Ultrasonic Imaging of the Coronary Arteries in Open-chest Humans: Evaluation of Coronary Atherosclerotic Lesions During Cardiac Surgery

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SUMMARY We explored techniques that would allow the surgeon to localize coronary artery lesions demonstrated angiographically or to supplement angiographic information in patients who are undergoing coronary artery bypass procedures by intraoperative scanning of the coronary arteries using ultrasound. A 9-MHz electronically focused water-path ultrasound scanner was first used to image the coronary arteries in three anesthetized, open-chest sheep. In a subsequent study, 10 human subjects undergoing cardiac surgery for valve replacement who had normal coronary angiograms were scanned during heart surgery to provide images of normal coronary arteries. The ultrasound probe was sterilized with gas and placed directly on the beating heart by the surgeon. In the third phase of this study, 21 patients with coronary artery disease were scanned and the ultrasonic appearance of their imaged coronary lesions was compared to independently interpreted angiographic estimates of percent obstruction, with close correlation (r = 0.91). The ultrasound scan could be used to identify lesions in vessels beyond proximal occlusions, which are not visualized well angiographically, and could localize the site of lesions to determine placement of saphenous vein bypass grafts. This new technique may provide a method of evaluating coronary atherosclerotic lesions during coronary artery surgery and aid decisions regarding placement of saphenous vein grafts.

SINCE initial encouraging results with saphenous vein bypass grafting for coronary disease, many patients have had impressive symptomatic relief, and life has been prolonged in many others. While ultrasound has been used noninvasively in attempts to image the proximal coronary arteries, coronary angiography remains the standard for diagnosis and estimation of the severity of coronary artery disease. Although angiography usually provides adequate detail, angiographic imaging of some coronary lesions and objective, reproducible interpretation of coronary angiograms may be difficult to achieve.

Initial attempts to use M-mode echocardiography intraoperatively for evaluation of cardiac morphology have been followed by efforts using intraoperative M-mode and two-dimensional echocardiography to evaluate valvular anatomy and physiologic effects of valvular disease. Recently, because of questions about the physiologic significance of coronary obstructions observed angiographically and difficulties with coronary angiography as a standard, Wright and co-workers explored a method of assessing coronary obstructions in man during cardiac surgery.

We report the use of high-frequency, high-resolution ultrasound for scanning the coronary vascular bed in open-chest humans for imaging coronary vascular anatomy before and after saphenous vein bypass grafting.

Methods

Study Population

Three study groups underwent cardiac imaging.

Group 1

Initially, three full-grown, open-chest sheep were studied, during ventilation with a Harvard pump, and under general anesthesia in the supine position. The sheep weighed 25–30 kg and all had undergone a median sternotomy. They were imaged without prior gas sterilization of the ultrasound probe. In two sheep, intraaortic injections of indocyanine green dye were used for echocardiographic contrast validation of coronary artery imaging. This procedure was a feasibility study for coronary artery imaging and, aside from lack of probe sterility, scanning was performed in a fashion identical to the studies in humans as described below.

Group 2 — Humans with Normal Coronary Arteries

Ten human subjects undergoing mitral or aortic valve surgery were imaged to attempt to define the ultrasound appearance of the normal coronary vascular bed. Five of these subjects were younger than 25 years of age and were assumed to have normal coronary arteries. The other five patients were 45–55 years old and had undergone coronary arteriography, and no abnormalities were demonstrated.

Group 3 — Humans with Coronary Atherosclerosis

Twenty-one human subjects with a variety of angiographically demonstrated coronary artery lesions were studied in order to obtain ultrasonic angiographic correlations for coronary artery disease. Most had multi-
ple coronary artery lesions; in each, selected portions of the coronary artery bed were scanned. Six of these patients had saphenous vein bypass grafts imaged after placement; three of the grafts imaged were between the aorta and left anterior descending coronary artery and three between the aorta and the right coronary artery.

