

TECHNICAL NOTES

Three-dimensional reconstruction of autologous vein bypass graft distal anastomoses imaged with magnetic resonance: Clinical and research applications

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High-resolution magnetic resonance imaging was combined with computational modeling to create focused three-dimensional reconstructions of the distal anastomotic region of autologous vein peripheral bypass grafts in a preliminary series of patients. Readily viewed on a personal computer or printed as hard copies, a detailed appreciation of in vivo postoperative features of the anastomosis is possible. These reconstructions are suitable for analysis of geometric features, including vessel caliber, tortuosity, anastomotic angles, and planarity. Some potential clinical and research applications of this technique are discussed. (*J Vasc Surg* 2003;38:621-5.)

Failure rates for autologous vein peripheral arterial bypass grafts remain significant.¹ Most failures during the intermediate follow-up period (1-12 months) are attributed to hyperplastic graft stenosis, which develops in approximately a third of grafts.^{2,3} A disproportionate number occur in the vicinity of the distal anastomosis.^{4,5}

Surveillance for stenosis is possible with a number of methods, but at present duplex ultrasound (US) scanning is favored by many. Although widely used, duplex US scanning has several well-recognized limitations. Among others, these relate to operator dependability, postoperative swelling or inflammatory changes, patient body habitus, and heavy vessel calcification. Angiography can be useful, but is not routinely used because of the invasive nature of the procedure and risk for contrast medium toxicity. More recently magnetic resonance angiography has become a versatile noninvasive method for vascular imaging, but at present resolution is inadequate to display important fine

geometric features. When performed with contrast agents a greater degree of anatomic detail can be appreciated; however, this incurs greater costs and possibly greater risk to the patient. There are some disadvantages to all of these methods, and there is potential for development of a noninvasive method capable of providing detailed three-dimensional (3D) images.

In addition to potential clinical applications, there are also research implications. There remains considerable debate regarding local factors that may influence development of stenosis at the distal anastomosis. Flow features, determined with vascular geometry and wall compliance, can be studied with computational simulations based on these detailed geometric reconstructions from in vivo data.

TECHNIQUE

Only patients with infrainguinal autologous vein bypass grafts, without clinical contraindications to magnetic resonance imaging (MRI), were considered for the study. Before surgery, consent was sought, in accordance with approval obtained from the local research and ethics committee. At the time of operation the use of titanium clips and their position, as well as measurements of arterial and graft caliber, angle of anastomosis (surgeon estimate), and extent of calcification and atheroma in the vessels were recorded and operative photographs were obtained. Approximately a fourth of the patients were subsequently found to be unsuitable for the study, for the reasons listed in the Table.

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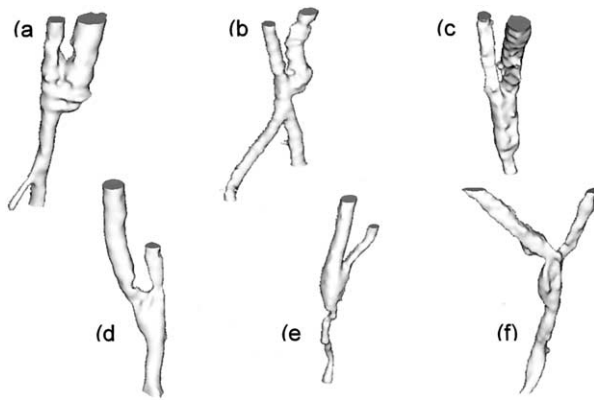


Fig 1. Examples of three-dimensional reconstruction of distal anastomotic region of six grafts.

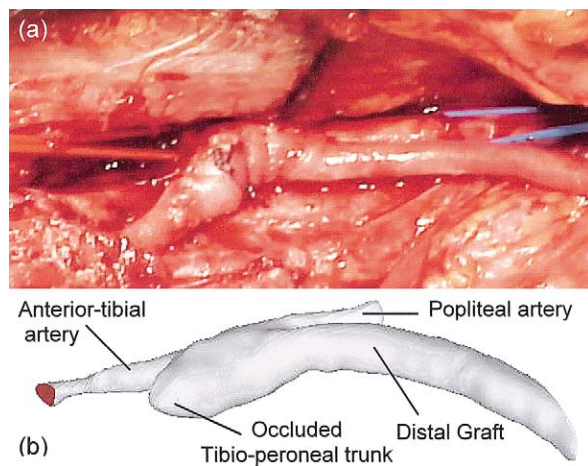


Fig 2. Comparison between operative appearance of a tibio-peroneal trunk anastomosis after restoration of flow (a) and postoperative (1 week) reconstruction (b). Distal tibio-peroneal trunk, thought patent at completion of the procedure, is occluded, and main run-off is via the anterior tibial artery, slung deep within the wound. Graft also demonstrates greater angulation and curvature above the anastomosis, and the hood of the graft is distended.

