer-based examination to evaluate the practical skills of trainees following structured training in obstetric ultrasound [52]. In addition, trainee physicians with little formal ultrasound training have been shown to improve their sonographic skills *via* short-phase virtual-reality simulation training [53]. Rosen *et al.* conducted a prospective, randomized, single-blinded trial to compare simulator- vs. patient-based obstetric ultrasound training (fetal brain anatomy) [54]. First, all trainees underwent a real patient pre-test, then a training session (simulator vs. real patient), and lastly a post-test on a real patient. All images were scored by maternal-fetal medicine staff based on image quality, landmarks, and measurements. Pre-test competence was found to be similar between the two groups. All trainees demonstrated significant overall score performance (mean score pre-test 14.6 vs. post-test 26.6; $p < .04$) regardless of the training method [54]. Therefore, simulator-based obstetric ultrasound training performed as well as real patient training, and there was a high rate of acceptance by the trainees.

An important question is whether simulation-based ultrasound training has an impact on clinical performance and quality of care. There is some evidence suggesting that clinical training alone is not sufficient to ensure adequate ultrasound skills [14]. Tolsgaard has hypothesized that providing systematic basic ultrasound training using simulation-based medical education could prepare one for future clinical learning, and that training effects would be sustained after several months of clinical training [14]. In a randomized clinical trial, obstetrics and gynecology residents were randomized to initial simulation-based ultrasound training and clinical training (intervention group) vs. clinical training only (control) groups [55]. When comparing OSAUS (objective structured assessment of ultrasound skills) scores between the groups, the intervention group had significantly higher scores vs. the control group (59.1 ± 9.3 vs. $37.6 \pm 11.8\%$; $p < .001$). Moreover, the authors showed that initial simulation-based ultrasound training led to substantial improvements in clinical performance that were sustained after 2 months of clinical training [55]. The provision of initial systematic simulation-based ultrasound training (and subsequent improvement in ultrasound skills) interacts with clinical training by decreasing the need for supervision and repeated patient examinations [14].

A serious and real issue that can be addressed by ultrasound simulation is that the availability of certain cases or experiences in the real world is not under the control of the learner. There may be a long interval between certain types of patient encounters (i.e. inadequate exposure to congenital anomalies), since the incidence of fetal anomalies is low – only 2% for all major anomalies, to 5% for all minor anomalies [56–60]. Moreover, some practices have a small case load, so that some congenital defects may be seen infrequently. This leads to a problematic environment for learning and improving one's sonographic skills for such conditions [22]. It is known that developing competency in obstetric ultrasound is heavily dependent on both the variety and number of cases seen in clinical practice [61]. Ultrasound simulation, however, allows the user to examine a library of both normal and abnormal sonographic cases in an abbreviated time period.

It is noteworthy that *transvaginal ultrasound* is especially difficult to teach within a clinical setting, since it requires extensive training time, experienced teachers, and a wide variety of compliant patients (with normal and pathological findings) who are willing to undergo an intimate examination on multiple occasions [44]. Moreover, transvaginal transducers display anatomical structures in a way that is unique to this approach [62], and ergonomic factors are different from that of transabdominal transducers. Fortunately, transvaginal sonography is now available for some simulators and therefore, simulation-based training is particularly advantageous in this setting [63]. Madsen *et al.* recently studied the learning curves of ultrasound novices and obstetrics/gynecology consultants using a high-fidelity simulator designed for transvaginal sonography [63]. The performance of novices improved with practice, and their learning curves plateaued at the level of expert performance after 3–4 h of simulation training.

Types of obstetric ultrasound simulators

Current ultrasound simulators are generally composed of a human mannequin, mock transducer, and computer [44]. Typically, the transducer is connected directly to the computer, and electromagnetic tracking systems are used to define the probe's position [44]. The transducer contains a sensor that can acquire virtual position data instantaneously; the computer is able to evaluate the position and location of the transducer on the mannequin, leading to a display of sonographic images on the computer screen [44,60,64–67]. In contrast, some simulators use a haptic (or touch; from the ancient Greek work *haptikos*) device which is mechanic sensing, rather than a mannequin. Movement of the mock transducer provides realistic force-feedback technology that replicates the "real-feel" of scanning an actual patient [63,68]. The computer monitor simultaneously shows real sonographic images (from actual patients), along with a 3D animated illustration of the mock transducer's anatomical scan position and the surrounding anatomy [63]. However, the range of transducer movements may be limited.

Overall, there are three methods to generate sonographic images using simulation [44]. The simplest ultrasound simulators use a "fetal" *phantom* that is scanned using a regular ultrasound machine. The phantom represents an organ system, or entire anatomic region [69]. Recently, an anatomy-based fetal pig simulator has also been used to improve the sonographic scanning skills of participants [70]. *Interpolative model-based simulators* generate 2D sonographic images based upon 3D volume datasets previously acquired during actual ultrasound exams [71]. The main advantage is that the images are realistic and include artifacts. However, generated images depend upon the original volume dataset acquired, along with its image quality, resolution, etc. Finally, *generative model-based simulators* reconstruct 2D ultrasound images *via* software. Such images are synthesized and therefore, appear "cartoon-like" and simplified [44]. However, both maternal and fetal anatomy are depicted on the computer screen and cardiac movement is also present [72]. The software reconstructs the corresponding 2D image, depending upon the angle at which the mock transducer is applied to the mannequin [44,69].

For a more detailed description of ultrasound simulators in obstetrics and gynecology (some of which have been reported in the scientific literature), the reader is referred to a recent and informative Editorial [44].

What are the current problems/gaps in ultrasound simulation?

There is clear evidence that simulation allows one to learn how to perform sonographic exams, and that there are a wide variety of simulators available. Yet, the following problems/gaps exist: 1) expense of equipment, technology and/or simulation centers; 2) equipment maintenance requirements; 3) need for specific types of equipment (e.g. ultrasound machine);

Figure 1. Optical positioning ultrasound simulator with a virtual convex transducer. The system is composed only of a flat-scanning pad (left), camera, and virtual convex transducer with optical positioning signs printed on the probe (right). A standard computer or laptop (not shown here) is used to load ultrasound cases.