**Equipment**

The ultrasound scanner used was a Biodynamics Biosound, a 9-MHz (water path) near-field scanner with variable electronic focusing on transmit phase. It was designed as a portable vascular and small parts scanner. The probe has a trapezoidal-shaped enclosed water path chamber housing a 4-cm-long water path (fig. 1). The sound energy passes from the piezoelectric array to a parabolic mirror that steers the ultrasound energy mechanically by oscillation to achieve cross-sectional scanning. The depth of electronic transmit-and-receive focus can be optimized by a three-position switch on the probe to maximize resolution in regions 0.5–1.5 cm (near), 2–3 cm (mid) and 2.5–4 cm (far). This provides the following optimized resolution capabilities in these zones measured against a needle target and a water tank in standard fashion: ± 0.3 mm axial resolution, ± 0.5 mm lateral resolution (6 db) and an azimuthal slice thickness of approximately 1.5 mm. The scanner produces an image field of 4 cm long with a 4-cm depth of interrogation as a 525-line video output image at 30 frames/sec. A range-gated Doppler flow capability is available along the center scan line of the image field when cross-sectional scanning is stopped; the range gain depth is determined by the position of a joystick cursor.

The probe itself is slightly bulky for intrathoracic use. Its contact end is 5 cm long and the water path chamber is 7 cm long and 6 cm high. The motor drive is contained within the handle and does not interfere with scanning. The major determinant for cardiac contact is the water path portion of the head. One-hundred-ten-volt, 60-Hz power for the scanner in New Zealand was provided by a quartz crystal current converter that also provided independent grounding. Before use in humans, the probe was gas sterilized by the ethylene oxide technique and degassed for 18–24 hours.

**Scanning Technique**

With the aorta and venae cavae cannulated (i.e., with the patient prepared for cardiopulmonary bypass), the scan probe was placed gently on the heart by the surgeon. The probe was oriented to scan either longitudinally or transversely directly over the coronary artery to be examined. For coronary arteries within 2 cm of the scan face, that is, directly beneath the scan probe, the scanner was placed in a near-field focus configuration. Fine angulations and probe contact were maintained by the surgeon, who did all scanning with constant hemodynamic monitoring.

The left anterior descending coronary artery was imaged in the interventricular sulcus from its appearance on the anterior surface of the heart to as close to the apex as the scan head would fit. The left main coronary artery and proximal left anterior descending and circumflex coronary arteries were imaged with the probe placed obliquely over the pulmonary artery, which served as a window. The probe was placed into a far-field focus configuration, and the surgeon gradually angled the scan plane onto the superior surface of the heart until the left main coronary artery and its bifurcation were visualized. The right coronary artery was imaged from its appearance on the right side of the aorta down along the atroventricular sulcus to as close to the diaphragmatic surface of the heart as the scan head would reach. The bulk of the probe did not allow it to be placed on the acute or obtuse margins of the heart or allow placement over the posterior descending coronary artery until after the patients were placed on cardiopulmonary bypass. These areas of the coronary vascular bed were scanned after cardiopulmonary bypass had been instituted and cardioplegia administered.

In all instances, for the posterior descending or obtuse marginal branches of the circumflex coronary artery or rarely for the left main coronary artery itself, scanning was performed after administration of cardioplegia. After cardioplegia and with the patient on bypass, the apex of the heart was tilted up and the scan head placed directly over the coronary artery to be scanned or where the surgeon thought the coronary artery was located if he could not see it. After cardioplegia, there was no motion of the heart. This allowed slow and progressive scans to be performed with transducer contact maintained by moderate pressure. Nonetheless, without normal phasic coronary circulation, the scans after cardioplegia resulted in a significantly collapsed appearance of the coronary artery. Such scans after cardioplegia were therefore used in general in group 2 for sighting coronary arteries and in group 3 for sighting lesions as bright echogenic areas of plaque or for finding distal lumen in relation to saphenous vein bypass grafts. The images obtained after cardiopulmonary bypass and cardioplegia were not, however, used for angiographic/echocardiographic ultrasonic correlations of severity mentioned below because of the lack of physiologic distension of these coronary vessels when they were imaged.

