Remodeling in peripheral vein graft revisions: Serial study with three-dimensional ultrasound imaging

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Objective: Remodeling of vein grafts in the lower limb can lead to stenotic lesions that threaten long-term graft patency. Progressive changes in vein graft geometry were measured at sites of repaired stenoses with three-dimensional (3D) ultrasound imaging.

Methods: Ten vein graft revisions with patch angioplasty were followed up for 31 to 47 weeks. Four revisions were at valve sites, and six were at sites of diffuse intimal hyperplasia. Sets of spatially registered two-dimensional (2D) cross-sectional ultrasound images were assembled to create 3D computer models of each vein graft. Cross-sectional area measurements in planes normal to the vessel center axis were calculated from the 3D surface reconstructions. Data sets from serial studies were registered in a common coordinate system, and cross-sectional area measurements were compared at matched sites.

Results: Three of the four vein graft revisions at valve sites changed by less than 18%, and one decreased in cross-sectional area by 61%. Five of the six revisions at sites of diffuse intimal hyperplasia demonstrated significant decreases in lumen area ranging from 26% to 61%, and one revision exhibited no significant change in cross-sectional area. Reproducibility of the cross-sectional area measurements derived from the 3D imaging technique was 6.9%.

Conclusions: Sequential area measurements from 3D ultrasound scans demonstrated different remodeling patterns and rates of change among revision sites within the vein grafts. Lumen narrowing documented with 3D scanning was not associated with consistent flow velocity changes on conventional duplex graft surveillance scans. (J Vasc Surg 2003;37: 798-807.)

Chronic arterial occlusive disease of the lower limbs leads to claudication, ischemic rest pain, and tissue loss. Diseased arteries are often successfully treated with vein bypass grafting. However, stenotic lesions develop in approximately 15% to 40% of these grafts, 80% within the first 2 years after graft placement. The most common cause of vein graft failure is myointimal hyperplasia. The biologic characteristics of this lesion seem to be a combination of smooth muscle activation, proliferation of smooth muscle, and production of extracellular matrix. Changes in flow rates and the associated shear and tensile stress result in arterial wall remodeling.

Restenosis associated with vessel remodeling can affect any area of the cardiovascular system that has undergone some type of injury, including surgery and angioplasty. In some areas of the circulation where vein bypass grafts are used, such as the coronary arteries, it is difficult to identify or monitor changes in the grafts over time. The invasive nature of arteriography and intravascular ultrasound scanning limits the frequency of their use in follow-up studies. In the lower extremity, however, the status of vein bypass grafts can be assessed with ultrasonic duplex scanning from the time of implantation. Graft patency can be assessed, and in most instances lesions that may either compromise flow or lead to graft thrombosis can be detected. These examinations depend exclusively on identification of hemodynamically significant areas of narrowing by studying the flow velocity patterns throughout the length of the graft. Duplex scanning has been successfully used in the clinical setting to identify lesions that must be revised to preserve graft function.

In our laboratory, surveillance studies of restenosis secondary to myointimal hyperplasia have involved the carotid artery and peripherally placed saphenous vein grafts. This experience clearly showed that progression and regression is a characteristic of myointimal hyperplasia. These lesions can develop rapidly and progress to high-grade stenosis or regress to lesser narrowing. However, nearly all of our information on these lesions in human beings is related to hemodynamic changes rather than to anatomic changes associated with the geometric effects of the lesions and the vessel response to injury. Investigation continues regarding the anatomic changes that occur as the vein graft in the leg matures and as stenotic lesions develop. For instance, it has not been established whether the vein grafts adapt to the developing lesions with compensatory dilation as occurs in native arteries in response to development of areas of narrowing. This information could help predict the influence of remodeling on the geometry of the vein graft and its long-term patency.

While the resolution of two-dimensional (2D) ultrasonic B-mode scans has improved, it is still not possible
with this method alone to accurately characterize myointimal lesions in terms of their exact location within the graft and their extent, both circumferentially and longitudinally. Therefore we are exploring the clinical utility of serial cross-sectional area measurements derived from three-dimensional (3D) ultrasound scanning of lower extremity bypass grafts to quantify changes in vein graft architecture. The current study focused on sites of vein graft revision with patch angioplasty, which represent well-defined segments for which progressive changes in geometry can be tracked over time. Our goal was to provide precise documentation of the anatomic changes in the vessel at these sites.

