Three-dimensional ultrasound imaging of the prostate

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ABSTRACT

Ultrasonography, a widely used imaging modality for the diagnosis and staging of many diseases, is an important cost-effective technique, however, technical improvements are necessary to realize its full potential. 2D viewing of 3D anatomy, using conventional ultrasonography, limits our ability to quantify and visualize most diseases, causing, in part, the reported variability in diagnosis and ultrasound guided therapy and surgery. This occurs because conventional ultrasound images are 2D, yet the anatomy is 3D; hence, the diagnostician must integrate multiple images in his mind. This practice is inefficient, and may lead to operator variability and incorrect diagnoses. In addition, the 2D ultrasound image represents a single thin plane at some arbitrary angle in the body. It is difficult to localize and reproduce the image plane subsequently, making conventional ultrasonography unsatisfactory for follow-up studies and for monitoring therapy.

Our efforts have focused on overcoming these deficiencies by developing 3D ultrasound imaging techniques that can acquire B-mode, colour Doppler and power Doppler images. An inexpensive desktop computer is used to reconstruct the information in 3D, and then is also used for interactive viewing of the 3D images. We have used 3D ultrasound images for the diagnosis of prostate cancer, carotid disease, breast cancer and liver disease and for applications in obstetrics and gynaecology. In addition, we have also used 3D ultrasonography for image-guided minimally invasive therapeutic applications of the prostate such as cryotherapy and brachytherapy.

Keywords: Three-dimensional, 3D imaging, 3D ultrasound, image guided therapy.

1. INTRODUCTION

During the seventy years after the discovery of x-rays, many attempts have been made to develop imaging techniques producing 3-dimensional images of the human body. The development of ultrasound, CT and MRI revolutionized diagnostic radiology, as for the first time, 3D information was recorded. However, this information was presented as 2D images, requiring advances in computer technology before 3D visualization came into wide spread use.

Computer technology and software advanced sufficiently in the past five years to allow real-time reconstruction of 3D images and their visualization and manipulation on inexpensive desktop computers. Only now, can we begin to explore the full potential of true 3D imaging and visualization for both diagnostic and therapeutic applications.

The medical uses of ultrasound progressed slowly from A-mode systems showing tissue interfaces on an oscilloscope-like trace, to ones producing real-time tomographic images of the anatomy and blood flow. The resolution and image quality of medical ultrasound has advanced sufficiently to make it an important and indispensable tool in obstetrics and in the diagnosis and management of diseases. Nevertheless, ultrasound imaging still suffers from several disadvantages related to its 2-dimensional nature, which 3D imaging attempts to address. Despite decades of exploration, it is only in the past five years that 3D imaging in ultrasound moved out of the research laboratory to become a commercial product for routine clinical use.

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2. LIMITATIONS OF 2D ULTRASOUND ADDRESSED BY 3D

A major advantage of 2D ultrasound is its flexibility, allowing the sonologist to manipulate the transducer and view the desired anatomical section. Paradoxically, this advantage is one of its weaknesses that 3D imaging attempts to address:

1) Using conventional ultrasonography, only one thin slice of the patient can be viewed at any time, and the location of this image plane is controlled by physically manipulating the transducer orientation. Consequently, the diagnostician or the therapist/surgeon must mentally integrate many 2D images to form an impression of the 3D anatomy and pathology. This process is time-consuming and inefficient, but more important, variable and subjective.

2) It is difficult to place the 2D image plane at a particular location within an organ, and even more difficult to find the same location again later. Thus, 2D US is not optimal for planning or monitoring therapeutic procedures, or for performing quantitative prospective or follow-up studies.

3) Due to the patient's anatomy or position, it is sometimes impossible to orient the 2D ultrasound transducer to obtain the optimal image plane. 3D imaging will allow arbitrary orientation of the image viewing plane within the data volume.

