METHODS

Anatomic-Ultrasound Correlations for Intraoperative Open Chest Imaging of Coronary Artery Atherosclerotic Lesions in Human Beings

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This study was performed to further validate a method for intraoperative ultrasound imaging of coronary arteries. Ultrasound images of coronary atherosclerotic lesions were compared with anatomic specimens of the coronary arteries obtained from open chest human subjects. The anatomic specimens were derived from four cardiac transplant recipients, accepted as candidates for transplantation because they had severe diffuse atherosclerotic disease, and one patient who died in the early postoperative period after a coronary artery bypass procedure. Twenty-six ultrasonically imaged atherosclerotic areas of the coronary arteries in these patients were compared with formalin-fixed and decalcified anatomic specimens.

Specific ultrasound appearances for atherosclerotic lesions were observed, including 1) discrete (focal) ste-

cousing fibrous/atheromatous plaques; 2) diffuse nonob-

structive fibrous/atheromatous disease (detectable even in anatomically small vessels); 3) complete occlusion by fibrous/atheromatous lesions or organizing thrombus; and 4) "shadowing," an ultrasound pattern characteristic of significant calcification within atherosclerotic plaques.

As part of this study, a new 12 MHz water path probe was evaluated for coronary artery scanning. The new probe allowed improved access to coronary arteries and increased detail of anatomic visualization. Both the performance of the new high resolution probe and the knowledge gained by the anatomic correlations obtained in this study should aid the development of intraoperative coronary artery scanning for surgical localization of atherosclerotic disease during coronary bypass surgery.

Although angiography remains the reference standard for the diagnostic evaluation of coronary artery disease, recent studies have questioned both the reproducibility of interpretation of coronary angiograms (1–3) and the anatomic accuracy of angiographic visualization (4,5). Complete angiographic occlusion often leaves doubts regarding the suitability of the distal coronary artery bed for receiving bypass grafts (5), and surgeons may at times have difficulty in determining the exact site of angiographically demonstrated coronary artery lesions. Ultrasound has been increasingly applied as a means for providing information about the effects and results of heart surgery and as an aid in making decisions (6–10). We reported a method (11), developed in conjunction with the surgeons at the Cardiothoracic Unit of Green Lane Hospital, Auckland, New Zealand and engineers at the New York Institute of Technology Research and Development Center, which uses a high frequency water path scanning device to provide detailed visualization of coronary artery anatomy during coronary bypass surgery. We demonstrated that this method can be safely applied to provide detail which enhances the information provided by angiography and aids in localization of angiographically demonstrated lesions.

In the present study we used a 9 MHz water path scanner previously described (11) as well as a new high resolution 12 MHz scanner of smaller, more compact design to derive ultrasound images of coronary atherosclerotic lesions to compare them with anatomic specimens derived from a non-survivor of coronary artery bypass surgery and four patients who received cardiac transplantation for diffuse atherosclerotic coronary disease. All the patients underwent open chest ultrasound scanning shortly before the cardiac specimens became available. The goal of the study was to document

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the content and accuracy of the ultrasound images and determine the ultrasound appearance of different kinds of atherosclerotic disease.

Methods

Study group. The hearts of five patients were examined in this study. All previously underwent angiography and were found to have severe coronary artery disease. One of the patients, a 52 year old man, underwent scanning as part of our previous investigation of open chest artery imaging during coronary bypass surgery (11) and died of a perioperative myocardial infarction 36 hours after the bypass procedure. The other four patients received a cardiac transplant as part of the transplantation program at the University of Arizona Health Sciences Center because they had severe diffuse atherosclerotic coronary artery disease with extreme cardiac dysfunction. One of the transplant patients had had coronary artery bypass grafts to the right and left anterior descending coronary arteries which had subsequently been proven to be occluded by angiography. The cardiac transplant recipients ranged in age from 36 to 52 years. Angiograms of all patients had been reviewed and specific areas of the coronary artery bed were selected for scanning. After giving informed written consent for the procedure as part of an approved research protocol involving human subjects, all patients underwent intraoperative scanning.

