Three-dimensional Ultrasound Imaging

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***Abstract*— Three-dimensional ultrasound (3DUS) has become an increasingly important component of clinical imaging. While early applications have been focused on cardiac, obstetric, and gynecologic applications its capabilities continue to expand throughout the clinical arena. This expansion is driven by important improvements in technology, image quality and clinical ease of use. This paper will provide a brief review of the technology behind 3D and 4D ultrasound imaging, clinical considerations in acquiring, displaying and analyzing 3D/4D ultrasound data and the clinical contributions this exciting technology is making.**

***Index Terms*— Three-dimensional, ultrasound, volume imaging**

I. Introduction

Ultrasound is a versatile imaging technique that can reveal the internal structure of organs, often with astounding clarity. Ultrasound is unique in its ability to image patient anatomy and physiology in real time, providing an important, rapid and noninvasive means of evaluation. Ultrasound continues to make significant contributions to patient care by reassuring patients and enhancing their quality of life by helping physicians understand their anatomy in ways not possible with other techniques.

Three-dimensional ultrasound (3DUS) is an increasingly important area of ultrasound development [1]. 3DUS exploits the real-time capability of ultrasound to build a volume that can then be explored using increasingly affordable high-performance workstations. 3DUS is a logical evolution of ultrasound technology and complements other parallel developments underway at this time, including harmonic imaging and the development of ultrasound contrast materials.

The continued clinical acceptance of 3DUS depends on three broad areas: these are volumetric data acquisition, volume data analysis and volume display. The particular strategy chosen by a vendor significantly shapes the scanner performance and resultant clinical versatility. A fourth consideration underlies the others, but ultimately will play a significant role affecting the clinical acceptance of the 3DUS. That is, the performance of 3DUS scanning systems must meet or exceed that of current 2DUS imaging systems with respect to image quality, features and interactivity.

This paper will provide a brief review of the technology behind 3D and 4D ultrasound imaging, clinical considerations in acquiring, displaying and analyzing 3D/4D ultrasound data and the clinical contributions this exciting technology is making.

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II. Equipment Design

Design of clinically useful scanning equipment is crucially dependent on having an easy-to-use system that provides rapid feedback to the clinician user in a straightforward manner. While superb image quality is expected, it also is important to avoid an overabundance of *bells* and *whistles* that often distract and overwhelm users rather than enhance the clinical imaging experience. Fundamental to an optimal operational environment is a highly functional, ergonomically designed user interface (Fig. 1). Selection of scanner features should

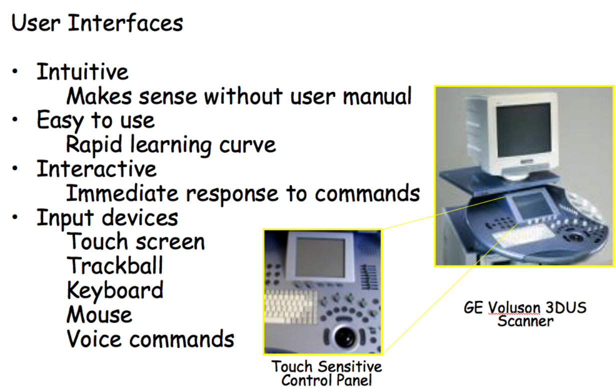

Fig. 1. Scanner interface considerations

be task related, obvious and context dependent. Most modern scanners provide the capability to acquire a variety of ultrasound data types (Fig. 2). Data display and analysis integral to the scanner should provide interactive functionality with an intuitive user interface. Scanner operation should seamlessly transition between acquiring data, displaying the results and saving or sending to a Picture Archiving Communications System (PACS).

III. Purchase Considerations

Decisions regarding purchase of a particular piece of ultrasound equipment often are driven from a variety of considerations.

From a practical point of view there are several considerations in selecting clinical scanning system. Fundamentally, it is important to consider the clinical application and need(s) to be met. It is important to understand the operational requirements for each type of clinical study to obtain good clinical results. Evaluation of the skill level required to obtain diagnostic information for each type of study is essential. A review of the scanner features essential to obtain sufficient information to accomplish the clinical scanning is required.