4) requirement for a room, center or facility/space for labs (vs. a "personal" and portable simulator); 5) accessibility to trainees is limited; 6) cases are limited to those provided by the simulation manufacturer; 7) images may not be actual or real ultrasound images; 8) need for an on-site instructor to supervise and provide performance evaluation/feedback for trainees; and 9) time constraints of faculty or instructors. Moreover, the world of graduate medical education has changed, in that time limits are now placed on resident and fellow trainee work hours. Depending upon the degree of simulation fidelity, the price for equipment alone can range from several thousand to $250,000 [24].

What is optical positioning ultrasound simulation and how does this address the current gaps in simulation?

Optical positioning ultrasound simulation (Volutracer O.P.U.S.®; Medge Platforms, NY) is an innovative high--fidelity simulation learning system for ultrasound that is an interpolative model-based type of simulator (Figure 1, Video S1). There is no human model/mannequin or phantom involved. The technology uses a camera-based optical tracking system [71] in which the virtual transducer is imprinted with a black coded pattern (i.e. optical positioning signs) that is detected/tracked by the camera, allowing the sonographic image to be depicted on the computer screen (standard computer or laptop). The physical components include (Table 1): 1) camera (i.e. regular webcam); 2) flat scanning pad; 3) standard computer or laptop; and 4) virtual transducers that are similar in size and shape to real ultrasound transducers. Both convex (for "transabdominal" scanning) and transvaginal probes (Figure 2) are available. Due to a limited amount of hardware, the simulator is compact, portable and personal. This is relevant, since it allows multiple trainees to practice and learn simultaneously in a room using their own simulator. Moreover, personal ownership of a simulator allows one to practice indefinitely, and training can be performed at one's own individual pace.

The computer or laptop is used to load actual (vs. artificially created) ultrasound cases, which are 3D or

Table 1. Characteristics of the optical positioning ultrasound simulator.

Characteristics of Optical Positioning Ultrasound Simulator	
Overall characteristics	• High-fidelity simulation learning system (interpolative model-based type of simulator) • Optical tracking system • Camera (i.e. regular webcam), flat scanning pad, standard computer or laptop, virtual transducers • Human models/mannequins and phantoms are not required • Compact, portable and personal ^ Trainee can practice for an unlimited time, and training can be performed at an individual pace • Affordable
Virtual transducers	• Convex and transvaginal transducers • Optical positioning signs (black coded pattern) are imprinted on the transducers, which are detected/tracked by the camera • Transducers move with six degrees of freedom* to obtain any desired image ^ *Translational* movements in three perpendicular axes: 1) left/right; 2) up/down; 3) forward/back ^ *Rotational* movements about three perpendicular axes: 1) pitch (x-axis); 2) yaw (y-axis); 3) roll (z-axis) ^ Six degrees of freedom allows simulation of a real-time ultrasound examination, since the transducer may be moved in all these directions
Ultrasound cases	• Uses actual sonographic volume datasets that are organ-specific • Volume datasets are 3D or 4D STIC ^ 4D STIC volumes (fetal heart in motion) can be grayscale, color, or power Doppler ^ Color Doppler volumes of other organs • Original anatomy orientation can be modified (e.g. from fetal vertex to breech presentation) • Learning environment can be designed through a library of normal and abnormal ultrasound cases (including one's own) • Additional cases can be downloaded from an internet-based cloud
Sonographic images	• Real-time sonographic images (2D, color or power Doppler) are displayed on the computer screen that correlate with the virtual transducer position, placement, and orientation • Sonographic images are high-resolution, since they are derived from actual volume datasets • No noticeable lag between movement(s) of the virtual transducer and corresponding images (i.e. a smooth visual experience and minimal motion blurring)
Operational use	• Adjustable image settings (zoom, brightness, midtones, contrast, color controls) • Tutorial videos are available before each lesson (e.g. education about the *target plane*** of interest) • Two operational scanning modes: ^ *Freestyle Mode*: without any simulator instruction ^ *Guided (or GPS) Mode*: simulator voice commands, contextual videos and animation, graphic feedback to guide user toward obtaining the correct target plane of interest (i.e. "virtual teacher") □ *Fluency*: delivers information quickly and with expertise □ *Accuracy*: tracking system measures the position and rotation angle with an accuracy of within 1 mm and 1 degree, respectively • *Inclinometer*: depicts the accuracy of a plane obtained by the user compared to the target plane ^ Coordinates reflect the virtual transducer's movements relative to the target plane in three areas (Rock, Angle, Rotate) ^ Purpose is to visually understand which specific movement of the virtual transducer is incorrect • *Cube*: solo image showing the: 1) ultrasound volume dataset; 2) relationship of a plane obtained by the user vs. the target plane; and 3) distance to the target plane • Measurements using calipers are possible (e.g. length)
Performance metrics	• Recorded automatically by the simulator (e.g. time to obtain the target plane) • Based on a user's performance metrics, the simulation system can offer additional courses/lessons to address any limitations • Allows users to gain specific information to improve one's scanning skills • Simulator may be programed by an instructor to create specific target planes

*Degrees of freedom refers to the freedom of movement of a rigid body in three-dimensional space.
**Target plane refers to the "gold standard" plane of interest or the pre-determined "correct" sonographic image based on expert opinion.
2D: two-dimensional; 3D: three-dimensional; 4D: four-dimensional; GPS: guided positioning system; STIC: spatiotemporal image correlation.