Not every coronary artery was examined in every
patient, but a record was kept of successful imaging compared to attempts to image a specific coronary artery. In the patients without coronary artery disease, scanning was arbitrarily limited to 4 minutes total time before cardiopulmonary bypass was instituted and another 3 minutes afterwards.

In the patients with coronary artery disease, specific lesions were selected for imaging and attempts were made to image these vessels only. No attempts were made to produce a general survey of the coronary vascular bed. In the patients with coronary artery disease, scanning was limited to 10 minutes before institution of cardiopulmonary bypass and 5 minutes afterwards.

In six coronary patients, saphenous vein bypass grafts were imaged after they were placed. We attempted to image three grafts from the aorta to the right coronary artery circulation, and three from the aorta to the left anterior descending coronary artery. In these patients, the probe was placed directly over the proximal or distal insertion of the saphenous vein bypass grafts and attempts were made to image the grafts themselves and their anastomoses with either the aorta or the distal coronary bed. While gross motion of the beating heart during cardiac scanning precluded Doppler interrogation of the native coronary artery circulation, the saphenous vein bypass grafts, which were not attached to the heart, could be held stationary under the probe to allow Doppler interrogation for phasic flow. Output of the Doppler flowmeter consisted of an oscillating dot on the real-time image and an audio signal, but no phasic flow traces as hard copy output were obtained.

Data Storage and Analysis

Videotape images of the patients’ coronary artery images were reviewed by playback in the operating theatre to assure that the images were of adequate quality. The videotape results were then reviewed to catalog successful imaging of specific coronary arteries in patients in group 2, and to catalog coronary lesion imaging in group 3. In group 3, we also measured the percent obstruction from the ultrasound image for the lesions that had been successfully imaged in the 21 subjects with coronary artery disease. There were 26 lesions for which the angiographic and ultrasonic images were acceptable for correlation. The angiograms were reviewed before surgery by both an angiographer and an ultrasound interpreter to identify lesions to be imaged. The ultrasound scans were later coded and reinterpreted by two observers, the results averaged, and then compared with the angiographic reports. Percent obstruction on angiography was estimated from relevant views of the multiple-projection coronary angiograms. Average loss of lumen between views was expressed as percent cross-sectional area reduction, calculated by the formula

\[
\frac{(D_{\text{control}}/2)^2 - (D_{\text{residual}}/2)^2}{(D_{\text{control}}/2)^2} \times 100
\]

where \(D = \) vessel luminal diameter and \(\pi\) in all three terms cancels out. In this system, a 67% diameter loss = a 90% area reduction, and a 50% diameter loss = a 75% area reduction, and so on. From the ultrasound image, the percent cross-sectional area reduction was also estimated using the same formula with diameters obtained from longitudinal views of the vessels and lesions supplemented by transverse views for 12 of the lesions. The probe configuration precluded adequate transverse plane imaging of the other 14 lesions; for these lesions, only single-plane ultrasonic views were used for the correlation to angiography.

A linear regression analysis was used for angiographic/echocardiographic comparison of percent obstruction.

Results

Group 1

The left anterior descending coronary artery and the right coronary artery could be visualized in all three sheep (fig. 2). The left anterior descending was approximately 1.5 mm in diameter on the ultrasound images lying in fatty tissue of the interventricular sulcus. The artery could be easily differentiated from the collapsible overlying coronary vein in the interventricular sulcus. The external caliper measurement of the thin-walled coronary artery at the site of scanning was within 0.25 mm of the ultrasonically imaged outer diameter at 10 sites on the left anterior descending and right coronary arteries at which the comparison was obtained.

Group 2

A human left anterior descending coronary artery imaged in the mid region is shown in figure 3. It is very similar in appearance to the normal vessel seen in the sheep, i.e., a smooth-walled, nontortuous vessel about 2 mm in diameter. Gross motion of the coronary arteries in and out of the scan plane with cardiac contraction and relaxation made it difficult to see the arteries throughout the cardiac cycle, but they could most often be visualized best during slow diastolic filling. Slow motion and stop-frame playback of the videotapes added significantly in evaluating vessel contour. Transverse plane imaging was also achieved for the left anterior descending coronary artery in the humans by rotating the probe into a position perpendicular to the course of the coronary artery.