Scanning methods. Two ultrasound scanning probes were employed in this study. Both were designed and built at the New York Institute of Technology Research and Development Center in Dania, Florida. The first scanner probe, a 9 MHz water path scanner designed for peripheral vascular imaging with a commercially available ultrasound unit (Biosound, Indianapolis, Indiana), has been described previously (11). Briefly, scanning is performed at 9 MHz interrogation frequency. Sound energy is mechanically steered by a mirror within a water path, and is focused both electronically from a piezoelectric array and acoustically through the mirror and a lens on the contact surface. The scanner has a 4 x 4 cm examination field and contains a water path housing 7 x 8 x 5 cm, making it somewhat unwieldy to manipulate within the open chest. Images are obtained at 30 fields/s with resolution capabilities at 9 MHz rated at 0.3 mm axial, 0.5 mm lateral (at the 6 dB level) and 1.5 mm azimuthal as tested in a water tank.

The second scanning probe was specifically designed for surgical scanning in response to difficulties that arose when attempting to image coronary arteries in our previous study (11). This probe functions at 12 MHz, uses electronic focusing and mechanical steering as before, and has a configuration similar to an electric toothbrush (Fig. 1). A 5 cm long cylindric water path extends from the motor drive and is interposed between the piezoelectric array and a steering mirror near the tip. There is also an acoustic focusing lens on the content surface. The contact surface is approximately 1 x 1 cm and is more easily applied to the surface of the heart. The scanning field is 2 x 3 cm, and resolution characteristics are 0.1 mm axial, 0.3 mm lateral and 0.2 mm azimuthal. For the present study, both probes could be run with the Biosound scanner and could be repeatedly gas sterilized using standard ethylene oxide technique.

Scanning technique. With the aorta and venae cavae cannulated, that is, with the patient prepared for cardiopulmonary bypass, scanning was performed by the surgeon. This was immediately before coronary artery bypass grafting in one patient and before cardiac explantation in four patients. Probes were lightly placed on the surface of the heart and oriented to achieve longitudinal visualization of the coronary artery that was to be examined. Both scan heads were used during all procedures except for the procedure performed in the patient who died after bypass surgery, because he was studied before the new probe was available. The 9 MHz scanner provided a larger field of view for survey and localization of imaging areas (11) on the left and right coronary arteries and the proximal left anterior descending coronary artery. The smaller probe could be placed closer to the acute and obtuse margins of the heart and between the aorta and pulmonary artery directly over the left main coronary artery.

Probes were placed gently on the surface of the beating heart before the institution of cardiopulmonary bypass. All scanning was performed with constant hemodynamic monitoring. Fine angulations of the probe were performed by the surgeon, maintaining contact between the scanner and the moistened surface of the heart while viewing real-time images on a video screen. Scanner gain, image acquisition and recording were controlled by another investigator.

The left anterior descending and right coronary arteries were always scanned with the probe placed directly over...

Figure 1. The small 12 MHz intraoperative probe. The position of the plastic lens on the 1 x 1 cm contact surface is visible.
Figure 2. **A**, Ultrasound image of the left coronary artery (LCA) orifice filled with atherosclerotic material. The orientation of the artery is inverted, with part of the aortic valve (AoV) visible at the bottom. The patient survived complete left coronary artery occlusion because he had anomalous origin of the circumflex branch from a separate ostium. The gray bar at the top of this and subsequent images change shade every 2 mm. **B**, Photomicrograph of the proximal left anterior descending coronary artery in the same patient, corresponding to the ultrasound image in A, shows complete obstruction by organizing thrombus (longitudinal section, hematoxylin-eosin stain, original magnification ×27.3, reduced by 26%). **C**, Photomicrograph of the proximal left anterior descending coronary artery from a different patient shows occlusion by predominantly fibrous, fibrous/atheromatous plaque. Tiny recanalized channels and a focus of calcification are present. The internal elastic lamina is focally identifiable (arrow) (longitudinal section, hematoxylin-eosin stain, original magnification ×27, reduced by 28%). The patterns shown in B and C could not be distinguished by ultrasound, except where they were contiguous in the same vessel. **D**, Ultrasound image of a right coronary artery (RCA) showing what was confirmed histologically as an atherosclerotic lesion underlying a superimposed thrombus.
them, as was the circumflex coronary artery. The very proximal left anterior descending and left main coronary arteries were scanned with the 9 MHz probe placed into a far field electronic focus configuration and obliquely over the pulmonary artery to use it as a window. The surgeon then angled the scan plane down onto the superior surface of the heart until the left main coronary artery and its bifurcation were visualized (11). In all these views, the motion of the heart moves the coronary arteries in and out the narrow scan plane, allowing it only to be visualized during part of the cardiac cycle. The proximal circumflex and left main coronary arteries could also be scanned with the small probe placed directly on the left main coronary artery by interposing it between the aorta and pulmonary artery (Fig. 2). In this view, the coronary artery could be imaged constantly with little motion between the probe and the imaging area. For imaging of bypass grafts, the grafts were placed directly beneath the scan face; because the grafts were not anchored to the heart, they could be held within the scanning field and viewed throughout the cardiac cycle. Grafts were scanned to image proximal and distal insertions and midgraft locations.