In addition to routine clinical follow-up and graft surveillance, patients underwent duplex US scanning to ensure graft patency, record the exact site of the anastomosis, and record hemodynamic parameters such as quantification of flow in the distal graft and an estimate of the flow split into native vessel upstream and downstream of the anastomosis. This was performed with a previously reported and reproducible technique⁶ before MRI.

Immediately after duplex US scanning, non-contrast agent-enhanced MRI was performed, with two-dimensional time-of-flight acquisition sequences on a 1.5 T MRI scanner (Horizon-LX EchoSpeed; General Electric Medical Systems, Milwaukee, Wis). This technique provided image sections with 512 (frequency) \times 256 (phase) pixel resolution with 256-level gray-scale intensity. Sections were ac-

Exclusion criteria

<i>Technical exclusion</i>	<i>Reason</i>
Ultrasound flow data not able to be acquired from graft	Unable to use computational flow modeling
Titanium clips within operative field	Created magnetic resonance signal artifact
Obesity or graft to upper thigh	Unable to apply leg coil
Early graft occlusion	No flow detected
Occluded segment of host vessel	Unable to perform analysis of geometric features

quired at 1.5-mm intervals and cardiac-gated with a digital pulse oximetry device to obtain images at the same phase in the cardiac cycle to reduce flow artifact. A saturation band technique was applied below the region of acquisition to further enhance the flow signal acquired from within the lumen of each image. This enabled in-plane resolution of 0.31 mm (1 pixel) and facilitated detection of vessel caliber changes on the order of 10% for the average graft or arterial vessel.

The data were exported from the MRI console, and the raw image sections were processed with DICOM viewer software on personal computer (PC) workstations with a semiautomated protocol that incorporated edge-detection software (Scion Image; Scion Corp, Frederick, Md) and spline-fitting algorithms to generate smoothly contoured slices. Sections were then stacked, and a dataset of 3D (finite element) reference points was calculated to provide a polygonized triangular mesh surface representation of the vessel lumen.⁷ This technique is similar to that used by Steinman et al⁸ and at Imperial College, London,⁹ in previous studies of carotid bifurcation geometry and hemodynamics.

Further application of a finer mesh provided better topographic representation of the surface features.¹⁰ Completed reconstructions essentially represent a 3D cast of the luminal surface of the anastomosis (see sample reconstructions in Fig 1). (All of our subjects' clinical summaries and processed graft geometries are available at our project website (<http://www.ae.ic.ac.uk/staff/sherwin/Smiths/index.html>), and can be viewed with standard PC-based software applications, such as Windows Media Player and Quick Time. The datasets are also available for download and use by other researchers.) The graft and host-vessel centerlines,¹¹ luminal cross-sectional areas, angles, or planes between vessels¹⁰ could then be defined. Validation of such measurements has taken place on stylized laboratory models (see website), but further in vivo validation versus angiographic and computed tomography angiography data is required.

CLINICAL AND RESEARCH APPLICATIONS

This interesting technique can be used to demonstrate many features of the graft anastomosis, both immediately postoperatively and at follow-up. Serial studies, if per-