The ultrasound appearance of a normal right coronary artery as it originates from the aorta is shown in figure 4. To achieve right coronary artery imaging in the patients, i.e., to place the scan probe over the atrioventricular sulcus, the probe had to be inverted, with the handle facing the left side of the thorax. Since there was no capability within the system for inverting the video raster, this inverted the image orientation of the right coronary artery showing its course upside down. In figure 4, and for all right coronary artery images, the inferior direction is shown at the top of the image and the superior direction is at the bottom of the image. The normal right coronary artery was 4–5 mm, with thin walls and normal smooth endothelium. Its origin from the aorta could be directly visualized with
the transducer sitting over the right coronary artery high in the atrioventricular sulcus. It was difficult to achieve transverse plane imaging of the right coronary artery because of the unwieldy size of the probe. Transverse images of the right coronary artery were obtained in only four of 10 group 2 patients.

The left main coronary artery and proximal left anterior descending and circumflex coronary arteries were imaged through the pulmonary artery (fig. 5). The origin of the left main from the aorta could be routinely visualized and approximately 1.5–2 cm of the proximal left anterior descending and proximal circumflex could likewise be imaged. The left main coronary artery was approximately 4–5 mm in diameter and the normal proximal left anterior descending and circumflex coronary arteries were usually about 3 mm in diameter on the ultrasound images. The left coronary artery and its bifurcation could also be visualized after cardioplegia, but had a collapsed appearance.

Figure 2. (A) Longitudinal image of the left anterior descending coronary artery (LAD) from an open-chest sheep. (B) The coronary vein (CV) overlying the LAD is visualized in transverse section. Both lie within the bright echoes of the fat pad in the interventricular sulcus. The faint vertical lines through the image represent the 2-mm graticule; thus, the LAO is 2 mm in diameter. This and all subsequent images are identical in scale.

Figure 3. A longitudinal image of a human left anterior descending coronary artery (LAD).
(fig. 6). Although the vessels themselves could be imaged after cardioplegia, it was difficult to estimate artery size once the vessel was collapsed.

All imaging in group 2 was achieved without hemodynamic compromise, except for intermittent premature ventricular complexes, which ceased immediately upon removal of the probe from the heart. No infectious complications occurred as a result of scanning in group 2 patients.

Success rates for imaging the individual coronary arteries were quite similar to those for group 3.

**Group 3**

Group 3 patients were studied to delineate specific lesions and allow angiographic/echocardiographic correlations of estimates of severity. With the exception of one episode of ventricular fibrillation during scanning (which may or may not have been related to scanning; the patient was immediately placed on cardiopulmonary bypass), there were no complications, infectious or hemodynamic, of the scanning procedures in the 21 group 3 patients with coronary artery disease.

The success rates for imaging specific areas of the coronary tree were similar to those in group 2. Of the 21 patients in group 3, 13 of 15 attempted visualizations of the left main coronary artery to the bifurcation were successful, but three were achieved only after cardioplegia. The proximal left anterior descending and circumflex coronary arteries distal to the bifurcation were visualized in 10 of the 15 patients in whom this maneuver was attempted, three after cardioplegia. The mid-left anterior descending coronary artery was visualized in 19 and the proximal right coronary artery in 20 of 21 patients. The distal left anterior descending coronary artery was visualized in seven of 10 patients (six after cardioplegia), and the distal right in six of 10 (four after cardioplegia). The posterior descending coronary circulation was visualized in three of six attempts, all after cardioplegia, and specific obtuse marginal vessels were visualized in three of six patients after cardioplegia. Specific diagonals suspected of disease were visualized in four of seven patients, two of these only after cardioplegia.

