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REVIEW ARTICLE

Accuracy of Ultrasound Measurements by Novices: Pixels or Voxels

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ABSTRACT

During the last two decades three-dimensional (3D) ultrasound has become increasingly popular around the world. There have been a great number of research papers studying its feasibility as well as reliability and accuracy. Compared to two-dimensional (2D), 3D ultrasound produces better visualization with minimal probe manipulation. The sonographer performing 2D ultrasound has to mentally assemble cross-sectional images of a structure and/or object into a 3D image. In cases with uncertain anatomic orientation less experienced examiners may experience difficulties in envisioning three dimensions of the visualized structure, lesion or organ. Patients and parents are often faced with similar problems. A number of studies have shown that novice operators can efficiently store and interpret the volume data by 3D ultrasound, which may have many positive implications in the practice.

Keywords: Novice, 3D ultrasound, 2D ultrasound.

INTRODUCTION

Three-dimensional ultrasound examination has four major steps: Data acquisition, 3D visualization, volume and/or image processing and storage of the volumes, images or sequences. A deluge of research across medical and surgical disciplines continuously demonstrates feasibility, reproducibility and validity of 3D ultrasound method.[1-6] 3D ultrasound consistently demonstrates better performance than 2D ultrasound in fetal biometry, assessment of gynecologic organs and lesions as well as imaging of the cardiovascular and musculoskeletal disorders.[7-12] For decades, computed tomography (CT) and magnetic resonance imaging (MRI) have enjoyed their unrivaled position as the superior diagnostic tools. However, with ease of use, lack of harmful ionizing radiation and cost effectiveness, 3D ultrasound presents as a very competitive imaging modality.

Compared to 2D, 3D ultrasound produces better visualization with minimal probe manipulation; meaning that the first step of the ultrasound examination, data acquisition, may be performed by operators who do not need to be extensively trained. Consequently, less experienced operators are able to perform tasks that have previously been reserved only for experienced sonographers. Given the important economic implications, there has been an increase of interest in studying the possibility of having less experienced sonographers, or even novices perform other steps of 3D ultrasound examination. The aim of this paper is to review the potential role of non-experts in performing 2D and 3D ultrasound and summarize data which were reported across disciplines.

2D ULTRASOUND

Sonography is based on different tissue interfaces within the body that scatter acoustic energy. The reflected energy is used to generate high-resolution, gray-scale images of the body as well as blood flow. Piezoelectric crystals in the transducer generate sound pulses used in sonography. Echoes return to the transducer and deform the crystals to produce a returning electrical pulse, which is then processed into an image. The larger the returning electronic pulse is, the brighter the image pixels will be. Brightness mode or B-mode is also known as two-dimensional gray-scale.[13] 2D imaging is used to evaluate anatomic distance and volume measurements, motion studies, blood velocity and 3D imaging. Harmonic imaging, 3D acquisition, power Doppler, and contrast agents are the focus of recent research and clinical practice.[14]

Ultrasound is not only used for obstetric imaging but also evaluates the cardiovascular, renal, hepatobiliary, ophthalmic and musculoskeletal systems. It can also be used for microinvasive procedures and biopsies and thermal sonography treatments. B-mode imaging is quite subjective due to operator dependent scanning and formula-based quantitative estimates. Sonography is a valuable imaging method with several advantages as compared to other imaging modalities, such as CT and MRI. Major advantages of sonography are lack of ionizing radiation, real-time nature of examination, multiplanar capability, portable nature of equipment and low cost.[15]

The most important drawback of 2D ultrasound is that the images are acquired in two of the three cardinal planes. Sagittal and transverse planes are obtained by transabdominal ultrasound, while the coronal plane is not accessible. Similarly, by transvaginal ultrasound the sagittal and coronal planes are obtainable, while the transverse plane could not be accessed.