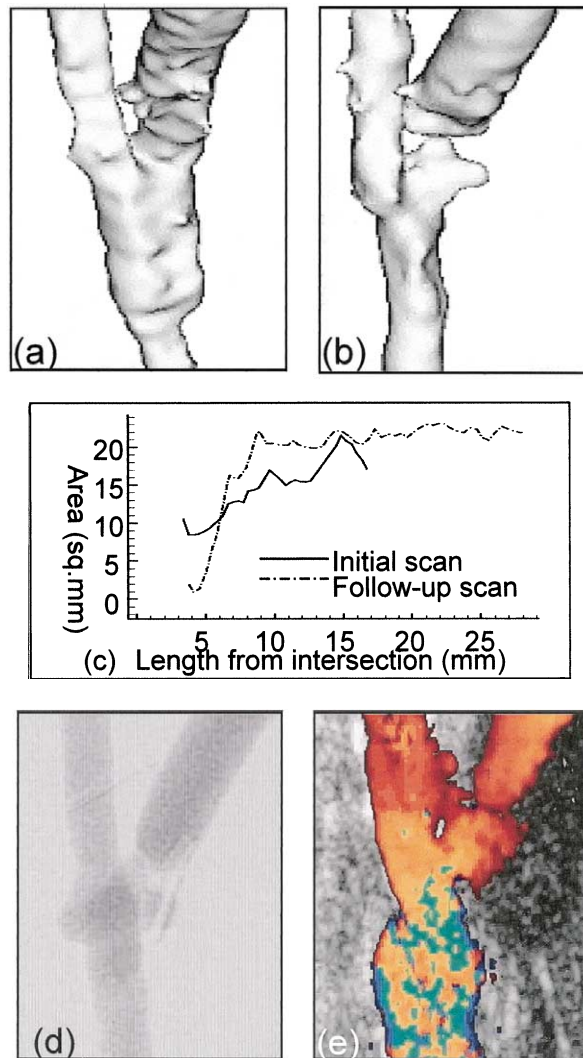


Fig 3. Initial postoperative (a) and 7-month follow-up (b) reconstructions of anterior tibial artery anastomosis. c, Change in cross-sectional area of the distal graft, focally decreased at a distance between 4 and 5 mm up from the intersection point of the graft and host-vessel centerlines, is objectively recorded. Reconstructions can be compared with color duplex ultrasound scan (d) and angiographic image (e) of the same anastomosis.

formed, can be used in a surveillance context to observe and quantify changes in caliber or configuration. Some potential applications are discussed below and illustrated with specific cases from our early experience.

Early quality control: Postoperative in vivo imaging in 3D. One potential application of this technique is examination of the anastomotic configuration postoperatively. Detailed anatomic images may be used for postoperative quality control, enabling measurement of lumen diameter and volume within an anastomosis, and can also illustrate the overall geometry after wound closure. Reconstructed scans acquired in the immediate postoperative period were compared with operative diagrams and intraoperative photographs. There can be considerable changes in the angle and orientation of the graft with the host vessel (Fig 2).

Surveillance for development of stenoses in perianastomotic region. Accurate images can be produced and used to study configuration changes within the graft over time. Two reconstructed MR images that demonstrate progression of stenosis over 7 months are shown in Fig 3.

Changes in vessel diameter can be objectively recorded with serial calculations of the luminal cross-sectional area at reference points along the axis of the graft (Fig 3, c). The distal graft stenosis that developed was confirmed at duplex US scanning and angiographic examination before successful graft revision. From previous studies of postmortem coronary artery graft distal anastomoses,^{12,13} the expected postsurgical changes within the graft hood, suture line, and to a lesser extent the floor of the anastomosis would lie within the resolution of our technique.