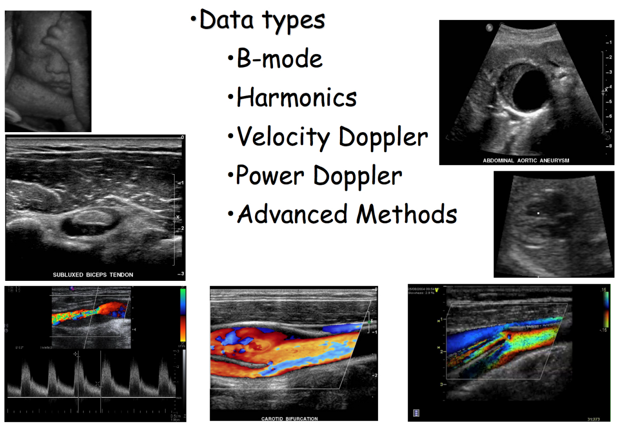

Fig. 2. Various types of ultrasound data. (Images courtesy of GE, Philips, Siemens)

It is important to maintain focus on the key features and not get overwhelmed by the flashy (and often expensive) unneeded features that might be available. Since clinical needs will grow over time it is important to determine if there is an upgrade pathway for future growth or expansion of scanner capability. Finally, an important consideration in purchase of any complex imaging equipment is to make sure that there will be adequate applications training at purchase and later on as needed.

If the scanner will be used for 3DUS applications then it is important to know what 3D/4D applications are most likely to be performed. Fetal heart scanning is more demanding than imaging the abdomen. Also, identification of whether multi-planar slices will be adequate or if rendering also will be necessary. If measurements are a part of the examination determine the type and complexity of the measurements needs to be known. For example, length and area are less challenging than a complete segmentation of a complex cystic structure.

Finally, determine if advanced imaging capabilities be available in the 3DUS imaging modes. Often these capabilities are part of the scanner but not available for 3D imaging.

IV. Acquisition Approaches

Acquisition of a data volume requires significant computing resources to process the acoustic and position data rapidly and create a volume. Various strategies are available in clinical scanners with most directed toward providing ”real-time” images to the clinical user.

Among the primary approaches employed are free-hand scanning with and without position sensing, mechanical devices integrated into the transducer and matrix array technology (Fig. 3). Mechanical devices may be integral within the scan head or external fixtures. Two-dimensional matrix array transducers promise to make real-time volume imaging a reality at the patients bedside in the near future.

Fundamental limitations in the speed of sound and the number of scan lines required to acquire a complete volume of data often impose tradeoffs between line density, frame rate and depth of field that can compromise data resolution (Fig. 4). Good interpolation algorithms can mitigate some of the effects although ultimately the limited amount of data can compromise diagnostic accuracy.

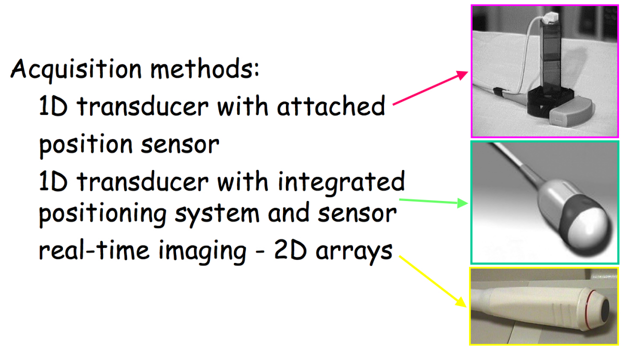

Fig. 3. Various types of volume acquisition transducers

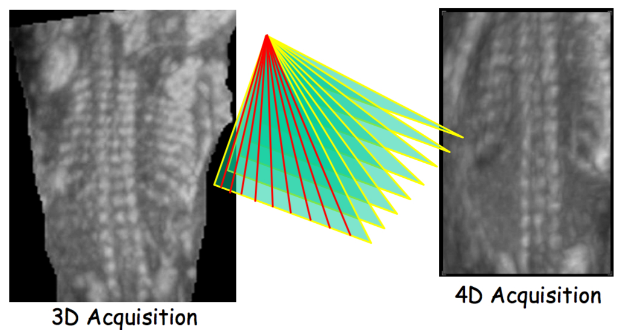

Fig. 4. Resolution variation between 3D static volume acquisition and 4D acquisition. The fewer number of scan lines reduces the resolution in the spine so that although detail is present it is not as good as in the static volume.