3D ULTRASOUND

Three-dimensional ultrasound was first demonstrated in the 1970s. 3D imaging uses a series of individual 2D B-scans of a volume of tissue to form the 3D data set by using known acquisition geometries of each 2D image. 3D ultrasound acquisitions can be accomplished by using linear, wedge, freeform and circular formats.[15]

Display techniques for 3D ultrasound imaging can be divided into three broad classes: Surface-based, multiplanar and volume-based rendering. The most common 3D display technique is based on visualization of surfaces of structures or organs. The operator or algorithm analyzes each voxel in the 3D image and determines the structure to which it belongs.[16] The boundaries of anatomical structures can be identified by the operator using manual contouring,[17-19] or by simple thresholding or more complex statistical algorithms and geometric properties of parts of the 3D image. Once the tissues or structures have been classified and their boundaries identified, the boundary is represented by a wire-frame or mesh and the surface is texture mapped with an appropriate color and texture to represent the anatomical structure. Wire-frame rendering has been used for displaying fetal anatomy,[20-22] various abdominal structures and cardiac imaging.[18,23-28]

Multiplanar viewing requires that either a 3D voxel-based image be reconstructed first or an algorithm be developed that extracts any arbitrarily oriented plane from the originally acquired images. Computer user-interface tools allow selection of single or multiple planes to create images similar to conventional 2D ultrasound and may be displayed on the screen simultaneously.[29-30] Another approach is based on multiplanar visualization with texture mapping. The 3D image presents as a polyhedron representing the boundaries of the reconstructed volume.[31] User interface tools allow the polyhedron to be rotated to the desired orientation of the image. This method allows the operator to have 3D image-based cues of the plane being manipulated in regard to the rest of the anatomy.[32-35]

Volume rendering presents the viewer with a display of the entire 3D image after it has been projected onto a 2D plane. The most common approach used in 3D ultrasound is the ray-casting technique,[36-38] which projects a 2D array of rays through the 3D image. Each ray intersects the 3D image along a series of voxels. The voxel values along each ray are examined and weighted to achieve the desired rendering result.

Ultrasound provides tomographic images at a high rate (15-60 images per second), and the orientation of the images is arbitrary and under user control, whereas CT and MR images are usually acquired at a low rate as a stack of parallel slices. The high rate of image acquisition, the arbitrary orientation of the images, and the unique problems imposed by ultrasound image speckle, shadowing and distortions are the most common technical problems to overcome in the applicability of 3D ultrasound.[39]

In echocardiography, 3D ultrasound has produced impressive results that are comparable to MRI.[2,40-41] MRI, may not be readily available in all clinical settings, is expensive and relatively contraindicated in patients with implanted medical devices, such as pacemakers, brain aneurysm clips, implanted neural simulators, cochlear implants, ocular foreign body, insulin pump or metal shrapnel or bullet.[41] MRI scans may require general anesthesia with possible mechanical ventilation and multiple breath holds which can interfere with hemodynamic stability of very ill patients.[2] On the other hand, 3D echocardiography (3DE) faces a different set of challenges, such as lower frame rates[40-41] and positioning constraint of large transducers on small-sized pediatric patients.[2] Newer 3D ultrasound technology holds the key to improving 3DE by having higher frequency, smaller sized probes and single-beat volume acquisition.

2D *VS* 3D ULTRASOUND

The advent of 3D ultrasound followed by a surge of research evaluating its accuracy and reliability results in a hypothesis that 3D ultrasound is superior to 2D ultrasound. Riccabona et al analyzed the accuracy of 2D and 3D ultrasound in distance and volume measurements in a series of *in vitro* experiments comparing the ultrasound assessment with real objects' volumes.[42-43] They showed that 3D ultrasound produced more accurate volume measurements compared to 2D method, especially for irregular shaped objects. Since 2D ultrasound utilizes the ellipsoid formula (length × width × depth × 0.524) to obtain approximation of volume rather than measuring the actual volume itself, estimation of irregular shaped objects would show more deviation from the true measurement. On the other hand, 3D ultrasound employs several techniques to calculate volume: inversion, segmentation, manual planimetry, and virtual organ computer-aided analysis (VOCAL), with VOCAL being the most accurate and frequently used method.[44] Using VOCAL, our currently undergoing research project also demonstrates that 3D provides more accurate volume measurements than 2D in both regular and irregular shaped structures. Additionally, we found that 2D ultrasound is less accurate in measuring an irregular shaped structure (breast carcinoma) than a regular shaped structure (gestational sac).

