Intraoperative evaluation of coronary artery bypass graft anastomoses with high-frequency epicardial echocardiography: experimental validation and initial patient studies

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ABSTRACT There is currently no accepted approach for intraoperative evaluation of the technical adequacy of coronary artery bypass graft anastomoses. High-frequency epicardial echocardiography performed intraoperatively could assess coronary artery bypass graft anastomoses by providing on-line short-axis (cross-sectional) and longitudinal two-dimensional images of the vessels. To validate measurements of anastomoses with high-frequency epicardial echocardiography, luminal diameter determined by high-frequency epicardial echocardiography was compared with that determined histologically after perfusion fixation in 12 dogs studied after coronary artery bypass grafting. Technical errors were deliberately created in some grafts. The results of these animal validation studies showed that maximum luminal diameter of the anastomosis by high-frequency epicardial echocardiography correlated well with histologic measurements (r = .92; high-frequency epicardial echocardiography = 0.8 histology + 0.3). All deliberately created technical errors were detected by an independent observer using high-frequency epicardial echocardiography. After completion of the animal studies, we demonstrated the clinical applicability of this approach in 12 patients. Fifteen coronary artery bypass graft anastomoses were examined intraoperatively with high-frequency epicardial echocardiography. The measured maximum luminal diameter of the anastomosis was greater than the maximum luminal diameter of the native artery, as expected, in all end-to-side anastomoses. However, the maximum luminal diameter of the side-to-side anastomoses was equal to or slightly less than that of the native artery. In this initial patient group, minor technical errors were noted in two of 15 graft anastomoses. In conclusion, high-frequency epicardial echocardiography can accurately measure coronary arterial bypass graft anastomoses and has potential for intraoperative detection of technical errors and inadequacies. Such information may provide a means to detect and correct these technical errors and inadequacies intraoperatively.

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THE INTRAOPERATIVE assessment of the technical adequacy of coronary artery bypass graft anastomoses has been hampered to date by a lack of appropriate tools and technology. Although several approaches, such as intraoperative angiography and various types of graft-flow measurements, have been tried, none are completely satisfactory. As a consequence of methodologic limitations, technical errors in the vein graft-to-artery anastomosis may not be detected at a time when surgical revision can be easily accomplished.

Echocardiography has been used in an attempt to visualize coronary arteries in closed-chest patients. Now, with the development of high-frequency epicardial echocardiography as an intraoperative tool, the potential for accurate assessment of coronary arterial morphology in vivo exists. We and others have previously evaluated high-frequency epicardial echocardiography and determined its accuracy for measure-
ment of coronary arterial wall and luminal dimensions using in vivo and in vitro validation techniques. We suggest that this technique can be used to evaluate the technical adequacy of bypass graft anastomoses both proximally on the aorta and distally into the native coronary artery.

The purposes of this study were (1) to validate the accuracy of high-frequency epicardial echocardiographic measurements of coronary artery bypass graft anastomoses in an animal preparation, (2) to test the ability of high-frequency epicardial echocardiography to detect technical errors at coronary artery bypass graft anastomoses in an animal preparation, and (3) to evaluate patient bypass graft anastomoses intraoperatively with high-frequency epicardial echocardiography.

Methods

Echocardiographic equipment. The imaging probe has a scanning frequency of 12 MHz. It is approximately 24 cm in length and 2.5 cm in diameter, with a 2 × 2 cm contact surface. The depth of field is 2 to 3 cm with a phantom 2 point resolution of 0.1 mm. The probe can be sterilized by standard ethylene oxide techniques. The imaging probe is connected to a commercially available scanner (Surgiscan, Biosound Corporation). Real-time images are displayed on a television monitor and recorded on a standard videocassette recorder.

Animal studies

Preparation. Twelve dogs (15 to 25 kg) were anesthetized with sodium pentobarbital (30 mg/kg iv), intubated, and ventilated. Either the lateral or medial saphenous vein was harvested, with ligation of side branches and irrigation with heparinized saline consistent with standard patient practice. The heart was exposed through a lateral thoracotomy incision. Each dog was systemically heparinized and killed and the heart was excised.

Saphenous vein-to-coronary artery anastomoses were fashioned with the use of 7-0 polypropylene suture, optical magnification, and standard microsurgical techniques by an experienced surgeon (L.F.H.). The coronary arteries selected were those of 1 to 2 mm internal diameter and saphenous veins were of 3 to 4 mm internal diameter, consistent with usual practice in patients.

The left anterior descending, left circumflex, and right coronary arteries and bypass grafts were cannulated with polyethylene cannulas and the cannulas were connected to a pressure perfusion system. The heart was placed in a tank filled with normal saline. Saline was perfused through the pressure system with a roller pump, and the pressure measured in a side branch of the saphenous vein was continuously monitored on a strip-chart recorder. Pressure was maintained at 80 to 100 mm Hg to approximate intraoperative patient conditions.