four-dimensional (4D) spatiotemporal image correlation (STIC) volume datasets (grayscale, color Doppler, or power Doppler) that are organ-specific. Such approach makes the educational experience more targeted, since the sonologist is learning to scan a specific organ/anatomic area vs. a panoramic area. Real-time sonographic images (2D, color or power Doppler) are displayed on the computer screen that correlate with the virtual transducer position, placement, and orientation. Since 4D sonography with STIC technology allows acquisition of a fetal cardiac volume dataset and displays a cine loop of a complete single cardiac cycle in motion [73,74], the optical positioning ultrasound simulator depicts fetal hearts in motion. The sonographic 2D images are high-resolution and realistic in quality, since they are derived from actual volume datasets. The main advantage is that once a volume dataset has been obtained by a

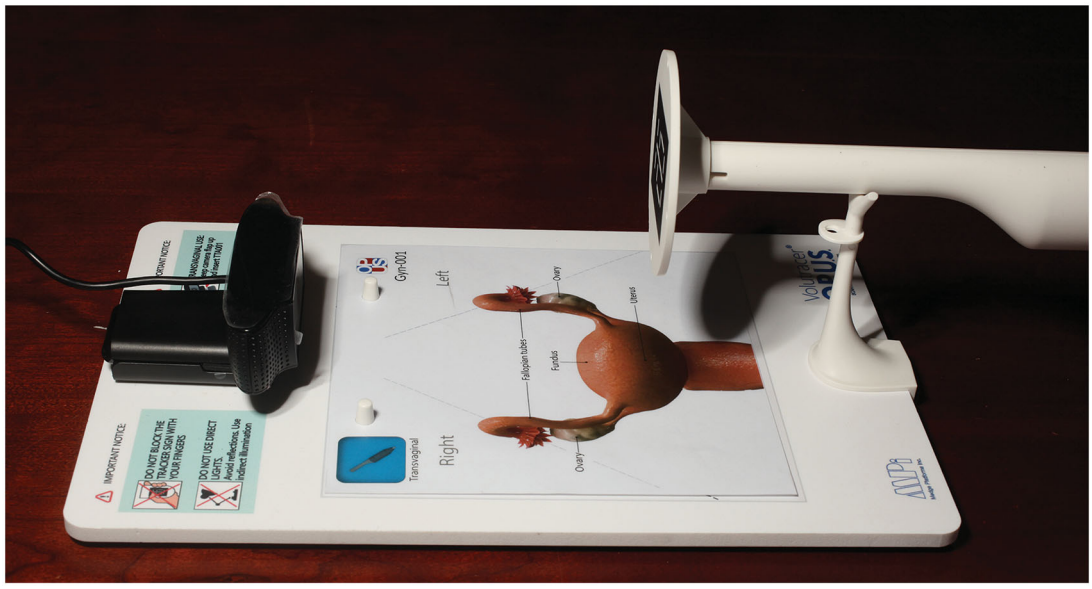

Figure 2. Optical positioning ultrasound simulator with a virtual transvaginal transducer. The system is composed only of a flat-scanning pad, camera (left side), and virtual transvaginal transducer (right) with optical positioning signs printed on a disk connected to the probe tip. The transducer is propped onto a plastic device to allow free mobility of the probe, similar to a real-time transvaginal sonographic examination. A standard computer or laptop (not shown here) is used to load ultrasound cases.

sonologist, the case can be examined indefinitely *via* the simulator by numerous users, enhancing both education and learning. This is especially invaluable in cases of fetal congenital anomalies or maternal pathology, which may be infrequently seen by some sonologists. Moreover, a learning environment may be designed around a library of normal and abnormal ultrasound cases, including one's own. Therefore, cases are not limited to only those provided by the manufacturer.

Since the optical positioning ultrasound simulator interrogates volume datasets, an argument could be made that such datasets could also be interrogated using software-based tools (rather than the simulation system) to study the anatomy. This is because a distinct characteristic of volumetric sonography is that datasets theoretically contain all the information acquired from the transducer sweep [13]. As a result, sonologists can dissect such datasets to examine anatomical areas of interest. Yet, this requires interaction of the operator with the 3D or STIC volume dataset *via* manual navigation (e.g. operating the x, y, z controls; scaling; and parallel shifting) [13]. Such navigation is often time-consuming and tedious, requiring considerable expertise.

A specific feature of the optical positioning ultrasound simulation system is that both of the virtual transducers may be manipulated using six degrees of freedom [75] to obtain any desired ultrasound image. This degree number allows for enhanced simulation of a real-time sonographic examination: 1) *translational* movements in three perpendicular axes: a) left/right; b) up/down; c) forward/back); and 2) *rotational* movements about three perpendicular axes; d) pitch (x-axis); e) yaw (y-axis); f) roll (z-axis). *Degrees of freedom* refers to freedom of movement of a rigid body in 3D space. By comparison, a computer mouse can only function with two degrees of freedom (i.e. left/right and forward/back). As a result, the optical positioning ultrasound simulator provides a realistic scanning experience that imitates both the transabdominal and transvaginal approaches. Specifically, angling and rotation of the transducers are possible.

The optical positioning ultrasound simulator has other unique characteristics that address the current problems/gaps in ultrasound simulation (described above), and these are depicted further in Table 1.

Scan modes and performance metrics of optical positioning ultrasound simulation

From a library of normal and abnormal cases (maternal or fetal), the sonologist loads a given case onto the computer. After placing the virtual transducer onto the flat scanning pad, the sonologist may "scan" in either of two operational scan modes: 1) *Freestyle*; and 2) *Guided or GPS (Guided Positioning System)*. For both modes, the goal of the trainee is to achieve an organ-specific *target plane*, which is considered the "gold standard" plane of interest, or the pre-determined "correct" sonographic image based upon expert