4) Quantitative estimate of volume needed for monitoring fetal growth, normalization of the PSA value and atherosclerotic plaque burden, is usually derived from one or two 2D images and the volume calculated based on an assumed shape. Since selection of the planes is arbitrary and controlled by the operator, variable and inaccurate values result.

3. BASIC PRINCIPALS OF 3D ULTRASOUND

Two types of 3D US systems have been developed, using either a series of 2D images produced by 1D arrays, or 2D arrays to produce 3D images directly. Although the 2D arrays approach would be the most convenient for the operator, this technology is still in the early stages of development. Most 3D US systems have used conventional ultrasound machines with 1D arrays to collect multiple 2D images and reconstruct them into 3D images. Two important criteria must be met to avoid inaccuracies or distortions:

- The relative position and angulation of the acquired 2D images must be accurately known so that the reconstructed 3D image is not distorted, and,

- The image acquisition must be carried out rapidly and/or gated to avoid artifacts caused by respiratory, cardiac and involuntary motion.

We have developed three approaches for 3D US imaging: tracked freehand, untracked freehand, and mechanical assemblies. In the following sections we briefly describe these approaches and review some important applications. For detailed descriptions of 3D US approaches, refer to review articles and two books that have appeared recently.[1-4]

3.1 3D US Scanning Mechanisms

3.1.1 Tracked Free-Hand Systems

The operator holds an assembly composed of the transducer and an attachment that provides information on the orientation and angulation of the transducer. To produce a 3D US image, the operator manipulates the assembly over the anatomy in the usual manner. The most successful approach for providing the geometrical information uses a 6-degree-of-freedom magnetic positioning device (Fig. 1a). Since 2D images are acquired with arbitrary position and angulation, two criteria must be met to reconstruct the 3D geometry properly:

- The exact relative angulation and position of the ultrasound transducer must be known accurately and precisely for each acquired image, and,

- The operator must ensure that no significant gaps are left between acquired images when scanning the anatomy.

3.1.2 Untracked Free-Hand Systems

In this approach, the operator moves the transducer in a steady and regular motion, while 2D images are digitized. To reconstruct a 3D image, a linear or angular spacing between digitized images is assumed. Since there is no direct information regarding the positions of the digitized images, the operator must be trained to move the transducer at a preselected linear or angular velocity to avoid distortions. Non-the-less, geometric measurements such as distance or volume may be inaccurate and should not be made.

3.1.3 Mechanical localizers

Freehand 3D scanning offers great flexibility, however, problems of noise and scanning gaps may reduce the image quality, particularly when imaging small structures at high resolution. One way to avoid these problems is to use a mechanical approach to move the transducer over the anatomy. In this way, the third dimension is obtained by a precise, predefined mechanical movement of the transducer.