Validation. With the high-frequency epicardial echocardiographic probe, the vessels were scanned by an experienced echocardiographer in short-axis (cross-sectional) and longitudinal sections, with particular emphasis being placed on visualization of the vein graft-to-native coronary artery anastomosis at its maximum diameter. Images were recorded on 3/4 inch videotape for later measurement. Measurements of the echocardiographic recordings were made later with a digitizing tablet (Inex, Cardio-80); the maximum diameters of the vein graft, the native artery, and the graft-artery anastomosis were visualized repeatedly, playing the videotape back and forth, and then the maximum diameters were measured. After recordings were completed, the hearts were prepared for histologic examination. The heart and perfusion apparatus were removed from the water tank, and the vessels were perfused with a barium, formalin, and gelatin mixture at the same mean perfusion pressure that had been recorded during high-frequency epicardial echocardiographic evaluation. After the vessels and grafts had been perfusion fixed, the entire heart was placed in 10% formalin and fixed for at least 48 hr. After fixation, the entire vein graft-native artery anastomosis was removed and embedded in paraffin. The region was then sectioned and stained with Verhoeff-van Gieson stain for histologic evaluation. Multiple sections were examined by projection of the microscopic image on a digitizing tablet (Carl Zeiss, MOP-3) to ensure that the maximum diameter of the anastomosis found by microscopy would be measured. The maximum luminal diameters of the anastomoses determined by high-frequency epicardial echocardiography and histologically were then compared.

Detection of technical errors. Technical errors were deliberately created in 14 anastomoses, and recorded by the surgeon. Technical errors included poorly placed sutures that narrowed outflow to the native coronary artery, flaps of intima or venous valves, and excessive purse-stringing. Images of anastomoses were evaluated by the independent observer who was not aware of either the presence or specific type of technical error created. Descriptions of surgical technique and images were then compared.

Patient studies. This study was approved by the Human Subjects Review Committee of The University of Iowa, and written informed consent was obtained according to institutional guidelines.

Twelve patients undergoing elective coronary revascularization were studied. Standard anesthetic management and exposure of the heart through a median sternotomy were used in all patients. Radial artery pressure, left atrial pressure, and the electrocardiogram were monitored continuously. Intravenous heparin was given to raise the activated clotting time to greater than 480 sec. Cardiopulmonary bypass was instituted by right atrial and ascending aortic cannulation. Moderate hypothermia (28 to 30°C nasopharyngeal), crystalloid cardioplegia, and a single period of aortic cross-clamping were used during the creation of saphenous vein-to-coronary artery bypass graft anastomoses. All anastomoses were constructed by use of spation of the vein, continuous 7-0 polypropylene, and optical magnification (2.5 to 3.5 times). Proximal aorta-to-saphenous vein anastomoses were constructed either before or after the period of aortic cross-clamping.

After completion of coronary artery bypass grafts and either just before or just after weaning from cardiopulmonary bypass, anastomoses were examined by high-frequency epicardial echocardiography. The sterile hand-held probe was placed with the contact area adjacent to the anastomosis to record longitudinal and short-axis (cross-sectional) images. Compression of the vessels was avoided by filling the pericardial well with warm saline that acted as a stand-off between the probe and the area to be imaged. Imaging required less than 10 min in all cases.

The maximum luminal diameter of the anastomosis was measured from stop-frame images of the continuous videotape recording and was compared with the maximum luminal diameters of the native coronary artery and of the vein graft. Qualitative evaluations for possible technical errors were made by two independent observers who had previously reviewed the results of the animal studies to familiarize themselves with the appearance of deliberately created errors. In general, evaluation of anastomoses was carried out in real time, but it was facilitated by rapid review of videotaped images.

Statistical analysis. Comparisons between histologic and
high-frequency epicardial echocardiographic measurements of diameters of grafts and anastomoses were made by paired t tests. Comparisons of echocardiographic measurements of the maximum luminal diameters of the anastomosis, native artery, and vein graft were made by analysis of variance. In addition, when appropriate, correlation coefficients and linear regression equations were determined. A p value of less than .05 was taken to indicate a statistically significant difference between the variables assessed. Data are reported as the mean ± SE.

Results

Examples of high-frequency echocardiographic recordings of the anastomoses are shown in figures 1 through 5.

Animal validation studies. A comparison of maximum luminal diameter measurements of anastomosis by high-frequency epicardial echocardiography with histologic measurements is shown in figure 6.