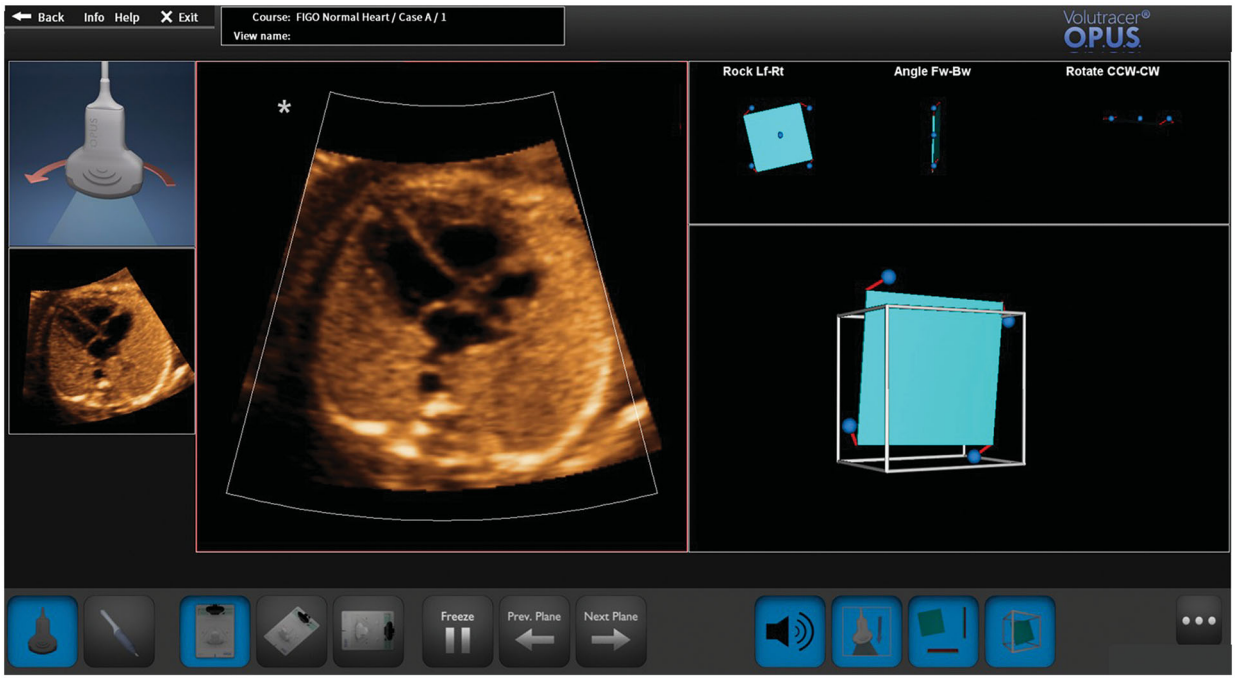

Figure 3. Scanning the fetal heart through the Guided (or GPS) mode of the optical positioning ultrasound simulator. A four-dimensional spatiotemporal image correlation volume dataset has been loaded onto the computer. The computer screen depicts the following: 1) *Target plane* (small image of four-chamber view) located on the left side of the screen; 2) *Plane being generated by the virtual transducer* (large image of the five-chamber view); 3) *Visual graphic* (left upper corner) provides instructions *via* contextual video and animation on how to move the virtual transducer to achieve the target plane; 4) *Inclinometer* (upper right panel showing 3 diagrams); and 5) *Cube* (lower right panel).

opinion. The simulator may be programed by the instructor to create specific target planes for users.

The *Freestyle* mode allows the user to scan without any simulator instruction, and is similar to conducting a real-time ultrasound examination. The *Guided or GPS* mode, however, provides: 1) simulator voice commands which instruct the user on how to manipulate the transducer (e.g. "tilt your probe forwards"); 2) contextual videos and animation; and 3) graphic feedback (see *inclinometer* and *cube* below) to guide the user toward obtaining the correct target plane of interest (e.g. four-chamber view) (Figure 3). Once the user has correctly reached the target plane, the word "OK" appears on the computer screen (Figure 4). It is noteworthy that the guidance provided by the simulator to reach the target plane is characterized by *fluency* (i.e. property of a system that delivers information quickly and with expertise), which is possible due to the six degrees of freedom associated with the virtual transducers (Figure 5) [76]. The simulator is also characterized by *accuracy*, because the optical tracking system measures the position and rotation angle with an accuracy of within 1 mm and 1 degree, respectively.

The term "GPS" is utilized because such scanning mode is similar to such navigation in a car, which guides the driver effortlessly toward a specific destination *via* voice commands and graphic imagery. Essentially, the simulator Guided mode provides an embedded "virtual teacher", similar to an experienced sonologist teaching a trainee at the bedside during an ultrasound exam. The virtual teacher monitors what the trainee is doing, and then provides specific guided instructions on how to correct transducer movement errors. Therefore, the simulator Guided mode now provides another option to improve performance in ultrasound examinations, in addition to the three currently used methods: 1) self-directed (i.e. autodidacticism); 2) observation of another sonologist scanning and duplication of transducer movements; and 3) coaching by an instructor at the bedside.

Optical positioning ultrasound simulation also has several features that allow understanding of the relationship between the plane obtained by the user and the target plane (Figure 3): 1) *Inclinometer*: depicts the accuracy of a plane obtained by the user compared to the target plane. The coordinates reflect the virtual transducer's movements relative to the target plane in three areas: a) Rock (right or left); b) Angle (forward or backward); c) Rotate (clockwise or counter-clockwise). The purpose is to understand visually which specific movement(s) of the virtual transducer is incorrect; and 2) *Cube*: a solo image comprised of: a) ultrasound