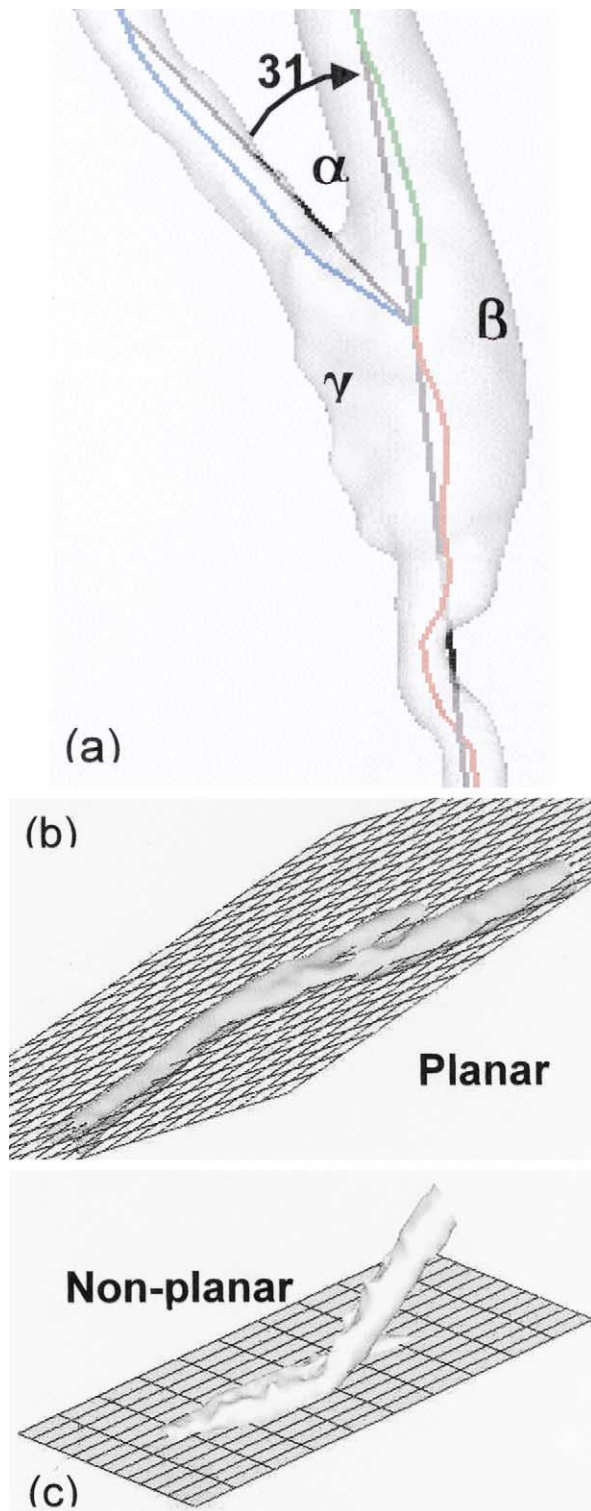


Fig 4. a, Angles were defined as α , β , or γ . Differentiation between planar configuration (b) and nonplanar configuration (c) was possible by defining a plane for the host vessel and quantifying the angle where the graft met this plane.

Analysis of geometric features: Vessel angles and planes. Geometry is believed to have implications for development of focal myointimal hyperplasia (MIH) within the anastomosis. The advantage of 3D imaging is the ease with which geometric features can be quantified. Angles between the graft and host vessel can be derived (Fig 4, a). Changes in those angles measured with reference points (function of the vessel length from the intersection point) can be used to quantify curvature and tortuosity of the vessels. Similarly, the planes described by the intersecting vessels can be calculated and planarity of the anastomosis can be studied (Fig 4, b, c).

Computational fluid dynamics modeling. Computer simulations can be performed with the 3D geometric dataset combined with the ultrasound-acquired velocity profile used to represent the distal graft (upstream boundary) flow conditions to generate particle flow studies and maps of several hemodynamic parameters, such as shear stress, oscillatory shear indices, and particle residence times. Such studies have already been undertaken with similar data from the carotid bifurcation,^{9,14} coronary arteries,¹⁵ and abdominal aorta.¹⁶ The study of these flow patterns in the vicinity of the anastomosis with computational flow dynamics techniques could prove to be a valuable research tool. The relationships between aberrant hemodynamic parameters and documented reductions in luminal diameter, which reflects development of MIH, may then be analyzed.

DISCUSSION

The above examples illustrate some advantages that this 3D MRI reconstruction technique has over current routinely used methods, such as angiography and duplex US scanning. The procedure does not use contrast agent; thus it remains noninvasive and without side effects. It can be performed at any stage after the procedure, if the patient is safe within the magnetic coil. It can also be performed painlessly, regardless of swelling, tenderness, or wound infection. Good images can be obtained despite heavily calcified vessels in the vicinity of the anastomosis, because of the different signal acquired with MRI. It may prove complementary to ultrasound.

Images can be printed as hard copies with appropriate anatomic orientation. However, the real advantage is appreciated when the 3D dataset is viewed with computer software, enabling interrogation of the anastomosis through 360 degrees. Surgeons, who may not personally evaluate the anastomosis postoperatively, may view detailed in vivo geometric features in a format that is much easier to interpret than US images.

The semiautomated technique used to generate the geometric dataset is potentially less operator-dependent and therefore not prone to so much interobserver error. Objective quantification of angles, curvature, luminal areas, and changes in these parameters over time is possible.

The prospects of research into the hemodynamics of the distal anastomosis with realistic geometries are exciting. With further observational studies, we hope to be able to

define an acceptable geometric configuration, to optimize graft hemodynamics. Abnormal configurations and their resultant hemodynamic aberrations may also be identified, which could have implications for anastomosis techniques and prosthetic graft design. Previous studies have relied on time-consuming experimental and computational simulations with stylized geometries.¹⁷⁻¹⁹ There is potential for identification of at-risk grafts with abnormal geometric features predictive of poor graft outcome, for example, low anastomotic angles rather than more perpendicular angles, large diameter discrepancies between graft and host artery, or nonplanar graft-artery anastomotic configurations, and this may be linked to surgical practice or used to select those grafts in need of surveillance.

Clearly, such a technique is not immediately applicable in clinical practice, because of limited resource availability and time constraints. Acquisition within the MR imager can take up to 45 minutes, and at present MR imaging time is not readily available in any but a few teaching centers. There are also some established contraindications to MRI that will exclude some patients from examination with this modality. Relative contraindications, such as titanium implants and surgical clips, can be accepted if the image quality is not affected adversely. We have also found some patients unacceptable in terms of body habitus, movement disorders, and anxiety disorders. The quality of images, however, is worthwhile in those patients who can tolerate the examination. Further evaluation is needed, but we believe this technique has clinical and research applications that may contribute to our understanding of the geometry, hemodynamics, and subsequent development of disease within distal graft anastomoses.

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