There was an excellent correlation over a wide range between measurements obtained by the two methods (high-frequency epicardial echocardiography = 0.8 histology + 0.3; n = 12; r = .92). The slope of the regression equation was not significantly different from one, and the intercept was not significantly different from zero.

Detection of technical errors. There were 21 end-to-side and six side-to-side anastomoses imaged in the animal studies. In 14 cases, there were deliberate technical errors created. Examples are illustrated in figures 2 and 3. In each case, the technical error was detected by the independent observer. In addition, another minor finding was that of the presence of venous valves

FIGURE 1. High-frequency epicardial echocardiographic image obtained in an animal study shows a cross-sectional view (short axis of both the native vessel and the vein graft) of a technically adequate end-to-side vein graft (G) to the coronary artery (LAD).

FIGURE 2. A deliberate technical error in the animal study. A large vein graft (G) was sutured end-to-side to a small coronary artery (LAD) with a venous valve flap (arrow) partially obstructing the anastomosis.
FIGURE 3. Animal study. On the left (A) is a longitudinal section of an end-to-side anastomosis. Note that the anastomosis diameter is approximately the size of the vein graft (G) and is much larger than the native coronary artery (LAD). A septal perforator (PERF) is seen. On the right (B), a deliberate technical error was created by placing lateral sutures too widely, resulting in tenting up of the back wall (arrow) of the native coronary artery (LAD). Note on the left that the frozen-frame image illustrates the largest anastomotic opening and not the largest native LAD opening.

near but not obstructing the anastomosis in two instances. The morphology of the technical error agreed well with the error as predicted and recorded by the surgeon.

Patient studies. Fifteen distal anastomoses (12 end-to-side, three side-to-side) were studied in 12 patients. Figures 4 and 5 show examples of intraoperative images obtained with high-frequency epicardial echocardiography. One minor abnormality in an anastomosis was noted (figure 4). In addition, in another patient, an atherosclerotic plaque opposite the site of the anastomosis was demonstrated (figure 5). No major abnormalities were visualized.

Figure 7 shows the maximum luminal diameter noted at the anastomosis, native coronary artery, and vein graft for each of the two types of anastomoses (end-to-side or side-to-side). For the end-to-side anastomoses, the maximum luminal diameter of the anastomosis was greater than that of the native coronary artery and not significantly different from the diameter of the vein graft lumen (table 1). In contrast, for the limited number of side-to-side anastomoses, the maximum luminal diameter of the anastomosis was equal to or slightly less than that of the native coronary artery and both were significantly less than the maximum luminal diameter of the graft (table 1). All proximal vein graft-to-aorta anastomoses (n = 15) were evaluated and no technical abnormalities were identified.

Discussion
In this study we have shown that high-frequency epicardial echocardiography can accurately measure the dimensions of coronary artery bypass graft anastomoses. In addition, technical abnormalities of bypass graft–native artery anastomoses can be detected.

The accuracy of high-frequency epicardial echocardiography in the evaluation of luminal diameters and areas and wall thicknesses of native coronary arterial vessels has been demonstrated.\textsuperscript{2-5} Especially with respect to measurement of luminal diameter, high-frequency epicardial echocardiography is an extremely accurate tool with little variability noted. However,
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It is unknown whether the size of the opening of the anastomosis determines long-term graft patency. Surgeons generally attempt to create an anastomosis opening greater than the luminal diameter of the underlying native vessel so as not to create an artificial gradient or obstruction to flow through the graft. Further evaluation of side-to-side graft anastomoses is required before major statements can be made concerning their optimum size in relation to other arteries and morphology.

High-frequency epicardial echocardiography can identify major and minor technical abnormalities at the site of the graft anastomoses. In the animal studies, all major technical abnormalities that were deliberately created were detected by an independent observer reviewing the echocardiographic studies. One minor abnormality was noted in a patient undergoing surgery; however, it is unknown if such minor technical abnor-

since vein graft–native coronary artery anastomoses have quite different morphologic characteristics and potentially could be more difficult to evaluate, it was important to establish the accuracy of high-frequency epicardial echocardiographic measurements of these anastomoses before the quantitative evaluation of this technique intraoperatively. Our animal experiments show that high-frequency epicardial echocardiography can indeed accurately measure maximum luminal diameter at the anastomotic site as determined by comparison with histologic results in vitro. Previous validation in vivo in our laboratory has also demonstrated the accuracy of high-frequency epicardial echocardiography for measurement of native coronary arterial diameter. Thus, a very important morphologic parameter, that of the maximum luminal diameter of the anastomosis, can be accurately assessed with high-frequency epicardial echocardiography.