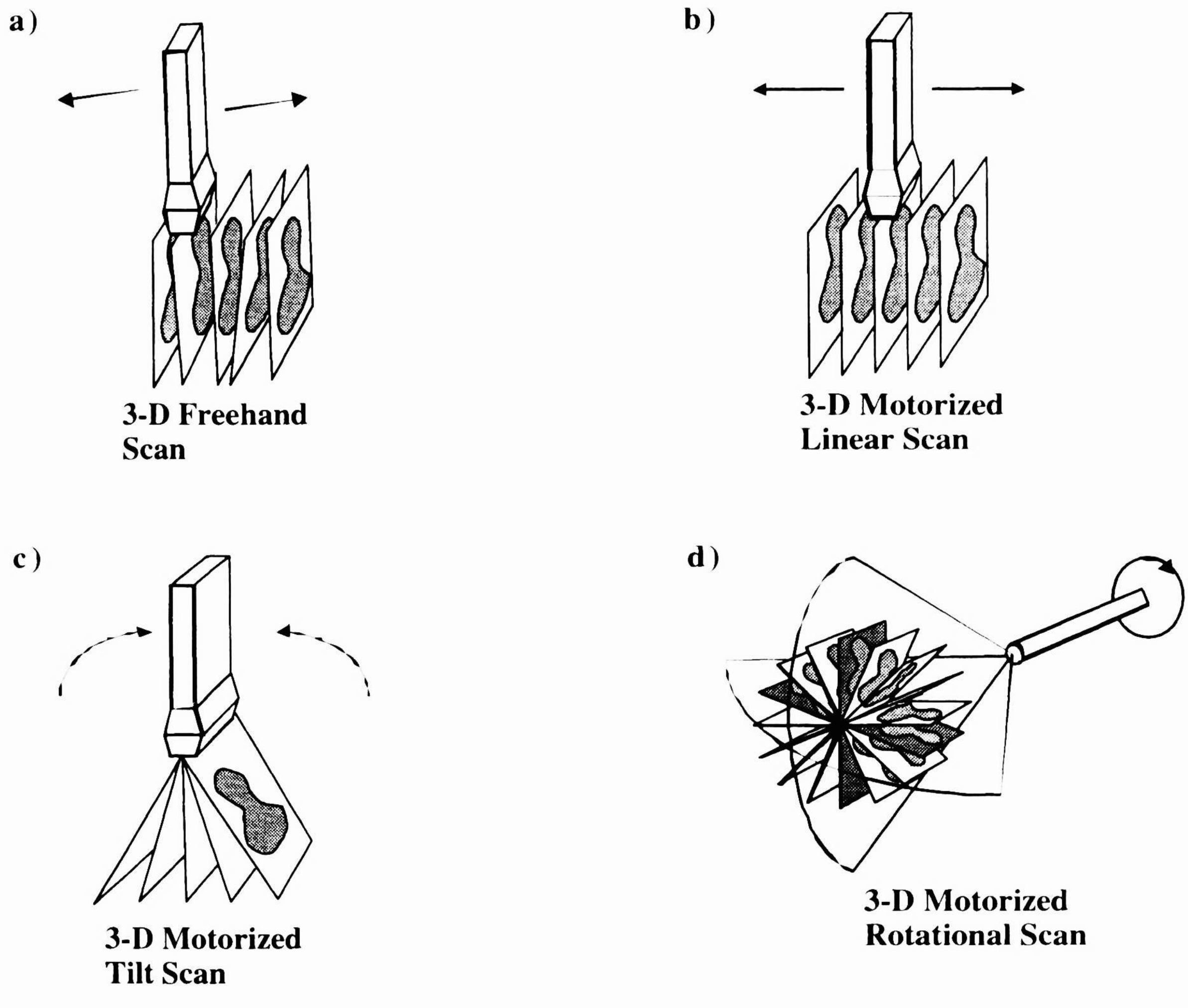

Figure 1. Schematic diagram showing various approaches to 3D ultrasound scanning using conventional ultrasound transducers. a) Free hand scanning with a magnetic positioning device. b) Mechanical scanning with linear motion. c) Mechanical scanning with tilting motion. d) Mechanical scanning with rotational motion.

As the transducer moves, 2D ultrasound images are acquired into computer memory at predefined spatial or angular intervals, so that the volume of interest is sampled properly without missing any regions. Many investigators and commercial companies have developed various kinds of mechanical 3D probe assemblies. These assemblies usually use conventional mechanical or linear-array transducers, which are mounted in an assembly to allow translation or rotation of the transducer by a motor. When the motor is activated, the transducer rotates or translates over the region being examined. Since the scanning geometry is predefined by the mechanical scanning assembly, no external frame of reference is necessary and the reconstruction is made efficient by pre-computing the required geometrical parameters.

The sizes of the assemblies vary from small integrated mechanisms housing the motor and transducer within the housing; to ones employing a motor attached to an external fixture, which houses a conventional 2D ultrasound transducer. The integrated mechanisms are advantageous since they are small, allowing easier use by the operator; however, the use of these special probes requires the purchase of a special ultrasound system. While external assemblies result in bulkier devices, they employ existing 2D transducers obviating the need to purchase an expensive new ultrasound machine to obtain 3D imaging capability. This approach to 3D imaging has been implemented with three basic types of motion, as shown schematically in Fig. 1: linear, fan and rotation scanning.