As with any imaging procedure that requires human interpretation, reproducibility, intra-observer and inter-observer variations are major concerns of quality assurance. Reproducibility in 3D ultrasound has been consistently demonstrated across medical specialties.[1-12] It has been shown that 3D reduces intra-observer and inter-observer variations in comparison to 2D ultrasound.[8-12] Since ultrasound is often used to follow fetal growth, monitor tumor size and document the progress of diseases, reliable measurements are critical to observation and treatment process. The reliability of 3D ultrasound has been demonstrated in both *in vitro*[42-43,45] and *in vivo* studies. *In vitro* studies have the ability to verify acquired measurements against the actual objects but they are laboratory-based. Conversely, *in vivo* studies represent the real condition on which ultrasound is used, but lack the ultimate verification against true measurements. Creative measures were carried out to replace inorganic objects, such as water-filled balloons or condoms with animal tissues like bovine liver and chicken breast in order to mimic real human tissue.[45] Ideally, ultrasound measurements should be compared with the actual organ or structure obtained after excisional surgery; but obviously this approach is not easily achieved.

Three-dimensional ultrasound allows separate process of data acquisition and interpretation. The total time of data acquisition is significantly reduced with 3D. Benacerraf et al showed that a traditional 2D fetal anatomy survey took an average of 19.6 minutes while 3D data acquisition only took 1.8 minutes.[46] Including approximately 5 minutes of off-line 3D interpretation, the entire process of fetal anatomy survey by 3D took slightly more than one-third of the time needed for the traditional 2D exam. This has the potential to lessen the repetitive motion injuries faced by sonographers.[46] Since 3D datasets can be analyzed on computers separately from the ultrasound machine without patients present, this allows efficient usage of ultrasound equipment and increase the number of patients examined.[47] Additionally, saved volumes can be used for a second opinion or examining an area of interest not recognized by sonographers during 2D scanning, without having to re-scan the patient.[46]

Improved images not only help sonographers but also enable the lay public to visualize and understand what they are looking at. This could have tremendous psychological impact on parental-fetal bonding, allowing parents to understand any fetal abnormalities or reassuring them of normal growth. A study of prenatal 3D ultrasound perception by medical professionals and the educated public represented by undergraduate students revealed that both groups would like to have 3D ultrasound for themselves in the future and believed it was valuable, although the student group was much more enthusiastic than the medical professional group (83 and 93% for the students *vs* 63 and 62% for the professionals respectively).[48] Given the public awareness of 3D ultrasound, health care providers should be familiar with 3D ultrasound and ready to offer it to the patients.

Despite the increasing reputation of 3D ultrasound, researchers in the field of fetal biometry recommend that 3D ultrasound should not be used alone, but in combination with 2D sonography to assess fetal anatomy and anomalies.[47,49] Contrarily, Goncalves et al concluded that 3D and four-dimensional (4D) ultrasound alone were adequate.[50]

However, in certain circumstances, 3D does not outperform 2D ultrasound.[51-52] Viewing 3D data sets in planes other than the plane of acquisition may reduce the image quality, and real time mode has better resolution than static mode.[49] Sometimes, during rotations of 3D image, certain components of the structure become difficult to identify, such that some 3D fetal anatomy scans do not reveal all of the anatomic landmarks which may lead to missed recognition of fetal anomaly.[46] However, given its numerous advantages and steady technical improvement, 3D ultrasound should be evaluated continually and utilized where it has been proven useful.