Similarly, due to the anisotropic resolution of most transducers used for 3DUS acquisition there is generally an optimal orientation for the volume acquisition (Fig. 5).

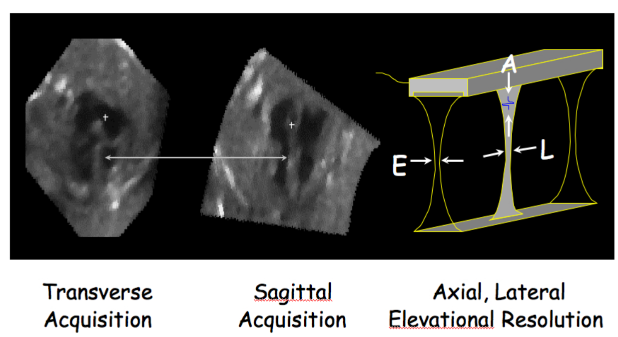

Fig. 5. Two different acquisition orientations for the same fetal cardiac patient (note the thickened cardiac ventricular septum). Due to anisotropic resolution the 2D acquisition plane should be optimized prior to volume acquisition. Typically this would be the 4-chamber view for fetal heart studies.

V. Display Strategies

Visualization of the relevant patient anatomy will ultimately determine the clinical utility of 3DUS. Although traditional methods of viewing multi-planar images provide much information, volume rendering for visualization of underlying patient anatomy including blood flow offers new ways to visualize complex anatomy in a single image and to enhance the visibility of structures that previously were difficult to appreciate.

Visualization depends on optimised algorithms to display the structure of interest and fast computing hardware to display the results fast enough to interactively adjust parameters or viewing orientation. Volume data currently are displayed using two primary methods: these are a series of multi- planar images (typically three slices that are orthogonal to each other), and rendered images that show entire structures throughout the volume (Fig. 6).

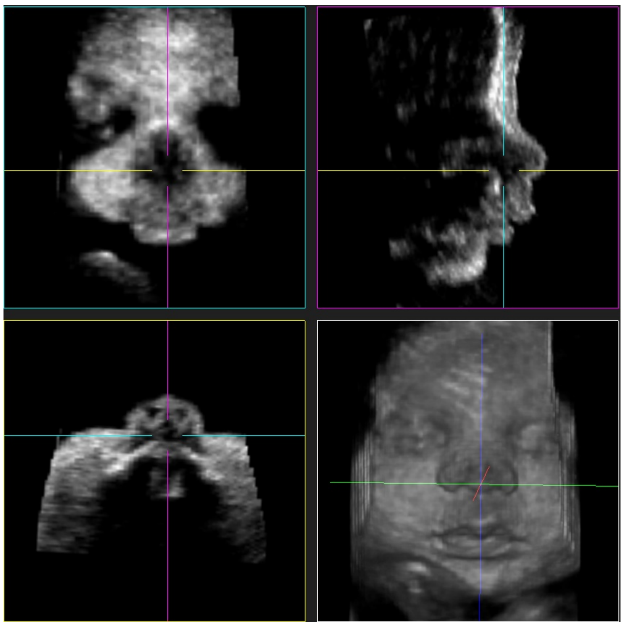

Fig. 6. Multi-planar and volume rendered display of fetal face showing cross-hair localization of planes to rendered image

Rendering parameters also can be varied to visualize different aspects of the acquired volume (Fig. 7).

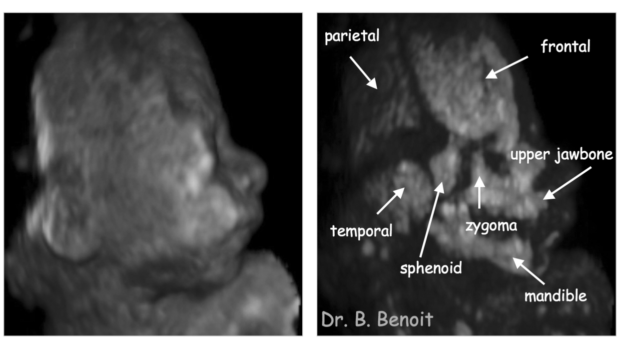

Fig. 7. Variation of rendering parameters to emphasize different features (*e.g.* skin surface, bone) in the volume

Rotation of the volume often is necessary to permit a structure to be optimally visualized. Rotation also assists in appreciating the relative position of the structure in the volume and its overall three-dimensional geometry (Fig. 8).