3.2 Reconstruction and Viewing

3.2.1 Reconstruction

3D image reconstruction refers to the generation of a 3D representation of the examined structures from the acquired set of 2D images. Here, the acquired series of 2D images are built into a 3-dimensional voxel-based cartesian volume by placing each acquired 2D image in its correct location in the volume. The grey scale or colour values of any voxels not sampled by the 2D images are calculated by interpolation between the appropriate images. In this way, all 2D image information is preserved, allowing viewing of the original 2D planes, and also other views. These techniques have been developed for both mechanical scanning approaches[2,5,6] and freehand approaches.[7]

3.2.1 Multi-Planar Reformatting

After the 3D image has been reconstructed, it is ready for viewing. Our approach for viewing the 3D image is based on multi-planar reformatting (MPR), with a texture-mapping, as well as volume rendering (VR). In the MPR technique, the 3D image is presented as a polyhedron and the appropriate ultrasound images for the polyhedron faces are texture-mapped onto them.[8] The polyhedron can be rotated to obtain the desired orientation of the 3D image. The faces can then be moved in or out, parallel to the original, or reoriented obliquely, while the appropriate ultrasound data is texture-mapped in real-time on the new face. In this way, the operator always has 3-dimensional image-based cues relating the plane being manipulated to the rest of the anatomy.[4,5,9,10]

3.2.2 Volume-based Techniques

The MPR technique reduces the presentation of the 3-dimensional data to a display of 2D information using planar surfaces. Since our visual senses are best suited for viewing and interpreting surfaces, the MPR approach is easily understood by the operator and requires little learning. However, this display technique presents only a small part of the complete 3D information at any time. An alternative viewing technique uses volume-based rendering, which presents a display of the entire 3D image after it has been projected onto a 2D plane. The most common approach uses ray-casting techniques to project a 2D array of rays through the 3D image.[11-13] Each ray intersects the 3D image along a series of voxels, which can be weighted and then summed in various ways to produce the desired effect. Common approaches in 3D US have been: maximum intensity projection, translucency rendering and surface enhancement as shown below.

Although depth cues can be added, the VR approach in viewing 3D US data results in images which are difficult to interpret. Therefore, this approach is best suited for images of simple structures in which anatomical surfaces are clearly distinguishable (fetal face surrounded by amniotic fluid) or for images in which clutter is not present or has been removed (power or colour Doppler images with the B-mode data removed). Successful uses have been demonstrated by investigators, particularly in displaying fetal[14-19] and vascular anatomy.[20,21]

a)

b)

c)

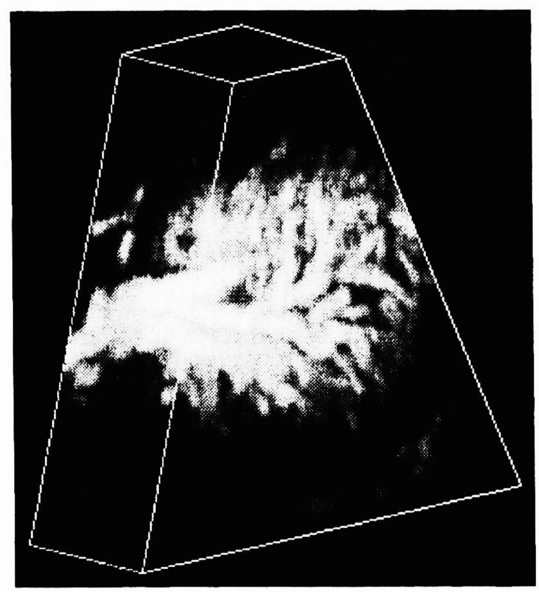

Figure 2. 3D ultrasound images showing the various ways in which they can be displayed. a) Multi-planar reformatting approach of a 3D image of first trimester twins with implantation bleeds. b) Volume rendering with enhancement of surfaces of the face of a fetus. c) Volume rendering using maximum intensity projection of a power Doppler image of a human spleen.