Specific examples of angiographic/ultrasound correlations for coronary lesions may be illustrated. Figure 7A is the angiogram of a proximal left anterior descending coronary artery lesion that was imaged just below the point at which the left anterior descending coronary artery reaches the anterior surface of the heart. The ultrasound image of this lesion is shown in figure 7B. The angiogram was interpreted as a 95% obstruction, and the echocardiogram suggested almost complete obstruction of the left anterior descending coronary artery. Bright echoes representing a plaque impinging on the lumen were visualized occluding the coronary artery and there was distal endothelial disease as well.

Figure 8A shows a severe angiographic (95%) obstruction of the right coronary artery; figure 8B shows the ultrasound image in the same patient. The right coronary artery was imaged in the atroventricular sulcus. The image orientation is inverted, with the proximal coronary shown at the bottom of the image and the distal coronary at the top. This lesion was imaged bulging into the coronary artery from its back wall and casting an ultrasonic shadow. In this example, the angiogram suggested an almost ring-like obstruction with an additional portion of the plaque impinging upon the vessel from the side wall. Thus, a portion of the plaque was not well imaged, because only a marginally acceptable transverse view was obtained, leading to an ultrasonic underestimation of the severity of

**Figure 4.** Two images of the orifice and proximal portion of the right coronary artery (RCA). The RCA is displayed in inverted fashion so that the more proximal portion of the RCA is at the bottom and the more distal portion at the top. The lower panel shows the origin of the RCA from the aortic root. The proximal RCA is shown in the upper panel.
the lesion compared with its angiographic appearance.

Figure 9A shows the angiogram of a moderately severe left anterior descending lesion that is quite discrete and localized; figure 9B shows the same lesion imaged ultrasonically as two regions of plaque impinging upon the lumen from opposite sides of the vessel. Figure 10A shows the angiogram of a complete right coronary obstruction bypassed by collateral vessels. The ultrasound image that corresponded to this type of lesion was different from those just described. The ultrasonic image, shown in figure 10B, seemed to represent a coronary artery lumen that was completely filled with echo-dense granular material, which we believe represents organized thrombus or atheroma, and was associated whenever we saw it with complete obstruction, and usually, with filling of the distal bed by collaterals. We visualized this type of ultrasound image in four of the lesions. One of these lesions, however, had progressed quite recently, since an angiogram 2 months previously had shown only a 50% obstruction in the area. The others had collaterals formed around them and appeared to be older complete coronary obstructions.

Figure 11A shows angiographic appearance of endothelial irregularities along the right coronary artery; figure 11B shows the corresponding ultrasonic appearance in the same patient, with thickening of the endothelium and bright echoes representing the atherosclerotic change. In other patients (fig. 11C), what corresponds to minimal angiographic disease often presented a more striking ultrasonic picture of endothelial irregularities.

Fifty-three lesions were imaged ultrasonically in the 21 group 3 patients. Twenty-six of the lesions were imaged adequately for quantitation before cardioplegia and corresponded to acceptable angiographic images for correlations. Of these, longitudinal as well as transverse ultrasound images were available for only 12...
lesions. There were 14 proximal left anterior descending lesions, six with transverse images available; seven proximal right coronary lesions, three with transverse images; and five left main coronary lesions, three with transverse images available for the comparison (fig. 12). Readings of the ultrasonic interpreters never differed by more than 20% cross-sectional area loss. Figure 13 shows the ultrasonic/angiographic correlation for percent of obstruction for these 26 lesions. There was a good correlation between angiographic and ultrasonic estimates of severity ($r = 0.91$). Nonetheless, compared with angiography, echocardiography underestimated severe lesions and overestimated minimal angiographic changes.

Imaging of Grafts

Six saphenous vein bypass grafts were imaged after placement, three to the right coronary circulation and three to the left anterior descending circulation. The proximal aortic end of the graft was imaged adequately in four patients and the distal insertion of the graft was imaged in five (fig. 14). The angle of distal insertion could be visualized and the left anterior descending coronary artery imaged near the anastomosis to assure that the graft had been placed into a nondiseased area. The Doppler sample volume was placed within the area of the imaged graft so as to allow the verification of flow through the graft. The graft to the left anterior descending artery (fig. 14) shows an inverted orientation because of the placement of the transducer. Doppler flow was verified in all six grafts.