Fig. 8. Rotation of the volume can assist appreciation of structural relationships.

Currently, the clinical utility of visualization strategies varies among manufacturers; some provide only a single rendered image, whereas others provide multiple slices plus rendering. Intuitive, fully interactive performance remains a goal yet to be reached by most vendors.

VI. Analysis Options

Although the particular method used to obtain volume data may vary, a central requirement after a volume is created is to extract meaningful clinical information. This can be challenging, since ultrasound data pose a major analysis challenge due to the speckle and signal-to-noise properties and the basic physics of how acoustic images are formed.

For many clinical situations direct viewing of volume data, whether as a multi-planar or volume rendered display is sufficient. In other cases, some form of quantitative analysis is necessary. Most commonly, this might represent identification of an organ boundary for segmentation or volume measurement or classification of tissue acoustic properties.

Organ volumes, especially irregularly shaped structures, may be more accurately measured using 3DUS than using 2DUS (Fig. 9). 3DUS leads to more reproducible measurements, which can assist therapy monitoring (e.g., following tumor growth), measuring ovarian follicles and management optimization. Automated or semi-automated algorithms will be crucial for clinical acceptance.

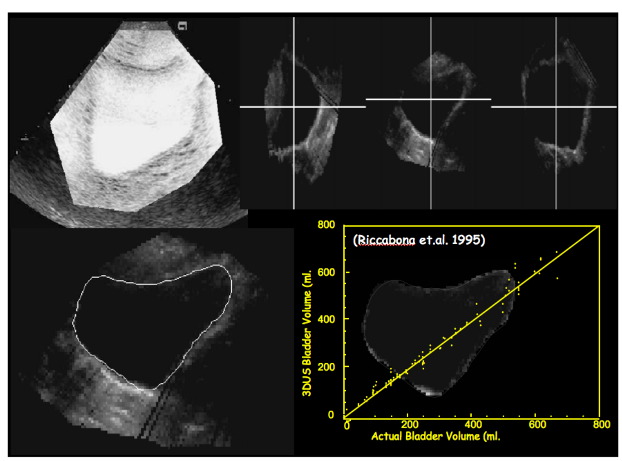

Fig. 9. Segmentation and volume measurement of the urinary bladder showing excellent correlation between voided volume and 3DUS measurements [2].

VII. Clinical Applications

Ongoing clinical research is evaluating clinical applications likely to have the greatest clinical impact on patient diagnosis and management. Several areas of 3DUS have emerged that offer advantages compared to 2DUS. A few examples will illustrate some areas in which clinical management improvements have been achieved.

To date, fetal, cardiac and gynecological areas have received the most attention (Fig. 10), with other clinical areas receiving increasing interest including imaging of vascular anatomy, prostate volume measurement and assessment of seed placement, guidance of interventional needles and catheters, neonatal head evaluation, and evaluation of breast mass vascularity.

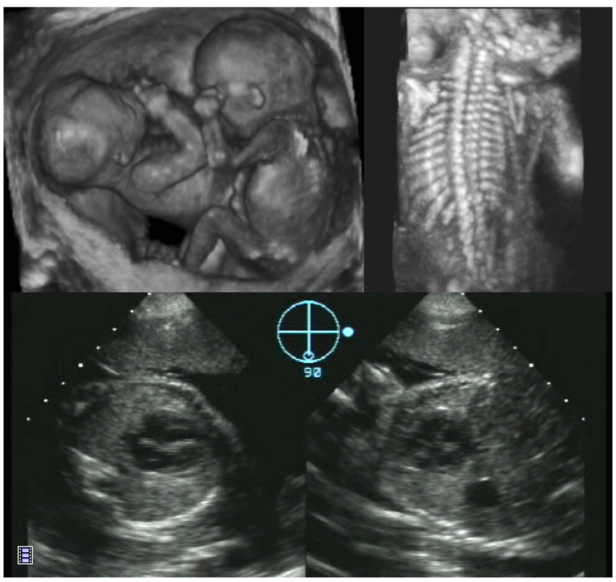

Fig. 10. Examples of clinical imaging in the fetus. Twins, a fetal skeleton and two orthogonal views of a fetal heart study using a matrix array (cardiac images courtesy of Philips).