4. APPLICATIONS

4.1 Prostate cancer

4.1.1 Medical Problem

Prostate cancer, the most commonly diagnosed cancer in men,[22] has the second highest mortality rate among all cancers in men in North America. The annual incidence rate of prostate cancer has been increasing every year since 1980. Many prostate cancers grow slowly. However, once the tumour is no longer encapsulated within the prostate, there is a dramatic increase of metastasis, and a corresponding decrease in the prospect of a cure. Prostate cancer is curable when diagnosed at an early stage, particularly if it is confined to the prostate gland. While treatment can still be effective in the later stages of the cancer, early diagnosis and accurate staging of prostate cancer, as well as effective treatment is very important.

Transrectal ultrasound (TRUS), introduced in 1971, provided information about the size and shape of the prostate. Since then, TRUS has become the dominant imaging modality for diagnosis of prostatism, detection and staging of prostate cancer, and for real-time image guidance of minimally invasive therapeutic procedures. With its increased utility, the number of TRUS systems and the number of radiologists/urologists performing TRUS have greatly increased.

Based on investigations at many institutions, it is generally agreed that the conventional TRUS examination is an important, cost-effective and useful technique for imaging the prostate, for use in the interpretation of the PSA assay, for monitoring response to nonsurgical and surgical therapy, and for providing image guidance during some minimally invasive procedures. However, it is also agreed that conventional TRUS has serious limitations (as discussed above) and that technical improvements are needed before its full potential for diagnosis, staging and management of prostate cancer can be realized.

4.1.2 3D TRUS Imaging

We have developed a 3D TRUS system that overcomes some limitations of conventional 2D TRUS listed above. The 3D TRUS system for imaging the prostate consists of three major components: (i) an ultrasound machine with a transrectal ultrasound transducer, (ii) a microcomputer with a video frame-grabber, and, (iii) a motorized assembly to rotate the transducer under computer control.[2,9,10,23] The microcomputer is also used for image reconstruction, display, manipulation, and analysis of the 3D images. Figure 3 shows the operating principle of our approach. The TRUS transducer is mounted in the assembly, covered with a water-filled condom and inserted into the rectum in the same manner as for a conventional TRUS examination. When the motor is activated, it rotates the transducer around its long axis. As the transducer is rotating at constant speed, conventional B-mode images are digitized and stored in the microcomputer. For a typical 3D scan, the transducer rotates through about 80° while 100 images are digitized at 15 or 30 images/sec, so that the entire data acquisition can be completed in a few seconds. After the rotation is complete and the necessary images digitized, the series of 2D images are reconstructed into a single 3D image. The resulting 3D image is then viewed on the microcomputer monitor and manipulated using interactive 3D visualization tools.[9,23,24]

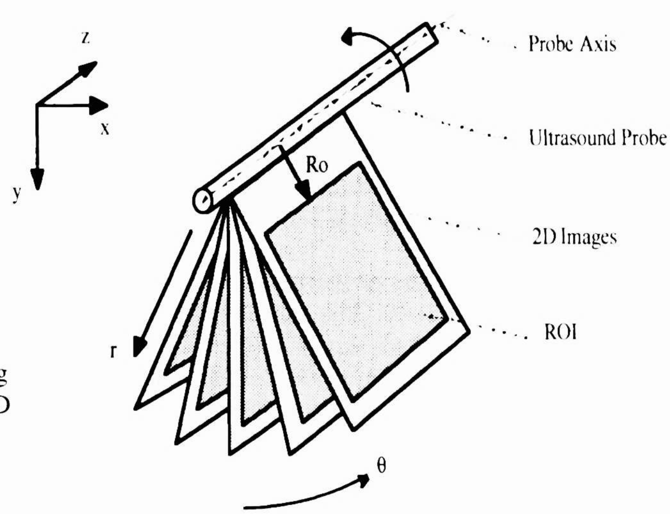

Figure 3. Schematic diagram showing a side-firing transrectal ultrasound transducer being rotated for a 3D imaging scan.