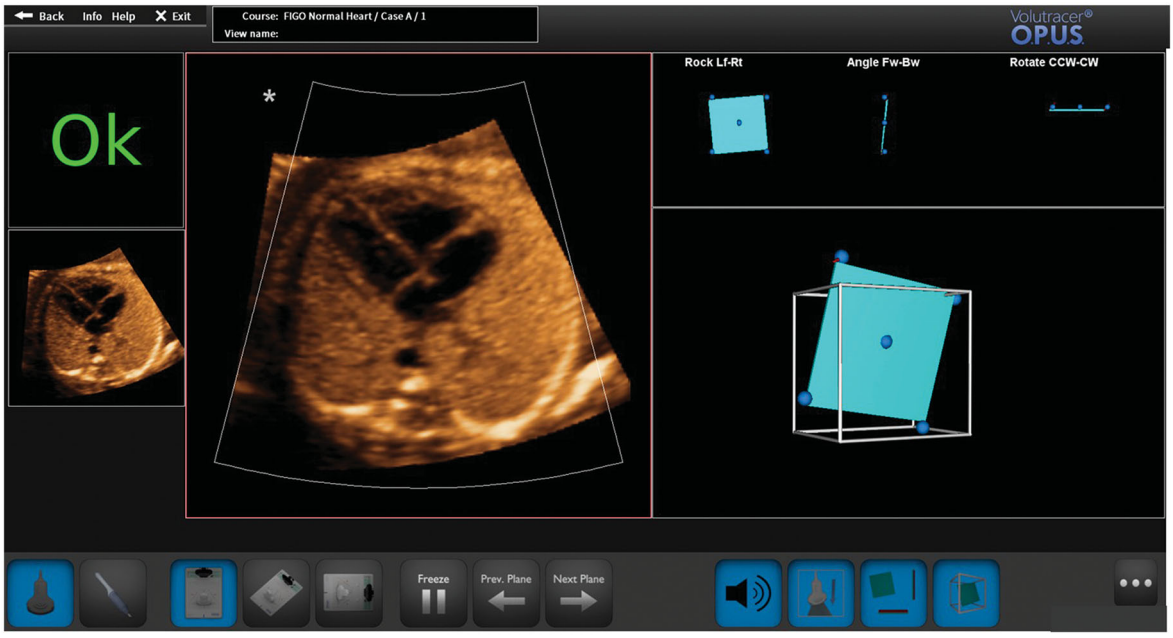

Figure 4. Target plane has been successfully obtained using the optical positioning ultrasound simulator. Compare this computer screen image to that of Figure 3. The target plane (i.e. four-chamber view) has successfully been obtained by the user using Guided (or GPS) mode. This is indicated by the word "OK" appearing on the computer screen. Notice that the target plane image (left side) completely matches the plane generated by the virtual transducer (large image in middle of screen). GPS: guided positioning system.

volume dataset; b) relationship of the plane obtained by the user vs. the target plane; and c) distance to the target plane.

The simulator also automatically records advanced metrics for performance and competency evaluation in scanning. This allows the establishment of a learning curve for users. Examples of such metrics include: 1) time to obtain the target plane of interest; 2) distance of transducer movements; and 2) accuracy of the achieved target plane (presented as a score). Based upon a user's performance metrics, the simulation system can offer additional courses or lessons to address any limitations. The advantage of providing empirical data is that it allows users to gain specific information to improve one's scanning skills.

Limitations

Since the optical positioning signs imprinted on the virtual transducers are detected and tracked by the camera, there are several requirements for sonographic images to be adequately depicted on the computer screen: 1) an adequate light source is necessary in the vicinity of the simulation system; and 2) the transducer face with the black coded pattern must always be in the line of sight of the camera. Therefore, if the transducer face is turned away from the camera, no sonographic image will be depicted, and a red warning sign ("Tracker sign not detected") will appear to alert the user.

Similarly to other interpolative model-based simulators, optical positioning ultrasound simulation generates sonographic images based upon volumetric datasets previously acquired during an actual ultrasound examination. Therefore, some limitations of the simulator are related to volumetric sonography: 1) an ultrasound machine that can acquire volume datasets is necessary; 2) volumetric datasets should be appropriate and of high quality so that they are informative, thus making this an operator-dependent task. For example, if there is fetal motion or shadowing present during volume acquisition, this will affect the simulated image on the computer screen. Moreover, if the region of interest (ROI) box or acquisition angle of the volume is inadequate, the target plane or anatomical structure(s) of interest may not be contained within the volume dataset. The ROI box determines the height (y-plane) and width (x-plane) of a volume dataset, while the acquisition angle determines the acquisition depth (i.e. amount of information acquired in the z-plane) [74]; and 3) if the acquisition plane of the volume dataset is a transverse plane (e.g. four-chamber view), sagittal planes depicted by the simulator (e.g. aortic arch) will be reconstructed and therefore,