NOVICES IN ULTRASOUND

One of the biggest challenges in 2D ultrasound is the maneuvering of the probe to obtain the specific standard views from which the measurements are generated.[53-54] Additionally, sonographers have to mentally construct a 3D image of the structure while scanning in 2D.[55] This is a skill that only comes with highly trained and experienced sonographers. Computational integration and software advances available with 3D ultrasound reconstruct the structure in three dimensions, essentially allowing operators with little experience to visualize the structure clearly. Specifically, in echocardiography, 3D ultrasound can compensate for sonographer's inexperience, such that novices generate more accurate results using 3DE than 2DE.[53] The novices in this study were three cardiology fellows with 1 to 3 weeks of echocardiographic training. It was found that by using 3DE, the novices were able to produce similar results as the experts who use 2DE. This is possible because 3DE allows incorporation of data from off-axis views with minimal distortion and utilizes flexible volume computation algorithm that integrates even partial endocardial contours. Despite the favorable results, the authors did not recommend inexperienced sonographers to replace experienced sonographers because 3DE also improved the accuracy of experts and within the same ultrasound modality experts have always outperformed novices.[53] Additionally, the study utilized an expert reader to analyze the images. Given the complexity of cardiac anatomy and the difficulty of cardiac ultrasound image interpretation, a less experienced reader may not be able to reliably analyze the images acquired by novices.[53]

In contrast to the 3DE study, Moawad suggested that ovarian follicle count can be done by novices using off-line 3D data sets since the novice's 3D count is similar to the expert's 2D count.[56] The novice was a resident in the obstetrics and gynecology department, who had received basic training in sonography and only one hour of instructions including 3D interpretation with VOCAL. Using real-time 2D ultrasound, a transvaginal probe was used to identify the follicles from one ovary at a time, which could be time-consuming and uncomfortable for the patients. Ovaries with more than ten follicles show more count variation.[56] Although the difference between the novice's 3D and expert's 2D counts is twice as large as the difference between the expert's 2D and 3D counts (22% *vs* 10%), novice's 3D count may be used to substitute expert's 2D count depending on the cut-off point of acceptable count variation without affecting patient treatments. When both the expert and novice used 3D ultrasound, the count difference was reduced to 16%, which suggests that when 3D ultrasound is exclusively used to count follicles, the intermethod variation can be eliminated. The period of time it takes to train a sonographer to adequately assess ovarian follicles is extensively longer than the time it takes to train a novice to count the follicles using 3D ultrasound. It is likely that providing more training in interpretation from stored 3D data sets, novices can perform the follicle count accurately and reliably.[56]

Another potential area where novices can be of use is the computer-based volume measurement of stored 3D ultrasound data sets. Though not as challenging as performing a 2D ultrasound scan, acquiring 3D data can take some time to learn, especially the freehand technique. Since the data acquisition process is not involved in measuring from stored volumes, these novices neither need to be trained to operate ultrasound machines nor do they need to understand the physiomechanical aspect of scanning or have the basic ultrasonography knowledge.

Our current research project studied a group of 30 medical students who have no experience in either 2D or 3D ultrasound scanning and interpretation. They were asked to measure the volumes of three structures: Liver, gestational sac and a breast lesion using VOCAL, after a 5-minute tutorial. The results showed that as a group, their measurements were comparable to those of the experts, especially in a structure with clear margin, such as the gestational sac. Our data suggested that with an additional training session, complete novices without any ultrasound knowledge have the potential to perform accurate volume measurements of stored 3D ultrasound data sets.