In the fetus, improved visualization of fetal features, including the face and limbs, has improved anomaly identification and been immediately appealing for clearly sharing development information with the family.

Cardiac applications have provided a surgeon's eye view using transesophageal and transthoracic techniques to assess valve geometry and motion and to plan operative procedures. Fetal cardiac imaging has become an increasingly important part of prenatal diagnosis as a result of the development of four-dimensional imaging methods [3], [4]

Gynecological applications include evaluating congenital anomalies of the uterus, endometrial cancer, adnexal masses, intrauterine device position and follicular cysts. With 3DUS, it is possible to obtain the coronal plane of the uterus (Fig. 11), which is not possible with 2DUS. This view greatly facilitates identification of uterine anatomy, which can be important in managing infertility and congenital anomalies [5].

Volume rendering methods of the entire volume permit the continuity of curved structures such as liver vessels, the fetal spine or fetal face to be viewed in a single image. Clear

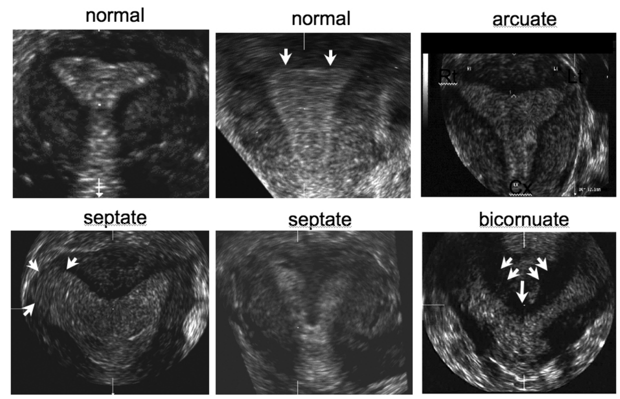

Fig. 11. Variations in uterine anatomy. These orientations are only available via 3DUS rotation of the acquired volume.

viewing of the fetal face has greatly assisted identification of normalcy and anomalies [6].

Applications in other specialties such as dermatology and ophthalmology are expanding the range of applications for 3DUS methods. Applications of 3DUS in clinically related research, such as, mouse imaging is playing an important role in studying the role of gene expression in disease.

Volume data may be used to guide interventional procedures, providing accurate identification of needle/ catheter placement. Combined viewing of resliced planes and rendered images facilitates localization of anatomy and devices within the volume. Such information can be invaluable in guiding therapeutic procedures such as placement of a shunt in a TIPS procedure [7], a cryoprobe or needle biopsy in the prostate [8] or agent administration.

Clinical imaging greatly benefits from viewing volume data using planar (coronal, sagittal and axial planes) or rendered images in a standard anatomic orientation plus orientations that are difficult or impossible to obtain with conventional 2DUS. Interactive review also permits viewing structures from multiple orientations or perspectives, enhancing the understanding of the patient anatomy of interest.

Finally, volume data may be archived and subsequently retrieved for further critical review or teaching purposes on site or via the network after the patient has left the clinic.

VIII. Conclusions

An important question, that remains unresolved to date, concerns the ultimate impact of 3DUS on patient care and management. In the current managed care environment, new technology must not only provide comparable performance, but also improve patient management and quality of care by proving its cost-effectiveness as well as delivering in the technical prowess area.

The clinical applications of 3DUS are expanding rapidly as a result of improved visualization tools, which enable reslicing the volume or rendering, in a single image, the complex anatomy of a fetal face or vascular bed.

Ultimately, although 3DUS technology will provide a central, integrating focus for clinical ultrasound imaging, the success of 3DUS methods will depend on providing performance that equals or exceeds that of 2DUS, including real-time capability and interactivity so that clinicians will embrace this exciting technology.

One of the most important requirements for long-term clinical acceptance of 3DUS is that clinical scanning systems provide superior image quality and interactivity to manipulate the data in real time as part of reviewing the patient study. Increasingly, clinical scanners are becoming available that can accomplish this feat at the patients bedside although scanner ergonomics often lack an intuitive user interface.

Through rapid transmission of volume data to specialists at distant locations, patient care will benefit from improved diagnosis and treatment. As 3DUS continues to develop, the presence of real-time 3DUS imaging equipment in the clinical setting will expand and stimulate new areas of investigation and identify new areas where 3DUS can further enhance clinical care.

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