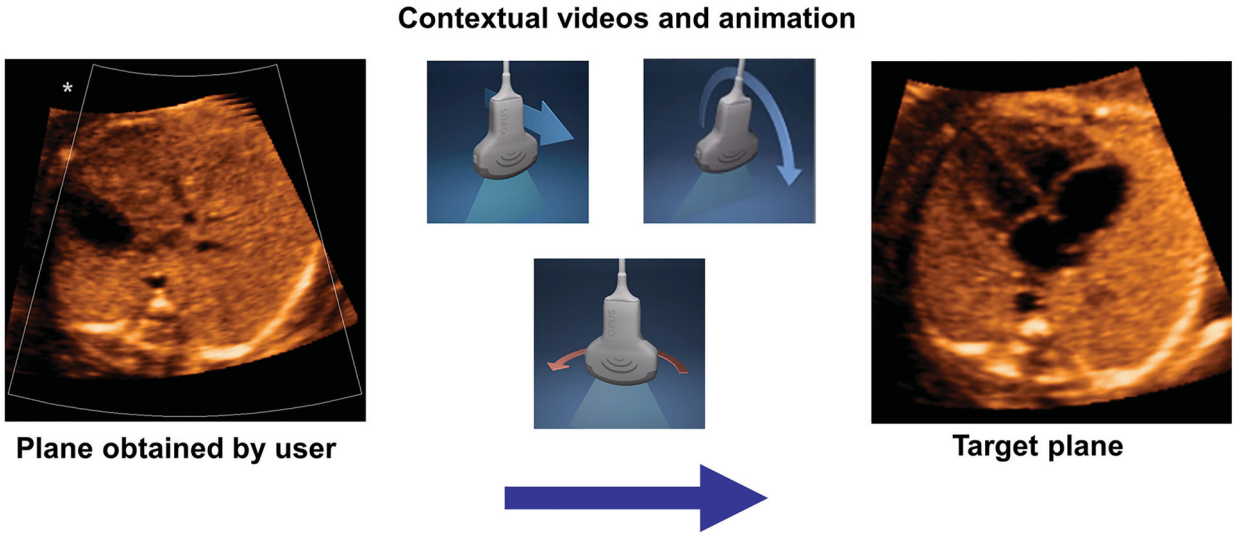

Figure 5. Concept of fluency in optical positioning ultrasound simulation. Guidance provided by the simulator to reach the target plane is characterized by *fluency* (i.e. property of a system that delivers information quickly and with expertise). This is possible due to the six degrees of freedom provided by the virtual transducers. For example, when a user is trying to obtain the target plane (i.e. four-chamber view) from the current plane (i.e. fetal stomach), the simulator provides detailed step-by-step instructions (through voice, video, and animation) on how to manipulate the virtual transducer (e.g. "tilt your probe forwards"). A series of sequential instructions are provided to reach the target plane, rather than providing just a single and simple direct movement instruction.

images will be characterized by a lower resolution than that of the acquisition plane. The acquisition plane is defined as the starting 2D plane for a volume acquisition [74].

Finally, while optical positioning ultrasound simulation provides a realistic scanning experience that *imitates* the performance of sonography, it can never replace real-time sonographic examination of an actual patient. The virtual transducer's movements during simulation cannot correspond exactly with that of an actual ultrasound scanning experience. Indeed, this applies to all current ultrasound simulation systems.

An increasing number of simulation companies have cases available on a "cloud" server. As a result, an image sharing network allows others to study reference datasets of cases with proven diagnoses using the simulator system. However, robust methods are necessary for quality control of shared cases by others, and also to ensure the integrity and privacy of image data loaded onto the cloud server.

Conclusions

Ultrasound examinations are recommended for all pregnant women. Yet, sonography is a highly operator-dependent modality that is challenging to master. Simulator training is a reliable tool to assess learners, and improves healthcare education and practice, as well as patient safety. There is broad consensus on the value of integrating simulation into ultrasound education and training programs. Ultrasound simulators are an innovative and effective means of teaching obstetric sonography, because it provides training, deliberate practice, and performance evaluation/feedback which allows continuous and critical self-evaluation. Moreover, teaching occurs in a controlled and safe environment, where skills can be practiced repetitively, and without patient anxiety and medicolegal concerns. Simulation-based training also allows trainees to practice a systematic approach to ultrasonography before the start of clinical training. Optical positioning ultrasound simulation is a high-fidelity simulation learning system which can address many of the current problems/gaps in ultrasound simulation, due to its unique characteristics.

Future studies are necessary to demonstrate that simulation training in obstetric ultrasound improves patient outcomes. Yet, our view is that enhancing traditional clinical education in sonography *via* simulation-based medical education and deliberate practice should be an important priority for our discipline.

Acknowledgments

Dr. Romero has contributed to this work as part of his official duties as an employee of the United States Federal Government. This article is a U.S. Government work and is in the public domain in the United States.

Disclosure statement

The authors report no conflict of interest.

Funding

This research was supported in part by the Perinatology Research Branch, Division of Intramural Research, Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD), National Institutes of Health (NIH), Department of Health and Human Services; and in part with federal funds from the NICHD, NIH, under contract [No. HHSN275201300006C].

References

[1] Abuhamad A, Minton KK, Benson CB, et al. Obstetric and gynecologic ultrasound curriculum and competency assessment in residency training programs: consensus report. J Ultrasound Med. 2018;37(1):19–50.

[2] Committee on practice bulletins—obstetrics and the american institute of ultrasound in medicine. practice bulletin No. 175: ultrasound in pregnancy. Obstet Gynecol. 2016;128:e241–e256.

[3] Salomon LJ, Alfirevic Z, Berghella V, et al. Practice guidelines for performance of the routine mid-trimester fetal ultrasound scan. Ultrasound Obstet Gynecol. 2011;37(1):116–126.

[4] Cargill Y, Morin L, Diagnostic Imaging Committee. Content of a complete routine second trimester obstetrical ultrasound examination and report. J Obstet Gynaecol Can. 2009;31(3):272–275.

[5] O'Keeffe DF, Abuhamad A. Obstetric ultrasound utilization in the United States: data from various health plans. Semin Perinatol. 2013;37(5):292–294.

[6] Saari-Kemppainen A, Karjalainen O, Ylöstalo P, et al. Fetal anomalies in a controlled one-stage ultrasound screening trial. A report from the Helsinki Ultrasound Trial. J Perinat Med. 1994;22(4):279–289.

[7] Grandjean H, Larroque D, Levi S. Sensitivity of routine ultrasound screening of pregnancies in the Eurofetus database. The Eurofetus Team. Ann N Y Acad Sci. 1998;847:118–124.

[8] Ewigman BG, Crane JP, Frigoletto FD, et al. Effect of prenatal ultrasound screening on perinatal outcome. RADIUS Study Group. N Engl J Med. 1993;329(12):821–827.

[9] Levi S. Ultrasound in prenatal diagnosis: polemics around routine ultrasound screening for second trimester fetal malformations. Prenat Diagn. 2002;22(4):285–295.

[10] Benacerraf BR, Minton KK, Benson CB, et al. Proceedings: beyond ultrasound first forum on improving the quality of ultrasound imaging in obstetrics and gynecology. J Ultrasound Med. 2018;37(1):7–18.

[11] Medical Imaging [Internet]. U.S. Food & Drug Administration. Available from: https://www.fda.gov/radiation-emitting-products/radiation-emitting-products-and-procedures/medical-imaging.

[12] Medical X-ray Imaging [Internet]. U.S. Food & Drug Administration. Available from: https://www.fda.gov/radiation-emitting-products/medical-imaging/medical-x-ray-imaging.

[13] Yeo L, Romero R. Intelligent navigation to improve obstetrical sonography. Ultrasound Obstet Gynecol. 2016;47(4):403–409.