METHODS
Scanning and reconstruction. 3D imaging was performed with a standard ultrasound scanner (Sonos 5500; Agilent, Andover, Mass) and a magnetic tracking system (Flock of Birds, Ascension Technology, Burlington, Vt) fitted to the scanner head to register 2D ultrasound images in a 3D coordinate system. Custom software running on a Unix work station (O2; SGI, Mountain View, Calif) was used to simultaneously acquire the ultrasound images and the associated location data. Examinations were performed with the patient on a wooden bed to minimize distortion of the magnetic fields generated by the 3D tracking system.

An image was recorded before each study with the scan head placed at a fiducial point, typically the proximal or distal end of the surgical scar line. The location information acquired at this site establishes a landmark in 3D space that is used to register serial data sets. The graft is then manually scanned in cross-section through a region identified with standard duplex scanning as an area of interest (Fig 1, A and B). Acquisition of a single image was initiated with a hand switch and gated to an echocardiographic signal. Imaging was performed in the power Doppler mode, with the gray-scale background included. The 2D images were gathered at intervals of 1 to 2 mm; 30 to 60 images were acquired in each area of interest. A set of images typically was acquired in 3 to 5 minutes.

Automatic color segmentation defines the boundary of the lumen on each of the 2D cross-sectional power Doppler views of the vessel (Fig 1, C). The segmentation is reviewed and manually edited if necessary. Editing is only required in regions of bruits or vessel branching, where adjacent color regions on the image overlap and confound the segmentation. The contour points are transformed to locations in the 3D coordinate system of the magnetic transmitter with use of the position and orientation information associated with each image plane. The center axis, defined by the centroids of the contours, is smoothed by a three-point running average; the contours are then shifted to the smoothed centroid locations. Custom computer software connects the contour points to neighboring outlines to form a surface representation of the vessel (Fig 1, D).

Patient studies. Ten graft revisions with patch angioplasty were followed up for as long as 1 year. The revisions were divided into two groups: revision of focal stenosis due to fibrotic valve leaflets, and revision of regions of diffuse lumen narrowing attributed to intimal hyperplasia. All grafts were placed for treatment of occlusive disease. Data for each case are summarized in Table I. Fig 2 shows representative 3D surface reconstructions of the patches because of valve stenosis or diffuse intimal hyperplasia. Table I includes a dilation ratio to characterize patch size relative to the normal graft, defined as the ratio of the maximum diameter in the revised segment to the adjacent unrevised graft diameter. Patients were followed up every 1 to 2 months for the first 6 months after revision, then at 3-month intervals for up to 1 year after surgery. Patients with notable changes in flow rate were followed up more frequently. Sixty-eight patient scans were compiled for this study. The imaging protocol was approved by the institutional review board, and all subjects gave informed consent.

Fig 1. Three-dimensional reconstruction procedure. A, Vessel is manually scanned in cross-section with power Doppler method. B, Stack of 2D images with corresponding location information is saved. C, Vessel lumen is segmented on each image. D, Individual outlines are registered in 3D space and connected to form a surface.
Cross-sectional area measurements were computed from the surface reconstructions by resampling the surface in planes perpendicular to the center axis of the vessel.\textsuperscript{13,14} This processing step prevents errors in cross-sectional area measurement due to oblique imaging planes. The resampling was performed at 1 mm intervals along the center axis path length, and the area of each of the resampled contours was calculated to generate a profile of cross-sectional area along the segment of the graft.

