Measurement of abdominal aortic aneurysms with three-dimensional ultrasound imaging: Preliminary report

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Objective: Accurate measurements of abdominal aortic aneurysms (AAAs) are required for surgical planning and monitoring over time. We have examined the feasibility of using a three-dimensional (3-D) ultrasound imaging system to derive quantitative measurements of interest from AAAs.

Methods: A normal aorta, a small AAA, and an AAA repaired with an endovascular stent graft were scanned with a 3-D ultrasound imaging system. For each case, a 3-D surface reconstruction was generated from manual outlines of a sequence of two-dimensional ultrasound images, registered in 3-D space with a magnetic tracking system. The surfaces were resampled in planes perpendicular to the vessel center axis to calculate cross-sectional area and maximum diameter as a function of distance along the length of the aorta.

Results: Cross-sectional area and maximum diameter were plotted along the length of the aneurysmal aortas from the renal arteries to the aortic bifurcation. The overall maximum diameter was found for both aneurysms. For the small AAA, the distances of the aneurysm from the renal arteries and the bifurcation were measured. For the repaired AAA, the location of the stent graft relative to the renal arteries was measured.

Conclusions: 3-D surface reconstructions from ultrasound images show promise for quantitatively characterizing the geometry of AAAs both before surgery and after endovascular repair. (J Vasc Surg 2001;33:700-7.)

Accurate measurements of abdominal aortic aneurysms (AAAs) are required for planning repair strategies. The maximum diameter of an aneurysm is used as a threshold to select candidates for surgical or endovascular repair. In general, AAAs with maximum diameters greater than 5 cm require some type of intervention. Additional measurements are needed to select those patients whose AAAs are suitable for endovascular repair. Candidates for endovascular repair require an adequate length (generally 1 cm) of nondilated aorta distal to the renal arteries. Accurate measurement of the diameter and length of the proximal neck of the aorta and the iliac landing sites, and the length of the aneurysmal segment are required for selection of the proper endograft. After placement, the location of the graft within the aneurysm is also of interest because migration could lead to failure of the repair.

Monitoring of aneurysm diameter over time is also a key component of AAA management. Precise measurements are needed for tracking the expansion of small AAAs, which may need surgical or endovascular repair in the future. After the placement of an endograft, continued expansion of the residual aneurysm sac indicates the presence of an endoleak. In addition, diameter changes can be used to evaluate the response to drug therapies intended to shrink the aneurysm or slow its rate of expansion.

The most common imaging modalities used for assessment of AAAs are two-dimensional (2-D) ultrasound scan and computed tomography (CT). Standard 2-D ultrasound is generally used for measuring and monitoring the size of AAAs. Helical CT, calibrated angiography, and intravascular ultrasound are often used to make the more detailed measurements needed for planning surgical and endovascular interventions. These methods are costly and invasive. An accurate, noninvasive, and rapid method of determining aneurysm size and suitability for endovascular repair would represent a significant improvement.

We have used a three-dimensional (3-D) ultrasound imaging system to generate computer reconstructions of the aorta from which quantitative measurements can be extracted. Measurements of interest are the distances of the aneurysm from the renal and iliac arteries, the diameter and cross-sectional area of the aneurysm, and in the case of endovascular repair, the location of the stent graft.

METHODS

Three-dimensional imaging was performed with a standard ultrasound imager (Sonos 5500; Agilent/Hewlett-Packard, Andover, Mass), modified with a magnetic tracking system (Flock of Birds; Ascension Technology, Burlington, Vt) to register 2-D images in a 3-D coordinate system (Fig 1). The magnetic tracking system consists of a small (2.5 × 2.5 × 2.0 cm) receiver that is mounted on the scanhead; a transmitter, which is placed under the examination bed; and an electronic control unit. The tracking system measures the position and orientation
of the scanhead in space within a 90-cm radius of the transmitter. System calibration as described by Leotta et al4 allows registration of the individual 2-D ultrasound images in a common 3-D coordinate system. Data capture, reconstruction, and analysis are performed on a Unix workstation (O2; SGI, Mountain View, Calif). The cost of the added components for 3-D imaging (tracking system and workstation) is approximately $10,000 (US).