[14] Tolsgaard MG. Assessment and learning of ultrasound skills in Obstetrics & Gynecology. Dan Med J. 2018;65:1–25.

[15] Eye-hand coordination [Internet]. Available from: https://en.wikipedia.org/wiki/Eye–hand_coordination.

[16] Carey DP. Eye-hand coordination: eye to hand or hand to eye? Curr Biol. 2000;10(11):R416–419.

[17] Bowman MC, Johansson RS, Johannson RS, et al. Eye-hand coordination in a sequential target contact task. Exp Brain Res. 2009;195(2):273–283.,

[18] Land M, Mennie N, Rusted J. The roles of vision and eye movements in the control of activities of daily living. Perception. 1999;28(11):1311–1328.

[19] Healthcare Simulation Dictionary. SSH (Society for Simulation in Healthcare) website [Internet]. Available from: https://www.ssih.org/dictionary.

[20] Lateef F. Simulation-based learning: just like the real thing. J Emerg Trauma Shock. 2010;3(4):348–352.

[21] The Link Flight Trainer: a Historic Mechanical Engineering Landmark. ASME (American Society of Mechanical Engineers) International website [Internet]. Available from: https://www.asme.org/wwwasmeorg/media/resourcefiles/aboutasme/who%20we%20are/engineering%20history/landmarks/210-link-c-3-flight-trainer.pdf.

[22] Ericsson KA. Acquisition and maintenance of medical expertise: a perspective from the expert-performance approach with deliberate practice. Acad Med. 2015;90(11):1471–1486.

[23] Vozenilek J, Huff JS, Reznek M, et al. See one, do one, teach one: advanced technology in medical education. Acad Emerg Med. 2004;11(11):1149–1154.

[24] Okuda Y, Bryson EO, DeMaria S, Jr, et al. The utility of simulation in medical education: what is the evidence? Mt Sinai J Med. 2009;76(4):330–343.

[25] Gaba DM. The future vision of simulation in health care. Qual Saf Health Care. 2004;13(suppl_1):i2–i10.

[26] Lumbreras-Marquez MI, Campos-Zamora M, Ramirez-De Avila AL, et al. Training for the surgical management of postpartum hemorrhage: a multicenter survey of resident physicians. J Matern Fetal Neonatal Med. 2019:1–7.

[27] Berkenstadt H, Ziv A, Gafni N, et al. The validation process of incorporating simulation-based accreditation into the anesthesiology Israeli national board exams. Isr Med Assoc J. 2006;8(10):728–733.

[28] Kudreviciene A, Nadisauskiene RJ, Tameliene R, et al. Initial neonatal resuscitation: skill retention after the implementation of the novel 24/7 HybridLab(®) learning system. J Matern Fetal Neonatal Med. 2019;32(8):1230–1237.

[29] Pittini R, Oepkes D, Macrury K, et al. Teaching invasive perinatal procedures: assessment of a high fidelity simulator-based curriculum. Ultrasound Obstet Gynecol. 2002;19(5):478–483.