**Figure 7.** (A) Angiographic image of a severe left anterior descending (LAD) lesion. (B) The corresponding ultrasonic image derived at surgery in the same patient.

**Figure 8.** Severe obstruction to the mid-right coronary artery (RCA) is shown angiographically. (B) Corresponding ultrasonic view shows a prominent, bright plaque indenting the RCA from behind and narrowing of the lumen. The RCA is shown in its usual inverted fashion, with the proximal (PROX) portion at the bottom and the distal (DIST) portion at the top. The lesion casts a shadow.
of the heart, and the technique of probing to establish luminal patency is considered crude by many surgeons. These problems, along with the difficulty of relating the spatial position of an angiographically demonstrated lesion to its position on the surface of the heart, led to attempts to localize coronary lesions at the time of surgery and to establish their physiologic significance.

Discussion

While angiography remains the standard test for visualization of coronary artery anatomy, the angiographic findings in patients referred for surgical treatment of coronary artery disease often do not totally answer questions relating to surgical management. Uncertainties often arise as to the necessity of additional bypass grafts, and patients may be referred for three vs four bypasses. Surgeons in this situation almost always choose to do the greater number, since there are difficulties in making anatomic diagnoses of additional coronary artery lesions at the operating table. The coronary arteries are often not visualized on the surface

Figure 9. The angiogram shows a discrete, fairly proximal left anterior descending coronary artery (LAD) lesion. (B) The corresponding echocardiographic image derived from the same patient during heart surgery shows a cross-section of a ring-like plaque with two bright echoes impinging on the lumen from both sides of the LAD. The solid arrow shows the orifice of a diagonal vessel.

Figure 10. (A) A complete obstruction of the right coronary artery (R) is shown angiographically with a muscle bridge (M) coming around the obstructed coronary artery. a = atrioventricular nodal artery. (B) Ultrasonic image shows a right coronary artery (RCA) lumen filled with echo-dense granular material.
Several significant problems are inherent in our method. Most obvious was the large size of the probe, which severely limited its maneuverability within the thorax. This essentially limited the major applications to the accessible coronary arteries, the left anterior ascending, the right coronary artery, the left main coronary artery and its bifurcation imaged through the pulmonary artery. Smaller probes capable of being moved around toward the posterior and inferior diaphragmatic surfaces of the heart would be useful in this regard. Nonetheless, one of the major requirements for achieving adequate resolution of the coronary arteries on the surface of the myocardium was the water path inherent in the present probe design, which allowed imaging of areas directly under the probe contact area. The “next-generation” probe designed for this investigation has very recently become available. It functions at 13 MHz, has a water path, and is the size of a large crayon. It has water tank and apparent resolution significantly better than the commercially available probe. The gross motion of the coronary arteries as they moved across the scan plane allowed them to be visualized only during certain phases of the cardiac cycle and required slow motion and stop-frame playback capability in order to review the anatomy. While the problems of probe manipulation and cardiac motion could be overcome by examining the heart after cardioplegia, an adequate method of physiologically distending the coronary arteries for this examination is needed.

Other problems in the present method relate to coronary anatomy and the spectrum of arteriosclerotic le-
FIGURE 13. Ultrasonically measured percent cross-sectional area reduction in relationship to angiographic percent reduction for the 26 lesions adequately imaged. The graph suggests that ultrasound might underestimate the severity of the severe lesions and overestimate the more minor angiographic changes.

FIGURE 14. An inverted image of a graft inserting into the mid-left anterior descending coronary artery (lad). The graft is actually passing inferiorly, but the image is inverted. The anastomosis of the vein graft to the native left anterior descending can be clearly seen, in the area around the letter "d" in the abbreviation "lad." The horizontal line next to the letter "t" in "graft" represents the position of the Doppler range gate in this image.