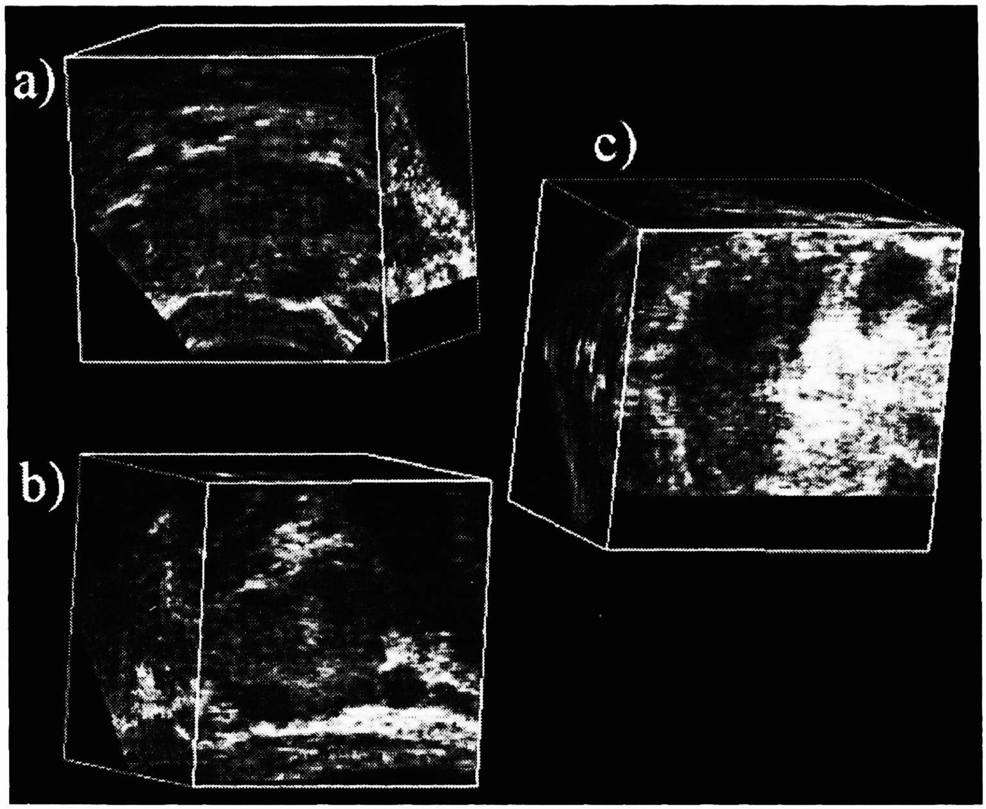

Figure 4. 3D TRUS image of a patient with prostate carcinoma. The 3D image is being viewed using the multi-planar reformatting approach, with the faces of the polyhedron oriented and positioned to display the pathology in the prostate.

4.1.3 Minimally Invasive Therapy of the Prostate

Minimally invasive procedures for prostate cancer are reducing patient morbidity, recovery time, hospital stay, and total cost. These benefits are especially welcome because of the significant morbidity currently associated with radical prostatectomy - the traditional therapy for prostate cancer. As a result, percutaneous ultrasound-guided prostate therapy techniques such as cryosurgery[25,26] and brachytherapy are currently under intense investigation. Although these techniques can destroy tumours while preserving adjacent structures, the inconsistency and wide variability of outcomes in different institutions suggest that current practice is highly operator-dependent. From our experience, we believe that the major source of this variability is the standard use of conventional hand-held 2D TRUS for treatment planning, implantation guidance, and treatment monitoring.