[30] Linn BS, Zeppa R. Stress in junior medical students: relationship to personality and performance. J Med Educ. 1984;59(1):7–12.
[31] McGaghie WC, Issenberg SB, Cohen ER, et al. Does simulation-based medical education with deliberate practice yield better results than traditional clinical education? A meta-analytic comparative review of the evidence. Acad Med. 2011;86:706–711.
[32] Rose K, Kwan L, Pluym ID, et al. Forceps-assisted vaginal delivery: the landscape of obstetrics and gynecology resident training. J Matern Fetal Neonatal Med. 2019:1–7.
[33] Iitani Y, Tsuda H, Ito Y, et al. Simulation training is useful for shortening the decision-to-delivery interval in cases of emergent cesarean section. J Matern Fetal Neonatal Med. 2018;31(23):3128–3132.
[34] Draycott TJ, Crofts JF, Ash JP, et al. Improving neonatal outcome through practical shoulder dystocia training. Obstet Gynecol. 2008;112:14–20.
[35] Seymour NE, Gallagher AG, Roman SA, et al. Virtual reality training improves operating room performance: results of a randomized, double-blinded study. Ann Surg. 2002;236(4):458–463.
[36] Blum MG, Powers TW, Sundaresan S. Bronchoscopy simulator effectively prepares junior residents to competently perform basic clinical bronchoscopy. Ann Thorac Surg. 2004;78(1):287–291.
[37] Barsuk JH, Cohen ER, Feinglass J, et al. Use of simulation-based education to reduce catheter-related bloodstream infections. Arch Intern Med. 2009; 169(15):1420–1423.
[38] Draycott T, Sibanda T, Owen L, et al. Does training in obstetric emergencies improve neonatal outcome? BJOG Int J O&G. 2006;113(2):177–182.
[39] Issenberg SB, McGaghie WC, Petrusa ER, et al. Features and uses of high-fidelity medical simulations that lead to effective learning: a BEME systematic review. Med Teach. 2005;27(1):10–28.
[40] Bosse HM, Mohr J, Buss B, et al. The benefit of repetitive skills training and frequency of expert feedback in the early acquisition of procedural skills. BMC Med Educ. 2015;15(1):10.
[41] McGaghie WC, Issenberg SB, Petrusa ER, et al. Effect of practice on standardised learning outcomes in simulation-based medical education. Med Educ. 2006; 40(8):792–797.
[42] Medical simulation in medical education: results of an AAMC survey. Association of American Medical Colleges website [Internet]. Available from: https://store.aamc.org/medical-simulation-in-medical-education-results-of-an-aamc-survey-pdf.html.
[43] Okuda Y, Quinones J. The use of simulation in the education of emergency care providers for cardiac emergencies. Int J Emerg Med. 2008;1(2):73–77.
[44] Chalouhi GE, Bernardi V, Ville Y. Ultrasound simulators in obstetrics and gynecology: state of the art. Ultrasound Obstet Gynecol. 2015;46(3):255–263.
[45] Simulation [Internet]. 2020. Available from: https://en.wikipedia.org/wiki/Simulation.
[46] Ericsson KA, Krampe RT, Tesch-Römer C. The role of deliberate practice in the acquisition of expert performance. Psychol Rev. 1993;100(3):363–406.
[47] Macnamara BN, Hambrick DZ, Oswald FL. Deliberate practice and performance in music, games, sports, education, and professions: a meta-analysis. Psychol Sci. 2014;25(8):1608–1618.
[48] McGaghie WC, Siddall VJ, Mazmanian PE, et al. Lessons for continuing medical education from simulation research in undergraduate and graduate medical education: effectiveness of continuing medical education: American College of Chest Physicians Evidence-Based Educational Guidelines. Chest. 2009; 135(3 Suppl):62S–68S.
[49] Croskerry P. The feedback sanction. Acad Emerg Med. 2000;7(11):1232–1238.
[50] Autodidacticism [Internet]. 2020. Available from: https://en.wikipedia.org/wiki/Autodidacticism.
[51] Nitsche JF, Brost BC. Obstetric ultrasound simulation. Semin Perinatol. 2013;37(3):199–204.
[52] Chalouhi GE, Bernardi V, Gueneuc A, et al. Evaluation of trainees' ability to perform obstetrical ultrasound using simulation: challenges and opportunities. Am J Obstet Gynecol. 2016;214(4):525.e1–525.e8.
[53] Burden C, Preshaw J, White P, et al. Usability of virtual-reality simulation training in obstetric ultrasonography: a prospective cohort study. Ultrasound Obstet Gynecol. 2013;42(2):213–217.
[54] Rosen H, Windrim R, Lee YM, et al. Simulator based obstetric ultrasound training: a prospective, randomized single-blinded study. J Obstet Gynaecol Can. 2017;39(3):166–173.
[55] Tolsgaard MG, Ringsted C, Dreisler E, et al. Sustained effect of simulation-based ultrasound training on clinical performance: a randomized trial. Ultrasound Obstet Gynecol. 2015;46(3):312–318.
[56] Lee K, Kim SY, Choi SM, et al. Effectiveness of prenatal ultrasonography in detecting fetal anomalies and perinatal outcome of anomalous fetuses. Yonsei Med J. 1998;39(4):372–382.
[57] Skupski DW, Newman S, Edersheim T, et al. The impact of routine obstetric ultrasonographic screening in a low-risk population. Am J Obstet Gynecol. 1996;175(5):1142–1145.
[58] Eurenius K, Axelsson O, Cnattingius S, et al. Second trimester ultrasound screening performed by midwives; sensitivity for detection of fetal anomalies. Acta Obstet Gynecol Scand. 1999;78(2):98–104.
[59] Levi S, Schaap JP, De Hava P, et al. End result of routine ultrasound screening for congenital anomalies: the Belgian Multicentric study 1984–92. Ultrasound Obstet Gynecol. 1995;5(6):366–371.
[60] Maul H, Scharf A, Baier P, et al. Ultrasound simulators: experience with the SonoTrainer and comparative review of other training systems. Ultrasound Obstet Gynecol. 2004;24(5):581–585.
[61] Heer IM, Middendorf K, Müller-Egloff S, et al. Ultrasound training: the virtual patient. Ultrasound Obstet Gynecol. 2004;24(4):440–444.
[62] Moak JH, Larese SR, Riordan JP, et al. Training in transvaginal sonography using pelvic ultrasound simulators versus live models: a randomized controlled trial. Acad Med. 2014;89(7):1063–1068.
[63] Madsen ME, Konge L, Nørgaard LN, et al. Assessment of performance measures and learning curves for use

of a virtual-reality ultrasound simulator in transvaginal ultrasound examination. Ultrasound Obstet Gynecol. 2014;44(6):693–699.

[64] Meller G. A typology of simulators for medical education. J Digit Imaging. 1997;10(3 Suppl 1):194–196.

[65] Meller G, Tepper R, Bergman M, et al. The tradeoffs of successful simulation. Stud Health Technol Inform. 1997;39:565–571.

[66] Ehricke HH. SONOSim3D: a multimedia system for sonography simulation and education with an extensible case database. Eur J Ultrasound. 1998;7(3): 225–300.

[67] Weidenbach M, Wick C, Pieper S, et al. Augmented reality simulator for training in two-dimensional echocardiography. Comput Biomed Res. 2000;33(1):11–22.

[68] Scantrainer. 2020. Intelligent ultrasound [Internet]. Available from: https://www.intelligentultrasound.com/scantrainer/.

[69] Lewiss RE, Hoffmann B, Beaulieu Y, et al. Point-of-care ultrasound education: the increasing role of simulation and multimedia resources. J Ultrasound Med. 2014;33(1):27–32.

[70] Akoma UN, Shumard KM, Street L, et al. Impact of an inexpensive anatomy-based fetal pig simulator on obstetric ultrasound training. J Ultrasound Med. 2015; 34(10):1793–1799.

[71] Liu L, Kutarnia J, Belady P, et al. Obstetric ultrasound simulator with task-based training and assessment. IEEE Trans Biomed Eng. 2015;62(10):2480–2497.

[72] Vimedix. 2020. CAE Healthcare [Internet]. Available from: https://caehealthcare.com/ultrasound-simulation/vimedix/.

[73] Yeo L, Romero R. How to acquire cardiac volumes for sonographic examination of the Fetal Heart: Part 1. J Ultrasound Med. 2016;35(5):1021–1042.

[74] Yeo L, Romero R. How to acquire cardiac volumes for sonographic examination of the Fetal Heart: Part 2. J Ultrasound Med. 2016;35(5):1043–1066.

[75] Six degrees of freedom [Internet]. 2020. Available from: https://en.wikipedia.org/wiki/Six_degrees_of_freedom.

[76] Fluency [Internet]. 2020. Available from: https://en.wikipedia.org/wiki/Fluency.