The minimum, maximum, and mean cross-sectional areas in the revised segment were computed for each study. Absolute and percent changes in mean cross-sectional area were computed relative to the first study after the revision. The mean cross-sectional area is equivalent to segment volume divided by segment length; percent changes in mean cross-sectional area are therefore equivalent to percent changes in volume. The revision site was delineated by manually marking the start and end points of the patch for the first study after the revision, based on the dilated region observed in the cross-sectional area profile. All subsequent studies were spatially registered with this reference scan so that the cross-sectional area comparisons were computed for the same segment of the vessel. Registration was performed by correlation of the cross-sectional area profiles after initial registration based on the fiducial points. In cases H2 and H6 focal stenoses developed that were greater than 75% with duplex scanning flow velocity criteria\textsuperscript{16}

### Table I. Vein graft revision with patch angioplasty\textsuperscript{*}

<table>
<thead>
<tr>
<th>Case</th>
<th>Patient (age/sex)</th>
<th>Graft type</th>
<th>Graft age at time of revision (wk)</th>
<th>Unrevised graft diameter\textsuperscript{†} (mm)</th>
<th>Patch type</th>
<th>Patch site</th>
<th>Patch length (mm)</th>
<th>Patch dilation ratio\textsuperscript{‡}</th>
<th>First study (wk)</th>
<th>Last study (wk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve stenosis</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1 52/M</td>
<td>RSV</td>
<td>24</td>
<td>4.7</td>
<td>Vein</td>
<td>Body</td>
<td>27</td>
<td>1.9</td>
<td>5</td>
<td>39</td>
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</tr>
<tr>
<td>V2 85/M</td>
<td>RSV</td>
<td>12</td>
<td>5.0</td>
<td>Vein</td>
<td>Body</td>
<td>30</td>
<td>1.6</td>
<td>3</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>V3 54/F</td>
<td>Transposed nonreversed</td>
<td>9</td>
<td>5.0</td>
<td>Vein</td>
<td>Body</td>
<td>16</td>
<td>1.5</td>
<td>3</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>V4 52/M</td>
<td>RSV</td>
<td>35</td>
<td>4.0</td>
<td>Vein</td>
<td>Body</td>
<td>32</td>
<td>2.2</td>
<td>4</td>
<td>43</td>
<td></td>
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<tr>
<td>Diffuse intimal hyperplasia</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>H1 56/M</td>
<td>RSV</td>
<td>54</td>
<td>5.4</td>
<td>Vein</td>
<td>Proximal anastomosis</td>
<td>75</td>
<td>2.7</td>
<td>4</td>
<td>31</td>
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<tr>
<td>H2 75/M</td>
<td>RSV</td>
<td>68</td>
<td>3.1</td>
<td>Vein</td>
<td>Body</td>
<td>32</td>
<td>3.2</td>
<td>2</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>H3 72/F</td>
<td>In situ</td>
<td>41</td>
<td>6.5</td>
<td>Vein</td>
<td>Body</td>
<td>40</td>
<td>1.7</td>
<td>2</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>H4 71/M</td>
<td>RSV</td>
<td>34</td>
<td>5.5</td>
<td>Vein</td>
<td>Proximal anastomosis</td>
<td>35</td>
<td>2.6</td>
<td>5</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>H5 58/M</td>
<td>Reversed cephalic vein</td>
<td>47</td>
<td>5.1</td>
<td>Dacron</td>
<td>Proximal anastomosis</td>
<td>41</td>
<td>2.6</td>
<td>4</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>H6 74/F</td>
<td>In situ</td>
<td>50</td>
<td>5.1</td>
<td>Vein</td>
<td>Proximal anastomosis</td>
<td>38</td>
<td>2.2</td>
<td>3</td>
<td>47</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{RSV, Reversed saphenous vein.}

\textsuperscript{*}Study times are relative to time of revision. Cases in each group are listed in order of total follow-up time.

\textsuperscript{†}Unrevised graft diameter: average for 1 to 2 cm segment adjacent to patch.

\textsuperscript{‡}Patch dilation ratio: Maximum patch diameter/adjacent unrevised diameter.

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Cross-sectional area measurements were computed from the surface reconstructions by resampling the surface in planes perpendicular to the center axis of the vessel.\textsuperscript{13,14} This processing step prevents errors in cross-sectional area measurement due to oblique imaging planes. The resampling was performed at 1 mm intervals along the center axis path length, and the area of each of the resampled contours was calculated to generate a profile of cross-sectional area along the segment of the graft.

**Fig 2.** Surface reconstructions of representative patch angioplasties. Top, Patch to repair valve stenosis (case V1, first study) in mid-graft. Bottom, Patch to repair stenosis due to intimal hyperplasia (case H1, first study) at the proximal anastomosis with the common femoral artery (CFA). Patched valve sites are generally smaller in both length and diameter than patched intimal hyperplasia sites. Blood flow is from left to right.
during the study period. The cross-sectional area at the stenosis was measured at all time points for these two cases.