Cross-sectional B-mode images were captured along the length of the abdominal aorta from the level of the renal arteries through the aortic bifurcation for (1) a healthy volunteer, (2) a patient with a known AAA, and (3) a patient who had undergone endovascular repair (AneuRx Stent Graft; Medtronic AVE, Santa Rosa, Calif) of an AAA 2 weeks prior. Examinations were performed on a wooden bed to minimize distortions of the tracking system’s magnetic fields. Scans were performed with a curvilinear 3- to 7-MHz scanhead or a phased array 2- to 4-MHz sector scanhead. The imaging protocol was approved by the Institutional Review Board, and all subjects gave informed consent.

The scanning and reconstruction procedure is summarized schematically in Fig 2. Between 30 and 60 images were acquired in each case; the scanhead was translated 2 to 8 mm between each image. Acquisition was initiated by a hand switch and triggered by an electrocardiogram (ECG) signal (end systole) to minimize variation in vessel size due to pulsation through the cardiac cycle. The subject was allowed to breathe normally throughout the study; the examiner initiated image capture at approximately the same point of respiration, generally end expiration. Image acquisition was completed in 3 to 5 minutes.

The outer wall of the aorta was manually outlined on the individual 2-D images (Fig 2, C). Custom software interfaced with the visualization software package AVS (Advanced Visual Systems, Inc, Waltham, Mass) provides...
on-line interactive display of the outlines as they are traced. Perspective views of the outlines in a 3-D coordinate system help the user to evaluate scan coverage, edit the traced borders if necessary, and exclude images that are misregistered because of patient motion. The origins of the renal arteries and the aortic bifurcation were marked by single points in the appropriate 2-D images. In the case of the repaired AAA, the stent graft was also manually outlined. Manual outlining takes from 10 to 30 minutes, depending on the number of images and the inclusion of an endograft.

The outlines of the aorta were connected by means of computer software to create a mesh and surface rendering of the vessels (Fig 2, D). An axis was constructed by linear interpolation through the centroids of the 2-D aorta contours, and a set of resampled contours normal to the center axis was calculated. The area of each of the resampled contours was found at points every 3 mm along the path length of the interpolated axis. The overall maximum diameter measured from the 3-D reconstruction is 4.1 cm; the clinical 2-D ultrasound examination reported a maximum diameter of 4 cm.

Fig 5 also incorporates distance measurements relative to landmarks of interest. In Fig 5, B, the reconstruction is displayed as a mesh so that the center axis of the vessel can be visualized. The levels of the renal arteries and aortic bifurcation are represented by markers on the center axis. A plot (Fig 5, E) displays the path length traversed along the center axis from both the left renal artery and the aor-
The distance from the left renal artery to the bifurcation is 12.0 cm. The proximal end of the aneurysm is 4.3 cm from the left renal artery; the distal end is 1.5 cm from the aortic bifurcation.

Combined views of the aneurysm sac and the endovascular stent graft for the third patient are shown in Fig 6.

The AneuRx stent graft uses a modular design consisting of a main body and limb in a single unit and a second limb that joins to the body. Rotation of the main body during placement resulted in a crossing of the limbs, which is visualized in the reconstruction. Fig 7 shows the measurements derived from the reconstruction of the AAA and the
stent graft. The proximal end of the graft is 1.0 cm from the left renal artery. The maximum diameter of the aneurysmal sac is 5.7 cm.

DISCUSSION

Accurate geometrical measurements and long-term monitoring are essential components of AAA management. Small aneurysms have been estimated to grow approximately 0.5 cm in diameter per year. Therefore, the size of small AAAs must be tracked to ensure that suitable treatment can be provided before the risk of rupture is significant. In addition, recent studies suggest that tetracycline derivatives may inhibit the growth of AAAs. Precise monitoring of aneurysm size will be required to test the efficacy of such treatments. In the case of endovascular repair, additional measurements of the aneurysm and surrounding vessels are necessary for proper selection of the endograft. After placement, extended monitoring is required to ensure that the endograft is stable and no leaks are present.

Ultrasound is an attractive imaging modality for the screening and monitoring of patients with AAAs. Because it does not involve radiation or contrast agents, ultrasound offers a safe, noninvasive, and relatively inexpensive method of measuring AAAs and following changes over time. However, dimensional measurements made with conventional 2-D ultrasound are sensitive to image plane orientation. In addition, the orientation and placement of the imaging planes change from visit to visit, which contributes to measurement variability in studies over time. This is also true of CT image planes, which can vary in location and orientation relative to the vessel axis.