With VOCAL, volume measurement is obtained through a series of rotations around a fixed axis. After each rotation, the contour of the structure of interest is retraced. Increasing number of rotational steps or decreasing the rotational angle of each turn results in enhanced surface details and more accurate volume measurement. With options of 6°, 9°, 15° and 30° rotation angle, correlating with 30, 20, 12 and 6 rotations, operators can choose the level of detail they want. However, completing 30 tracings per structure can be a time-consuming and tedious process. Other techniques, such as inversion and manual segmentation are sometimes used to save time; however, the inversion mode is not possible with solid organs and manual segmentation tends to overestimate.[44] Given its time-consuming limitation, VOCAL measurement by lay people has the potential to be extremely valuable. We speculate that the contour tracing speed is responsible for the time-consuming VOCAL measurement. Maneuvering the mouse to accurately follow the structure's margin can prove a tough challenge for novices and may take too long to be economically efficient. Our current study employed a pen-like mouse (trade name: Bamboo Pen by Wacom), which allows users to hold the mouse as a pen. With the traditional mouse, users control the mouse by moving the whole hand and fine movements are more difficult to achieve. The Bamboo Pen let the users outline the margin of the structure as if they were drawing with an actual pen. This improves the tracing speed significantly. Our volunteers who have never done a VOCAL measurement or used a Bamboo Pen can complete a structure with 12 tracings (15° rotation) in less than five minutes, which is approximately half the speed of the non-novice sonographers who performed 6 tracings (30° rotation) in approximately one minute.[44]

The level of experience of the sonographers affects scanning and acquisition times. Yang et al reported that inexperienced operators have spent a significantly longer time than experienced operators in obtaining standard views in real time 2D ultrasound scanning.[57] Fetal movement, unfavorable position and complex anatomy all contribute to the difficulty of performing 2D fetal biometry by an operator with little experience. Since 3D ultrasound allows viewing in any plane regardless of the plane of acquisition, an inexperienced operator can acquire a plane that is close to a standard plane in 2D and then perform multiplanar analysis to reconstruct the standard view for measurement. This also reduces the time the novice spends manipulating the probe to find the correct plane. Hence, it is recommended that inexperienced sonographers can use 3D ultrasound to overcome difficulty in obtaining standard planes or to familiarize themselves with the anatomy, which can later help them visualize and perform better in 2D mode.[57]

The ease of use of 3D ultrasound opens up many opportunities in medical practice. Unlike 2D ultrasound, novices with less training and experience can serve as operators. It allows for 3D scanning and remote expert interpretation, which can be exceedingly valuable in areas with less access to specialized services.[53] A recent study suggested using real-time 3D ultrasound operated by minimally-trained operator with the assistance of an outside expert to detect abdominal hemorrhage in the field setting.[58] In another study, a group of 20 second-year medical students with no prior experience in ultrasound received 10 minutes of instructions before successfully imaging the abdominal aorta and the kidney with remote assistance from experts.[59] In this study, the authors investigated the effect of a novel system that allowed the experts to give guidance via a visual system. With this system, the students were able to see the desired plane and the current plane in both 2D and 3D on a separate computer screen next to the ultrasound machine. This allowed them to picture the orientation and adjust the current plane to line up with the desired plane. The visual guidance system helped the students to produce more adequate visualization of the anatomy than with verbal guidance alone.[59]

Besides being a very useful teaching tool,[59] 3D ultrasound also allows for a rapid training period for novices. In echocardiography, basic assessment of the hemodynamic state by a novice using a third generation handheld device could be achieved only after 20 echo studies and all measured parameters were achieved after 40 studies.[60] Similarly, after attending an online course on nuchal translucency measurement, a medical student with no knowledge of ultrasound was able to measure nuchal translucency thickness with an intraoperator reliability approximating that of the expert's level.[61]

A recent retrospective study revealed that the clinical outcomes of ultrasound-guided embryo transfer do not depend on the experience of the operator performing ultrasound guidance.[62] Both the reproductive endocrinology and infertility fellow with over four years of ultrasound experience and the medical assistant without any formal ultrasound training produced similar pregnancy and live birth rates in a group of 201 and 118 women respectively. The medical assistant became familiar with using the ultrasound equipment while being guided by the physician who performed the embryo transfers. The use of a medical assistant instead of a physician or an experienced sonographer as the ultrasound operator not only has important financial implications, but also is feasible because the physician can aid the untrained operator initially and the operator's skills will likely improve with successive procedures.[62]