Reproducibility. Reproducibility is the variability observed in multiple measurements of the same quantity. Repeated scans of the revision sites were performed at 27 of the 68 patient visits, including 7 of the 10 patients. Measurements from the repeated scans were compared to provide an estimate of variability of the 3D reconstructions. The paired resampled data sets were registered in a common 3D coordinate system based on the fiducial points acquired with each scan. The mean cross-sectional area of the patched site was calculated for each data set, and the difference between the means was calculated. This difference was divided by the mean of the two results to yield a percentage disagreement. The mean and SD of the differences for all repeated studies were calculated.

RESULTS

The percent change in mean cross-sectional area from the initial study is plotted over time in Fig 3 for each case. The changes in cross-sectional area between the first and last studies are summarized in Table II for all cases. A detailed display for a representative case of vessel remodeling (case H1) is shown in Fig 4. The 3D surface reconstructions and corresponding cross-sectional area measurements demonstrate progressive narrowing throughout the patch, with the largest changes at the distal end. Narrowing of the lumen in the graft segment distal to the revision is also observed. This is reflected by the change in the graft minimum cross-sectional area in Table II, which represents the distal end point of the patch.

The reproducibility study demonstrated a difference of $0.1 \pm 2.5 \text{ mm}^2 (0.3\% \pm 6.9\%)$ in mean cross-sectional area for the repeated scans of the patched sites. On the basis of this variability measurement, seven revised graft segments demonstrated a significant decrease in cross-sectional area over time, ranging from 17% to 61%, averaged over the length of the revision. Three grafts exhibited no statistically significant change in size. Three of the four revisions at valve sites changed by 17% or less, and one decreased in area by 61%. Five of the six revisions at sites of diffuse intimal hyperplasia demonstrated decreases in lumen area ranging from 26% to 61%, and one case exhibited no significant change in cross-sectional area. Overall, larger changes in cross-sectional area were detected in the intimal hyperplasia group ($-39\%$ average change) compared with the valve stenosis group ($-19\%$ average change).

The final patch minimum and maximum values reported in Table II indicate that one revision (case V2) normalized to an essentially straight conduit (Fig 5); dilations in the revised segments were present in all other cases at the end of the study period. For comparison with case V2, Fig 5 also shows serial 3D surface reconstructions for case V4, which exhibited no measurable change in size over the same length of time.

Surface reconstructions of cases H2 and H6 clearly show the focal stenosis that developed during follow-up (Fig 6). The final minima for these two cases in Table II represent the cross-sectional area at the stenosis. The ste-
Table II. Mean cross-sectional area of patch for first and last studies of each revision and change in mean cross-sectional area

<table>
<thead>
<tr>
<th>Case</th>
<th>Initial mean CSA (range*) (mm²)</th>
<th>Final mean CSA (range*) (mm²)</th>
<th>Change in mean CSA† (mm²) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve stenosis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1</td>
<td>37.0 (19.7, 51.1)</td>
<td>30.7 (17.2, 38.6)</td>
<td>-6.3 -17.0</td>
</tr>
<tr>
<td>V2</td>
<td>31.0 (17.4, 38.8)</td>
<td>12.1 (10.9, 13.6)</td>
<td>-18.9 -60.8</td>
</tr>
<tr>
<td>V3</td>
<td>25.7 (20.8, 31.4)</td>
<td>26.8 (16.3, 33.2)</td>
<td>1.1 4.6</td>
</tr>
<tr>
<td>V4</td>
<td>42.4 (18.4, 54.0)</td>
<td>40.8 (21.0, 50.2)</td>
<td>-1.6 -3.8</td>
</tr>
<tr>
<td>Diffuse intimal hyperplasia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H1</td>
<td>52.1 (24.0, 95.0)</td>
<td>24.4 (5.8, 60.8)</td>
<td>-27.7 -53.3</td>
</tr>
<tr>
<td>H2</td>
<td>35.4 (10.4, 65.7)</td>
<td>19.8 (9.9, 50.7)</td>
<td>-15.6 -44.1</td>
</tr>
<tr>
<td>H3</td>
<td>57.8 (52.0, 66.7)</td>
<td>22.5 (10.3, 38.8)</td>
<td>-35.3 -61.0</td>
</tr>
<tr>
<td>H4</td>
<td>49.9 (24.6, 118.9)</td>
<td>26.1 (14.2, 74.3)</td>
<td>-23.8 -47.7</td>
</tr>
<tr>
<td>H5</td>
<td>54.7 (15.0, 93.4)</td>
<td>52.5 (17.6, 104.0)</td>
<td>-2.2 -4.1</td>
</tr>
<tr>
<td>H6</td>
<td>66.0 (30.9, 79.7)</td>
<td>49.1 (4.6, 69.5)</td>
<td>-16.9 -25.6</td>
</tr>
</tbody>
</table>