Prostate brachytherapy is a form of radiation therapy in which radioactive seeds are placed directly into the prostate gland, either temporarily or permanently. It is believed that brachytherapy has a role in the treatment of early-stage prostate cancer, and that it may be superior to both surgery and external-beam radiation when evaluated by current therapeutic and economic endpoints. To deliver a high conformal dose safely to the prostate, the radioactive seeds must be positioned accurately within the gland. Although technical strides in prostate brachytherapy have improved the accuracy and consistency of seed placement,[27-32] they are still limited by using conventional 2D TRUS guidance. Using 3D TRUS instead, would obviate the technical limitations of 2D TRUS as described above.

4.2 Vascular Imaging

4.2.1 Medical Problem

Because emboli are postulated to arise from structurally unstable regions and disrupted plaques, investigators have focused on identifying and quantifying carotid artery plaque morphology and composition in attempts to correlate these with risk for stroke and account for the disparity in clinical outcome in patients with stenosis of equal severity. Unfortunately, these efforts have met with varied success. Some investigators reported a high level of accuracy for identifying features such as intraplaque haemorrhage.[33-38] while others have found only moderate sensitivity and specificity.[39-41] Some of these discrepancies relate to lack of standardization, but others relate to the variability in the ultrasound exam (as discussed above). Nonetheless, it is generally agreed that both the characteristics of the plaque and the degree of stenosis should be considered in the examination of the carotids and that improved ultrasonographic techniques are required.

We have developed a 3D US system with real-time visualization of the plaque surface and measurements of the actual atheroma volume. 3D imaging of the plaque allows quantitative monitoring of plaque development (changes in volume and morphology) and provides important information about the natural history of atheroma growth. This information may help in identification of high-risk plaques that will cause stroke.

4.2.2 3-D US System for Imaging the Carotid Arteries

Our 3D US imaging system for imaging the carotid arteries is similar to the 3D TRUS system and has three components: image acquisition, reconstruction of the 3D image, and display. In producing a 3D image, the conventional linear array transducer moves over the vessels in a linear scanning motion, while 2D images are digitized and stored in a microcomputer. We have been pursuing two scanning approaches: mechanical scanning and freehand scanning.

Mechanical Scanning: Based on our earlier work,[5,42] we have developed a system in which the US transducer is mounted in a special assembly, which can be driven by a motor (Fig. 1b) to move in a linear fashion over the skin. The movement can be continuous, cardiac and/or respiratory gated, and the transducer can tilt to allow 3D colour Doppler imaging. In addition, the spatial-sampling frequency of the image acquisition can be adjusted based on the elevational resolution of the transducer and the depth of the region-of-interest. Typically, we collect 200 images (336 x 352 pixels each) at 0.5 mm intervals in a time that depends on the ultrasound machine frame rate and whether cardiac gating is used. All scanning parameters can be adjusted depending on the experiment and type of acquisition. For example: 1) 3D B-mode - we typically use two or three focal zones resulting in about 15 frames/sec and a total 3D scanning time of 13 seconds for 200 images; 2) 3D power Doppler - the persistence is increased and cardiac gating is not used, thus, we slow the acquisition to 7.5 images/sec resulting in a 3D scan of 20 seconds for 150 images.