Scanning was performed for a limit of 10 minutes before institution of cardiopulmonary bypass. During the scanning procedure, the surgeon identified the position of the lesion being scanned on the surface of the heart and measured its distance in centimeters from an external landmark. This information was recorded on the audio channel of the video tape recorder for later review.

Ultrasound data analysis. Videotaped images of the individual lesions studied by ultrasound were reviewed by two observers, and selected still photographs were obtained from the videotape for illustrative purposes using a Polaroid camera. During review, the type of obstruction, texture and other ultrasound features such as lesion density and ultrasound shadowing were noted. Percent obstruction was quantitated as 1 - the fraction of residual lumen x 100, with all judgments of control lumen and residual lumen made on the basis of ultrasound diameters in longitudinal views (Fig. 3A). Although oblique and transverse views could also, at times, be obtained on ultrasound scans, these were not emphasized during the scan procedure, because the method of gross anatomic evaluation likewise emphasized the longitudinal appearance of the coronary arteries (see later).

Anatomic specimens. The hearts removed from the four transplant patients and from the patient who died after coronary artery bypass grafting were fixed by immersion of the whole specimen in 10% neutral buffered formalin. The major subepicardial branches of the left and right coronary artery trees were dissected free from the heart, maintaining as much continuity as possible. The coronary ostia and any saphenous vein grafts were included. The coronary artery trees were fixed additionally in formalin before decalcification. During decalcification in hydrochloric acid (RDO rapid bone decalifier, Du Page Kinetic Laboratories, Naperville, Illinois), specimens were checked frequently with a sharp probe to avoid overdecalcification and loss of histologic detail. The specimens were sectioned longitudinally with a scalpel, and lesions corresponding to the ultrasound images were identified and photographed. Representative longitudinal and transverse sections were taken, processed and stained (hematoxylin-eosin and trichrome) by routine histologic methods, with subsequent histopathologic examination including photomicroscopy of selected areas.

Figure 3. A, Sharp protruding spicules of atherosclerotic material producing 90% obstruction (between the dots) are seen in this left anterior descending (LAD) coronary artery. The inner diameter of the vessel was 2 mm and the residual luminal diameter between the spicules was 0.2 mm, yielding a 90% obstruction. This ultrasound image shows close resemblance to the anatomic specimen shown in B. The anatomic specimen shows the stenosing atherosclerotic lesion (arrow) corresponding to the image in A.
Because of the potential for obliquity in longitudinal sectioning of some of the tortuous coronary artery segments and the possibility of variable shrinkage of different areas during fixation, percent obstruction was graded only greater or less than 60% for correlation with the ultrasound images, and was not further quantified. The individual lesions were evaluated independently by the pathologist with regard to location, contour, length and nature.

Statistical analysis. As stated, the potential for obliquity of either the ultrasound scans or anatomic sections precluded a strict quantitative comparison. Although the ultrasound images could usually be verified for the maximal vessel diameter and optimal imaging, especially when transverse views could be obtained, anatomic sectioning of the coronary arteries, once performed, was irreversible. Therefore, only a t test was performed for comparison between percent obstruction as graded ultrasonically and the categorization of lesions as greater or less than 60% obstruction anatomically. No attempts were made to strictly correlate anatomic versus ultrasonic estimation of the severity of obstruction.