CSA, Cross-sectional area.
*Range given as minimum and maximum values.
†Change in mean CSA given as final minus initial value.

Discussion

Since vein grafts are prone to develop stenosis that can lead to graft occlusion, extensive work has been done to detect these lesions at a time when they can be repaired safely. Ultrasound duplex scanning is used at frequent intervals to detect the high flow rate associated with development of stenosis. This surveillance protocol permits precise localization of the flow velocity increase at the site of narrowing. However, there is no information on the remodeling process that takes place within the vein graft. An unexpected finding in a previous long-term study of vein grafts was that stenosis developed in 90%, yet only 27% of the detected stenoses required repair. The remainder of the stenoses did not progress or appeared to regress. While the presumption is that a return of blood flow rate toward normal indicates that true regression has occurred, there is no imaging or histologic confirmation of this finding.

We present results from quantitative studies of revised peripheral vein bypass grafts using 3D power Doppler ultrasound scanning. 3D reconstructions have the potential to provide additional detail and precision in the surveillance of vein grafts, compared with 2D methods. Spatially registered cross-sectional area measurements in vein grafts cannot be made reliably with standard real-time 2D ultrasound, because of variability in image plane location and orientation. 3D representations preserve information about the complete vessel geometry while enabling comparison of spatially registered regions over time. Sections through the 3D surface at angles perpendicular to the vessel center axis also assure proper determination of the cross-sectional area.

Review of routine clinical duplex graft surveillance examinations in our study patients indicates that consistent flow velocity changes were not associated with the lumen narrowing documented with the 3D ultrasound scans. Changes in flow velocity can be particularly difficult to define in anastomoses and patched graft segments because of irregular geometry and complex blood flow patterns. Spectral waveforms in dilated segments are characterized by disturbed flow resulting from eddies, and it is difficult to determine an appropriate Doppler measurement angle relative to the vessel walls. These factors lead to uncertainty in the identification of peak systolic flow velocity. Therefore 3D scanning provides anatomic information that is not readily obtained with conventional duplex scanning.

Close serial follow-up with 3D ultrasound scanning provides not only a measure of lumen narrowing but also a record of the rate and pattern of change over time. Several studies demonstrated an increase in cross-sectional area relative to the previous measurement at 8 to 12 weeks during the study (Fig 3). Differences in narrowing rate were then evident at 12 to 32 weeks. Within this period a graft may be unchanged or enlarged and stable, narrowed and stable, or progressively narrowing. In addition, one case (case H6) demonstrated a change in the direction of the remodeling late during follow-up. In this case the mean cross-sectional area reached a minimum at 42 weeks (-38% change), after which the lumen enlarged. This change has...
been confirmed in follow-up studies for an additional 2 years beyond the other cases. Case H6 has been followed up to 134 weeks, and this patch has remained stable after the initial regression, with mean area reduction ranging from 21% to 28% over the past year.

3D analysis also enables comparison of changes in both extended segments and at focal sites such as stenoses or valves. This can help determine whether a stenosis forms as a consequence of a general narrowing of a graft or is associated with a localized response. For both stenoses
followed up in the current study, overall narrowing of the patch was also observed (Fig 6). In case H2, absolute changes in the stenosis and mean cross-sectional area were nearly equal (Fig 7, B). In Case H6, the rate and absolute amount of narrowing at the point of the focal stenosis was greater than that of the mean cross-sectional area. In case H2, however, the graft required further revision when symptoms returned at 32 weeks, whereas the stenosis in case H6 regressed over time. The small size of the initial graft in case H2 may have contributed to the return of symptoms in this patient.