We have been validating our technique with vascular phantoms of known geometry and reported on its accuracy and precision in measuring stenoses using colour Doppler and power Doppler imaging. Our phantom studies demonstrated that luminal geometry and stenoses can be accurately measured.[43,44]

Freehand Scanning: In the freehand 3D US scanning system, a magnetic positioning and orientation measurement (POM) device is mounted on the transducer. To produce a 3D image of the carotid arteries, the operator manually moves the hand-held transducer, while the POM device transfers the position and orientation coordinates of the transducer to a microcomputer. Simultaneously, 2D images are digitized by the same computer and associated with the appropriate coordinates. After the necessary 2D images are acquired (typically 60 - 160), the computer reconstructs the 3D image. Care is taken to scan the patient sufficiently slowly so that the region of interest is scanned with no gaps. Typically, the scan lasts 11 - 22 sec. while the patient holds their breath. To date, we have been exploring the utility of this approach without cardiac gating, since gating would considerably extend the time required for each scan. We have investigated the accuracy and precision of this approach and found that: geometric errors were, on average, less than 1%, location uncertainty was 0.15 mm.[7,45]

5. CONCLUSIONS

We reported on our development of a 3D ultrasound imaging system for a variety of applications. The 3D system can interface to any conventional ultrasound machine and can accommodate side-firing TRUS ultrasound transducers and linear transducer arrays used for vascular or abdominal imaging. After acquiring a series of 2D ultrasound images, a 3D image is reconstructed. The 3D image allows the physician to interactively view the organ under investigation in multiple simultaneous planes, or to view the surfaces of structures using volume rendering techniques that allow better visualization of its internal architecture. These approaches allow physicians to diagnose disease, measure volumes accurately, and plan and guide minimally invasive procedures.

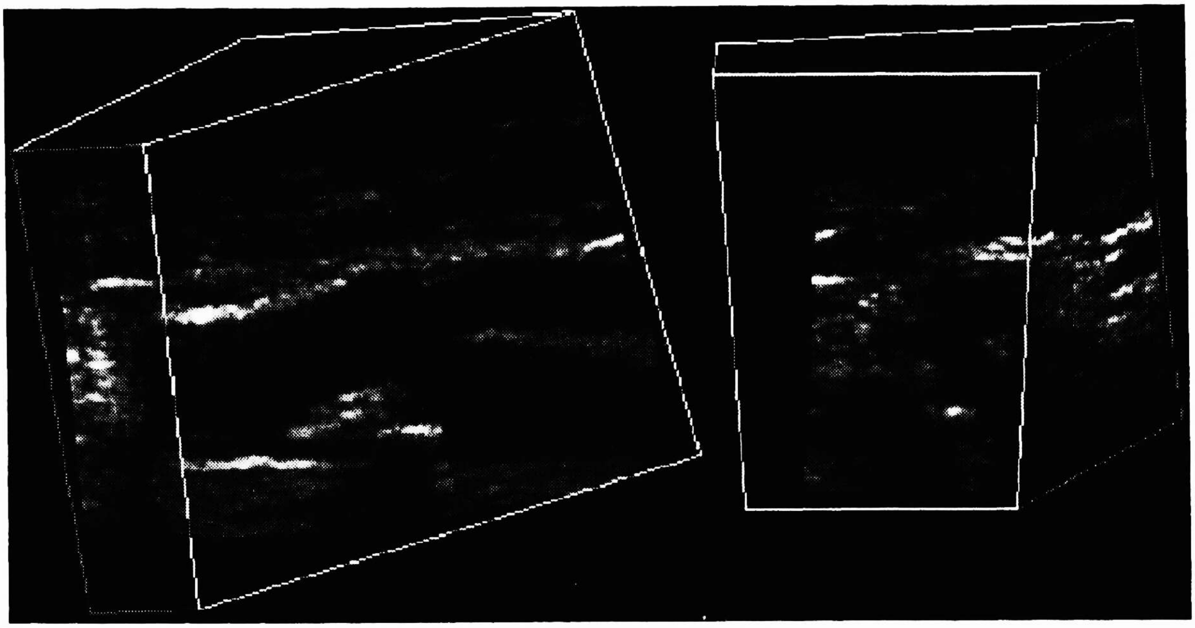

Figure 5. 3D US image of a patient with an atherosclerotic plaque in the common carotid artery at the entrance to the internal carotid artery. This image was obtained using the freehand approach using a magnetic positioning device.

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