Results

Anatomic lesions. From the five heart specimens, 26 lesions were specifically identified in the dissection for correlation with ultrasound images of the same lesions. Five of these were discrete stenosing lesions. Two of the latter were severely obstructive lesions that had been bypassed in the patient who died postoperatively. In all five of these lesions, the plaque was fibrous/atheromatous with variable calcium deposits. Nine coronary artery segments were completely occluded with fibrous/atheromatous plaque or organizing thrombus. Five coronary artery segments were anatomically small and showed diffuse mural thickening identified histologically as predominantly fibrous plaque. Five intramural, nonocclusive fibrous/atheromatous and variably calcified lesions were identified in which fine topographic details of the irregular luminal surface were easily appreciated. Two grafts completely occluded with thrombus and admixed atheroma were also studied. These had been obtained from the patient who received a cardiac transplant, but who underwent coronary bypass grafting 5 years before participating in this study.

Ultrasonic-anatomic correlates. Discrete lesions. The five discrete lesions presented a variety of ultrasound appearances, for the most part appearing as a bulging or protrusion of high intensity echoes into the lumen for a variable degree. The obstruction appeared either as sharp spicules (Fig. 3) of occlusive material or diffuse bulging of echoes (Fig. 4) and they showed various degrees of shadowing, that is, faint or absent echoes received from structures lying under the lesion caused by significant reflective properties of the lesion (Fig. 5). A high degree of morphologic sim-
Figure 5. This partially obstructive right coronary artery (RCA) lesion produces a significant calcium shadow (arrowhead).

Figure 6. A, An oblique short-axis ultrasound image of a small left anterior descending (LAD) coronary artery shows echogenic material within the walls but no luminal surface irregularities or occlusive plaque. B, Photomicrograph corresponding to the lesion shown in A shows mural thickening by predominantly fibrous plaque and a small residual lumen (cross-section, hematoxylin-eosin stain, original magnification ×27.3, reduced by 27%).

Similarity of the ultrasonic to the anatomic appearance of the discrete occlusive lesions was obtained in this study, as seen in Figures 3 and 4.

Complete occlusion. The ultrasound appearance of completely occluded coronary arteries was that of vessels filled with echo-dense and granular-appearing material; this material filled an ultrasonically identifiable but nonpatent lumen. Although the ultrasound appearance (granularity) of thrombus (Fig. 2B) was similar to that of the fibrous/atheromatous lesions (Fig. 2C), the two could be distinguished on ultrasound images where they were contiguous and could be compared side by side (Fig. 2D). When examined side by side, bright echoes from a fibrous/atheromatous plaque could be seen in association with thrombus, which had presumably formed as a complication on the underlying plaque. High calcium content within completely occluded vessels produced ultrasound shadowing.

Diffuse nonobstructive disease in anatomically small vessels. A close general correlation was obtained between vessel size on ultrasonic visualization and anatomic examination. The vessel shown in Figure 6A is a distal segment of a left anterior descending coronary artery which is small in caliber. The walls underlying the endothelium show bright echogenic areas. The histologic transverse section of this vessel shows mural thickening caused by predominantly fibrous plaque, and a small residual lumen (Fig. 6B).

Graft occlusion. Histologically, the grafts were occluded with unorganized thrombus variably admixed with atheromatous material. The unorganized thrombus/atheroma was ultrasonically indistinguishable from oc-
clusive fibrous/atheromatous plaque or organizing thrombus, all showing echo-dense granular material within the lumen. However, no discrete bright intramural lesions were imaged in the occluded grafts.

_Luminal surface of vessels._ Intramural, nonocclusive fibrous/atheromatous plaque that produced an irregular luminal surface was visualized ultrasonically (Fig. 7A). A significant residual lumen was often present within these areas. A high calcium content histologically in these lesions was associated with significant ultrasound shadowing (Fig. 7B and C), that is, the areas behind these bright reflectors showed significant attenuation of ultrasound energy and few echoes were received from them.