Three-dimensional imaging can minimize the errors associated with measurements made from 2-D slices. Three-dimensional ultrasound imaging can be performed with mechanical scanners, or freehand systems, based on spatial tracking. The magnetic tracking system used in this study is an example of the freehand imaging technique. Freehand scanning permits arbitrary manipulation and positioning of the scanhead by the examiner for optimal imaging of the aorta and any landmarks (renal arteries, iliac arteries) of interest. The magnetic system imposes no line-of-sight restrictions, which are normally associated with optical and acoustic tracking devices. However, the magnetic system is susceptible to interference from ferromagnetic materials in the vicinity. No interference due to the metal in the endograft itself was evident in the current study. The AneuRx stent graft framework is composed of nickel-titanium alloy (nitinol), which has been shown to be nonferromagnetic. The potential for interference from other grafts is expected to be low on the basis of the materials typically used in their manufacture, but specific testing would be required to rule it out in every case.

In this study we have demonstrated the use of a 3-D ultrasound imaging system to extract such information as the maximum diameter of the aneurysm, cross-sectional area along an extended segment, and the location of the aneurysm or endograft relative to selected landmarks. Three-dimensional reconstruction minimizes measurement variability due to ultrasound image plane orientation. The examiner is not required to search for a single view for which the image plane is normal to the vessel and the aneurysm appears largest. Precise replication of views is not required in subsequent examinations because the surface reconstruction is resampled in a standard orientation normal to the vessel center axis. The difference in measurements derived from the original image planes and the resampled normal planes is demonstrated in Fig 8 for the AAA shown in Fig 4. In particular, the cross-sectional
area is overestimated when the original image planes intersect the center axis at oblique angles.

The availability of 3-D data also provides documentation of the aneurysm size along its entire length. A recent study has demonstrated changes in aneurysm size after endovascular repair that were detected by volume measurement but not by maximum diameter measurement. This result indicates that a single diameter measurement may not be sufficient to accurately monitor aneurysm size. In addition, the landmarks included in the 3-D reconstructions can serve as fiducial points for registration of studies over time. Precise alignment will allow tracking of detailed regional shape and size changes of the aneurysm.

Ultrasound imaging of the abdominal aorta may be technically limited because of a patient’s obesity or excessive abdominal gas. However, with proper patient preparation (oral intake restricted to clear liquids for at least 8 hours before the examination), many of the body habitus pitfalls may be overcome. With an examination protocol...
that includes standard 2-D imaging and Doppler studies of the SMA, renal artery, inferior mesenteric artery, common iliac artery, external iliac artery, hypogastric artery, and common femoral artery, ultrasound may prove to be applicable for preoperative assessment and long-term follow-up of graft placement. Preoperative ultrasound assessment for endograft placement can also include detailed examination of the walls of the abdominal aorta and the iliac arteries for calcification or thrombus. In those cases where evaluation with ultrasound is inadequate, other imaging studies such as contrast CT or arteriography may be required.

CT will be used as a reference to evaluate the accuracy of the 3-D ultrasound imaging method. The reconstruction and analysis techniques used in the current study can be applied to the parallel-plane images of a CT scan, allowing direct comparison of the two methods. Reproducibility of the ultrasound technique will also be a key determinant of its potential for clinical use. The accuracy and reproducibility of 3-D ultrasound measurements can be affected by image registration, feature segmentation errors, or both. Misregistration of images in the 3-D coordinate system can be due to tracking errors or patient motion. Segmentation errors may be encountered when body

Fig 8. The effect of slice orientation on cross-sectional area measurements is demonstrated for the AAA shown in Fig 4. A, Cross sections corresponding to original image planes. B, Cross sections normal to vessel center axis. The 3-D surface was resampled with 6-mm spacing along center axis. C, Area measurements derived from cross sections in A and B. Cross-sectional area is overestimated when original image planes intersect center axis at oblique angles.
habitus degrades overall image quality or extreme scanhead angulation degrades boundary definition due to ultrasound beam thickness. These potential sources of error will be assessed in future studies.

Further development of the hardware and scanning method is expected to facilitate data acquisition and enhance the performance of the system. For instance, gating can be incorporated to reduce artifacts due to respiratory movement. Alternatively, continuous scanhead translation with ECG triggering may allow data acquisition within several breath holds. Future applications of the 3-D ultrasound technique include measurement of (1) diameter changes over time for monitoring of unrepaired aneurysms, (2) volume changes over time for leak detection in endovascular repairs, and (3) changes in location or shape of the endografts.

REFERENCES