The luminal diameters of side-to-side anastomoses approached or were less than those of their native arter-

FIGURE 4. Patient study. An end-to-side anastomosis (AN) of a vein graft (G) to a native coronary artery (LAD). There is mild narrowing of the proximal portion of the LAD at the anastomosis, but luminal diameters of the anastomosis and native artery are not compromised significantly. Also note a septal perforator (PERF) opposite the anastomosis.

FIGURE 5. Patient study. A side-to-side vein graft (G)-to-coronary artery (LAD) anastomosis (AN). Note the atherosclerotic plaque (ATH) along the back wall that could partially obstruct the outflow. Atherosclerosis in vivo gives gray specular reflectors that are well separated from the bright specular reflectors of the coronary artery media and underlying myocardium. Also note that the luminal diameter of the anastomosis of this side-to-side anastomosis more closely approximates the size of the native coronary artery, in contrast to the larger end-to-side anastomosis shown in figure 3.
malities play any role in early graft occlusion. In another patient, an atherosclerotic plaque was demonstrated to be present immediately opposite the site of the anastomosis. In this particular case, the anastomosis was not revised since the outflow from the bypass graft appeared adequate. Again, the clinical significance of this is uncertain.

Generally, cardiac motion has not been a major problem during intraoperative studies. Motion is minimized if the examination is performed during cardiopulmonary bypass. Since images are recorded on videotape, rapid review of stop-frame images is possible if questions arise during real-time examinations.

The time required to obtain and analyze an intraoperative image averages approximately 1 min per anastomosis. Clinically important findings such as the presence of a major graft obstruction can be extracted from the videotape in the stop-frame mode almost immediately. The time necessary for echocardiographic examination added to the time necessary for revision of the anastomosis might be considered excessive. However, the potential benefit of correcting an otherwise unsatisfactory anastomosis should outweigh the risk of the additional time spent.

Although high-frequency epicardial echocardiography can assess morphology quite well, this technique cannot assess function. With regard to the complete intraoperative assessment of coronary artery bypass graft anastomosis, the use of a method of flow reserve assessment might add to the efficacy of this technique. Previous investigations with intraoperative Doppler studies of functional reserve of bypass grafts are unfortunately of lesser value because in the early postcardiopulmonary bypass period, the vasodilator capacity of normal coronary vessels is severely disturbed.9

Another current limiting factor is the size of the hand-held probe (24 cm length, 2.5 cm diameter), which does not permit imaging of posterior coronary arteries and their bypass graft anastomoses without manipulation of the heart. The left anterior descending coronary artery and bypass grafts placed to that system can generally be imaged with the probe and minimal manipulation. Similarly, the right coronary artery and grafts to its proximal portion can be imaged easily. However, posterior descending and posterolateral right coronary branches as well as circumflex system branches and bypass grafts placed to these arteries require considerable retraction of the heart and can precipitate hemodynamic compromise, and are therefore best visualized in patients on cardiopulmonary bypass to eliminate hemodynamic problems due to manipulation of the heart. Furthermore, echocardiographic examinations can be done during the infusion of cardioplegic solution.

This study has several potential clinical implications. Approximately 10% of grafts occlude within the first year. There are many theoretical reasons for the development of early graft occlusion, including decreased flow from the graft into the distal artery,10 the underlying morphology of the coronary arterial wall, especially with reference to the presence of the significant diffuse atherosclerosis,11,12 and possible technical

### TABLE 1

Results of the study in patients of the maximum luminal diameters measured by echocardiography

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Graft</th>
<th>Native artery</th>
<th>Anastomosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-to-side</td>
<td>12</td>
<td>2.9 ± 0.2A</td>
<td>2.0 ± 0.1</td>
<td>2.5 ± 0.2A</td>
</tr>
<tr>
<td>Side-to-side</td>
<td>3</td>
<td>3.7 ± 0.5A</td>
<td>1.9 ± 0.3</td>
<td>1.8 ± 0.2</td>
</tr>
</tbody>
</table>

Values are mean ± SEM.  
A p < .05 vs native artery.
abnormalities at the time of grafting. If technical abnormalities do play a role in early graft occlusion, then the use of a technique such as high-frequency epicardial echocardiography that can assess the vein graft–to–coronary artery anastomosis at the time of operation would be important. Technical errors could be recognized intraoperatively and corrected. In addition, technically difficult anastomoses (those involving small or heavily diseased arteries) that may result in reduction in luminal diameter of the native artery after grafting could be quickly evaluated intraoperatively. Therefore, the assurance of technical adequacy of bypass graft anastomoses may be enhanced by the use of high-frequency epicardial echocardiography. Finally, this technique could be useful as a laboratory teaching tool to demonstrate to surgeons in training the results of what could be considered minor variations in suture placement but that may result in significant abnormalities in the morphologic characteristics of bypass graft anastomoses.

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