_Calcium content._ Verification was obtained in this study that lesions with high calcium content produced significant shadowing. Figure 7B shows a lesion with bright echoes and shadowing, which was associated histologically with calcium deposition as shown in Figure 7C. Figure 5 shows an example of calcium shadowing from a more discrete lesion.

_Severity of obstruction._ As stated in the Methods section, this study was not designed to provide a truly quantitative comparison of degree of obstruction. Nonetheless, the overall and luminal size of the ultrasonically imaged coronary arteries appeared to correlate grossly with the size of the anatomic specimens. When the percent obstructions estimated ultrasonically were compared with the anatomic judgments of greater or less than 60% obstruction, it appeared that the ultrasound images could clearly distinguish obstructions of significance. Lesions anatomically judged to rep-
resent less than 60% obstruction (n = 12) had a mean ultrasound grading of 39 ± 7% (± standard error) obstruction, and lesions anatomically judged greater than 60% or complete (n = 14) had a mean ultrasonic obstruction grade of 88 ± 4% (probability [p] < 0.001).

Discussion

This study was designed to validate the ultrasound appearance of coronary artery atherosclerotic lesions compared with anatomic specimens. Previous angiographic correlations suggested to us that ultrasound images were quite accurate compared with angiography, and our initial comparisons with anatomic specimens obtained in the patient who died after bypass surgery suggested that the fine detail in ultrasound images provided information not comparable with the angiographic information (11).

Ultrasound appearance of coronary atherosclerosis. A variety of ultrasound appearances were found in our earlier study, including complete obstruction of the ultrasound lumen by echo-dense granular material and calcium shadowing, which merited further investigation. The present study documented not only the ability of ultrasound to describe lesions as discrete or diffuse compared with anatomic specimens, but again allowed verification that the ultrasound technique could quite accurately localize the lesions. The ultrasound images also appeared to provide information about mural disease of a nonocclusive nature, overall vessel size and configuration, subtle luminal contour irregularities and the content of occlusive plaque or thrombus.

Potential importance of lesion composition. Although the severity of an atherosclerotic obstruction may be the major factor in making intraoperative judgments regarding bypass, lesion content and type are of potential importance concerning decisions relating to newer therapeutic maneuvers. For instance, this information could be of importance in deciding which lesions might respond favorably to streptokinase thrombolysis (12) or transluminal coronary balloon angioplasty (13), except that at the present time, images of coronary artery lesions, such as those available in this study, can be obtained only after the chest is open. Present standard cardiac echocardiographic techniques can derive images of the very proximal portions of the right and left main coronary arteries in adults through the chest wall but only with gross anatomic features definable (14). Should future scanners achieve penetration at high enough frequency to image small portions of the coronary arteries through the chest wall, these anatomic-ultrasound correlations may have additional relevance to these new modes of therapy for coronary artery disease which are performed as part of a catheterization procedure. Judgment of the nature of an atherosclerotic plaque, particularly in terms of calcium content, on the basis of ultrasound scanner results at the time of coronary bypass surgery may still be of relevance to the increasing interest now being shown for intraoperative transluminal balloon catheter dilation of coronary lesions performed during coronary artery bypass surgery (15).

Intraoperative scanning. Some of the uses of intraoperative coronary artery scanning identified in our previous study included identifying lesions distal to other lesions in areas of the coronary artery bed that were not clearly seen angiographically, identifying lesions that had progressed since angiography, clarifying orifice lesions, helping the surgeon localize disease and assessing the angle of insertion and adequacy of proximal and distal ends of coronary bypass grafts. The application of a new probe in this study was not directed toward using ultrasound to assist in making therapeutic decisions during surgery as in the previous study because four of these five patients were receiving transplants. Nonetheless, during the period of study, the new probe was also used for imaging during bypass grafting at our institution. It appears to provide higher resolution and is much more easy to manipulate within the thoracic cavity. The smaller configuration provides improved access to the circumflex and left main coronary artery.

Conclusion. The anatomic correlations obtained in this study should improve our understanding of the nature of the patterns observed on ultrasound imaging of the coronary arteries. In addition, we believe that the new probe with its ease of application and high resolution should assist in the further application of ultrasound scanning during coronary artery bypass surgery.

References