Along with the advancement of 3D ultrasound, the use of novices has become a real possibility and has been investigated and proven success by many studies, especially during the course of the past two years (Table 1). However, we need to keep in mind that novices may be able to perform relatively simple tasks, such as operating ultrasound guidance for embryo transfer or producing images of the abdominal aorta or kidney in the correct plane with remote assistance; but experience is still immensely important in sophisticated sonographic tasks. For instance, residents/fellows in obstetrics and gynecology with at least six months of gynecologic ultrasound training performed significantly poorer than experts in recognizing patterns of malignant adnexal masses in static 2D ultrasound images.[63] Similarly, physicians with experience in abdominal ultrasound but not familiar with contrast-enhanced ultrasound were less able to differentiate between benign and malignant liver tumors by interpreting tumor enhancement pattern after contrast injection.[64] Since both of these studies involved the use of static 2D images, the results may not be extrapolated to static or real-time 3D.

One limitation of the current literature involving the study of novice and expert performances in 3D ultrasound is the small number of participants. Most studies included only one novice operator (see Table 1). Unlike experts who have acquired a certain degree of performance stability, novices' performance can be easily influenced by multiple personal aspects, such as motivation, skillfulness, effort, concentration ability and willingness to learn. To avoid selection bias, studies with large number of novices are needed. Additionally, these novices are often residents or fellows who may possess above average mental capability, overall anatomy knowledge and learning receptiveness. Utilizing these novices may have little improvement in the economic impact of replacing experienced sonographers.

Our study of volume measurements using stored 3D data, including 30 novices, 15 sonographers and three experts, has just been completed. Its moderately large sample size promises statistically significant results.

Table 1: Ultrasound studies involving novices

Reference	*Novice and training*	*N*	*Activity*	*Performance compared with expert*
Yang et al[57] (2010)	3-month training in 2D and 3D	1	Fetal biometric measurement of 50 pregnancies	Novice produced reproducible results and showed good agreement with expert Same image quality score Novice 2D is three times slower Novice 3D is two times slower (expert uses 2D only)
Abele et al[61] (2010)	Medical student, no experience in US, attended one on line course	1	Measure fetal nuchal translucency thickness from 70 stored images	Using semiautomated inner-inner method, student produced accurate and reliable measurements
Sheehan et al[59] (2010)	Medical students, no experience in US, received 10 minutes of instruction	20	Imaged abdominal aorta and right kidney using visual guidance and verbal guidance	Both groups produced adequate and accurate anatomical visualization. Student group receiving visual guidance were more successful than the group receiving verbal guidance alone
Harris et al[62] (2009)	Medical assistant with on-the-job learning experience	1	Perform ultrasound guidance for embryo transfer	Produced similar pregnancy outcomes (pregnancy rate and live-birth rate) as the fellow with > 4 years of ultrasound experience
Moawad et al[56] (2009)	Ob-Gyn resident, had basic sonographic training and 1 hour of VOCAL training	1	Count ovarian follicles using 3D US in 50 patients	Novice's count is similar to expert's count using 3D-US
Royse et al[60] (2006)	Medical student, no experience in US, received five training sessions and five practice sessions	1	Hemodynamic assessment of cardiac function via hand held transthoracic echocardiography device in 30 healthy volunteers	Including training sessions, 20 sessions are needed to achieve acceptable basic hemodynamic measurements and 40 sessions are needed for all measurements using a third-generation device

N–number of novices within the study; US–ultrasound; OB-GYN–obstetrics and gynecology; VOCAL–virtual organ computer-aided analysis

CONCLUSION

There is no doubt that 3D ultrasound will enjoy a very bright and promising future primarily due to explosive advances taking place in computer technology. However, at the moment, there is a contrast between the fervent research front about 3D ultrasound and a somewhat less enthusiastic attitude in the real practice.[15] This is speculated due to a steady increase in price, compromises of image resolution seen with some 3D devices[15] or adding the cost of upgrade to 3D machines.[56] The precise tomographic examination and ability to scrutinize structures in surface rendering or transparent views opens up many new possibilities in clinical practice. The use of novices with 3D ultrasound may prove to be cost-effective and time saving, with no compromise of quality in certain practices. However, more research studies are needed, especially those with large number of novice participants.

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