Changes. Tortuosity of coronary arteries on the surface of the heart could cause discontinuities in the lumen as visualized and suggest false-positive lesions that appear to be obstructive. This did not seem to be a problem when careful scanning techniques and frame-by-frame videotape playback analysis were used, but these time-consuming review techniques are a problem for immediate recognition and reading of these studies in the operating room by the surgeon.

Also quite fundamental to the ultrasound approach are problems with the learning curve concerning the appearance of angiographic coronary artery disease on ultrasonic images. The variability of patterns we have seen includes discrete, ring-like, bright atherosclerotic lesions, thicker, more impinging coronary lesions that cast shadows, or vessels filled with echo-dense granular material. These observations suggest that a variety of ultrasonic appearances correlate with angiographic coronary artery disease. These may reflect varying fat content or varying calcium content in the atherosclerotic lesions themselves, as well as superimposition of thrombosis and fibrosis upon preexisting atherosclerotic lesions. An ultrasonic/anatomic correlation study is necessary. Unfortunately, since anatomic sections of coronary arteries containing these lesions are rarely removed during surgery, acquisition of these anatomic specimens for correlation requires necropsy material, as in the study by Isner and associates. Their study of angiographic and anatomic correlations suggested limitations of angiography for diagnosing coronary disease and suggested the need for using other methods to evaluate coronary disease. An ultrasonic/anatomic correlation study similar to Isner’s work is under way in our institution.

If parallels are drawn to the ultrasonic studies of atherosclerotic disease of the carotid arteries, even with high-resolution systems, imaging of soft plaque may remain a constant problem for the ultrasonic method. Plaque without significant fibrosis or calcific deposition may be invisible to ultrasound. The difficulties of partial visualization of plaque have been
overcome in peripheral vascular scanning primarily by Doppler flow mapping as an adjunct to ultrasound scanning. The Doppler interrogation capabilities of the system we used are limited. First, sampling is confined to the center line, but portions of the transducer array are used for sending and receiving in order to achieve Doppler measurement in vessels where flow is perpendicular to the scan head. Another major limitation to the accessibility of the coronary bed to Doppler flow mapping with the present imaging system has been the motion of the heart, a problem overcome in the method of Wright and co-workers, in which the Doppler interrogation system is attached to the heart surface by suction and moves with the coronary artery. It is unlikely that an imaging system with low enough mass to move with the coronary artery like their Doppler probe will be available soon, so a compromise combining the two methods would be most likely to provide both the imaging and the Doppler information.

Despite the potential risks involved in open-chest cardiac scanning, our experience in New Zealand with the 31 patients who were studied for coronary artery anatomy, and an additional 80 patients who were studied with phased-array scanners for imaging and clarification of valvular anatomy, pre- and postoperatively in the operating theatre, suggest that these studies are easy to perform and can be accomplished without major complications of infection or electrical or mechanical hazard.

The potential for imaging coronary anatomy at the operating table may permit the surgeon to clarify the position of angiographically demonstrated lesions, as well as to demonstrate lesions not seen angiographically because of technical problems or because of disease in proximal vessels, as in our study. The surgeon can also survey the coronary artery bed to determine a downstream site that is free of disease and of large enough caliber to accept a graft and can verify patency and adequate insertion of saphenous vein bypass grafts as in our study. The present technique does not allow a complete, rapid and accurate survey of the entire coronary tree, so it is unlikely to replace angiography. Nonetheless, patients with known angiographic lesions who are undergoing surgery because of an increase in symptoms might be studied for possible additional lesions without having repeat angiography. Other patients, bordering on a coronary age group who are being operated for clinical and two-dimensional echocardiographic findings of valvular disease, could also be screened in this fashion at the same time as their valvular surgery so that major coronary disease is not missed if angiography and catheterization were to be avoided.

Our pilot studies suggest that a high-resolution ultrasound system can demonstrate coronary arterial anatomy with enough detail to diagnose coronary artery disease and to achieve a semiquantitative estimate of its severity. Improvements in probe design and acquisition of an imaging-compatible Doppler flow analysis system in the future should make available to the surgeon a comprehensive ultrasonic method for evaluation of coronary artery anatomy and physiology during heart surgery.

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