Power Doppler imaging was used because it averts the problem of lateral dropout of the vessel walls that is common in B-mode ultrasound scanning. However, there are some limitations associated with the power Doppler imaging method. First, operator dependence can be a source of variability in quantitative measures derived from power Doppler images, in particular because the extent of the depicted flow region varies with the gain setting. This effect can be reduced by using the gray-scale display of the vessel walls to provide feedback to the operator as to the correct setting of the power Doppler gain. In addition, all patient examinations were performed by one sonographer. Second, note that the 3D surfaces generated by the automated color segmentation algorithm provide measurements of the vessel lumen only. Further studies to delineate the vessel wall will be necessary to characterize the complete vessel remodeling process.

The magnetic tracking system used for 3D registration permits arbitrary manipulation and positioning of the scan head by the examiner for optimal imaging of the vessels of interest. For typical vascular imaging applications the magnetic tracking system enables location of points in space with precision of 0.5 to 1 mm. However, the magnetic system is susceptible to interference from ferromagnetic materials in the vicinity, and care must be taken to minimize the presence of metals in the scanning area. Spatial registration of serial data sets can also contribute to measurement variability. Initial registration of serial data sets is achieved through use of fiducial points that are assumed to remain stable over time with respect to the vein graft. However, differences in placement of the transducer at the external fiducial landmark or changes in leg configuration from postoperative edema can lead to alignment errors. Therefore a correlation based on the cross-sectional area profile was used to optimize the final registration across studies.
The reproducibility results include the contributions of image acquisition, 3D tracking, vessel segmentation, and spatial registration to overall measurement variability. We measured reproducibility of 6.9% in cross-sectional area measurements. We can therefore consider cross-sectional area changes greater than 14% to be significant with 95% confidence. To appreciate the size changes detected, the area measurements can be described in terms of vessel diameter for the area-equivalent circular cross section. For vessels with initial diameter of 5 to 10 mm, an area change of 14% corresponds to diameter change of approximately 0.4 to 0.7 mm. Note that in a previous study we reported reproducibility of 12.2% for cross-sectional area measurements using a gray-scale image capture system and manual outlining. This previous study also reported a 6% error associated with manual outlining alone, based on repeated tracings of data sets. The 5.3% improvement in reproducibility observed in the current study can be attributed to the use of automated vessel segmentation with limited manual editing. Of 3011 borders detected with automatic segmentation for the repeatability study, 157 borders (5.2%) required manual editing.

While this study focused on dilated regions of the grafts, precise measurement of cross-sectional area may also reveal early size changes in straight segments of vein grafts. Absolute flow velocity changes between visits are not reliable indicators of uniform diameter changes in straight graft segments, and velocity ratios do not apply until narrowing is such that increased flow velocity can be detected. Early or progressive narrowing could indicate grafts that require more frequent surveillance. Detection of changes in graft geometry could also be useful in assessment of pharmacologic treatment intended to reduce the incidence of graft stenosis. Whether these changes in graft diameter can serve as early indicators of later risk for stenosis is a subject of continuing investigation with the 3D imaging method. Studies in our laboratory are proceeding to track 3D geometry changes in unrevised vein grafts.

CONCLUSION

Cross-sectional area measurements, spatially registered over time, have been derived from 3D surface reconstructions of revised sites in lower extremity vein grafts. These 3D reconstructions provide documentation of anatomic changes in areas of complex geometry where flow velocity measurements are difficult to perform and interpret. Various remodeling patterns were observed among a group of patch angioplasty sites in the first year after revision, demonstrating responses ranging from no appreciable change in dilation to normalization into a straight conduit. Quantitative monitoring of vein graft architecture may provide a means to differentiate normal remodeling from pathologic changes that lead to stenosis and threaten vein graft patency.
This study was supported by a grant (2 R01 HL52468-05A1) from the National Institutes of Health.

REFERENCES


Submitted Jun 12, 2002; accepted Sep 18, 2002.

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