A prospective study of the determinants of vein graft flow velocity: Implications for graft surveillance

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Purpose: Serial monitoring of vein graft peak systolic flow velocity (PSFV) has been endorsed as a technique for vein graft surveillance with low values (<45 cm/sec) considered a marker for impending graft failure. Optimal application of this method requires an understanding of the factors affecting PSFV in normal grafts. A prospective evaluation of 46 consecutive elective infrainguinal vein grafts (6 popliteal/29 tibial/11 pedal) was undertaken to assess the major determinants of PSFV.

Methods: Factors recorded for each patient included vein graft diameter (VGD), measured outflow resistance (MOR), conduit length, outflow level (popliteal/tibial/pedal), inflow level (femoral/popliteal), systolic blood pressure, cardiac ejection fraction, the presence of a patent plantar arch, and Society for Vascular Surgery/International Society for Cardiovascular Surgery resistance scoring. MOR was measured by occluding graft inflow and infusing saline solution through a proximal graft cannula at 60 cc/min while simultaneously recording the pressure at the distal anastomosis via a separate cannula. MOR was calculated by dividing the resultant pressure by the infusion rate. MORs were expressed in resistance units and were measured before and after the infusion of papaverine (MOR(PAP)). PSFVs and VGDs were measured 4 to 6 cm from the distal anastomosis 3 weeks after surgery with duplex scanning (60 degree angle with midstream sample volume).

Results: PSFVs ranged from 22 to 148 cm/sec and averaged 83.4 ± 4.8 cm/sec. Pedal bypass grafts had significantly lower PSFVs (64 ± 10 vs 89.5 ± 5 cm/sec, p = 0.02) and significantly higher MOR(PAP)s (0.86 ± 0.15 vs 0.51 ± 0.05 resistance units, p = 0.05) than bypasses to the popliteal/tibial level. When subjected to univariate analysis the factors correlating with PSFV were MOR (r = -0.59, p = 0.0001), MOR(PAP) (r = -0.69, p = 0.0001) VGD (r = -0.31, p = 0.06), the Society for Vascular Surgery/International Society for Cardiovascular Surgery score (r = -0.35, p = 0.04), inflow level (r = -0.47, p = 0.002), and outflow level (r = -0.35, p = 0.03). When subjected to multiple regression analysis, only MOR(PAP) (r² = 0.51, p = 0.001) contributed significantly to the overall model (r² = 0.65, p = 0.0001) with MOR(PAP) eliminating the effect of the other variables. The multiple regression model predicts PSFV as follows: PSFV = 176 + VGD(mmp)(-11.7) + MOR(PAP)(-63.4).

Conclusions: Clinically successful and hemodynamically normal vein grafts have widely variable, yet predictable flow characteristics that are influenced primarily by outflow resistance and VGD. This wide variability suggests that no single lower threshold value for PSFV is universally applicable in identifying all grafts at risk for failure. Detection of focal areas of flow acceleration within the graft may be more accurate in identifying grafts at risk for failure. (J Vasc Surg 1994;19:259-67.)
we documented that vein graft PSFV is inversely proportional to vein graft diameter and that pedal grafts were found to have significantly lower PSFVs than tibial or popliteal bypass grafts. We speculated that other important factors such as arterial outflow resistance, systolic blood pressure, cardiac ejection fraction, and vein graft length may also impact on PSFV in a predictable fashion. To more completely determine the influence of these and other factors on vein graft PSFV, a prospective study of 46 consecutive patients undergoing elective infrainguinal bypass surgery was undertaken.

PATIENTS AND METHODS

Forty-six consecutive patients who underwent elective infrainguinal bypass before December 1, 1992, were entered into this study. All bypasses were performed with autogenous vein (44 saphenous vein, 2 arm vein). Twenty of the bypasses were completed with in situ saphenous vein, 24 were completed with nonreversed, translocated vein with lysed valves, and two were completed with reversed vein grafts. The inflow vessel was the femoral artery (common femoral or proximal superficial femoral) 38 bypasses and the popliteal artery in eight cases. The outflow vessels included the popliteal artery in 6 cases, the tibial vessels in 29 cases (12 peroneal, 6 anterior tibial, 11 posterior tibial), and inframalleolar vessels in 11 cases (6 dorsalis pedis, 5 posterior tibial/plantar). The indications for surgery were rest pain or tissue loss in 42 (91%) patients and severe claudication in three (7%) patients. One operation was performed for a 6 cm popliteal aneurysm.

Patients enrolled in the study underwent routine preoperative assessment. Echocardiograms were obtained in patients for assessment of cardiac function. Echocardiograms completed up to 6 months before surgery were accepted for ejection fraction determination as long as no intervening cardiac events had occurred.

Measurement of outflow resistance. Distal bypasses were completed by our standard operative technique. Completion arteriograms were then obtained by proximal cannulation of the vein graft with a 20 gauge intravenous catheter. All arteriovenous fistulas were identified and eliminated by use of a combination of a careful Doppler ultrasound examination and intraoperative arteriography. After confirmation of a technically satisfactory result, outflow resistances were measured by a modification of the technique developed by Menzoian et al. As shown in Fig. 1, the proximal graft cannula was connected to a Medrad Mark II arteriographic injector (Medrad, Inc., Pittsburgh, Pa.). A number 23 gauge needle was introduced into the hood of the distal anastomosis and was pressure transduced to a Marquette 7000 RA monitor (Marquette Electronics (USA), Milwaukee, Wis.) allowing on-line monitoring and hard copy of
pressure tracings. Pressure measurements were obtained from the hood of the anastomosis to confirm that no significant lesions existed in the inflow vessels or vein graft conduit. Measured outflow resistance (MOR) was then obtained by clamping the proximal vein graft above the infusion cannula and infusing normal saline solution into the graft at a rate of 60 ml/min. The resultant pressures at the distal anastomosis were recorded. The distal pressures typically reached an initial peak followed by a slightly lower plateau pressure. Plateau pressures were used to calculate MaR as follows: MaR = Plateau pressure (mm Hg)/Infusion rate (ml/min). The MOR (in mm Hg/ml/min) was expressed as resistance units (RUs).

To correct for differing amounts of vasospasm between different patients, resistances were measured before and after the administration of 30 mg papaverine (MOR(PAP)) into the outflow bed via the vein graft. Intraoperative measurement of MOR was performed under a protocol approved by the New England Medical Center Human Investigation Review Board.

Other parameters recorded at the time of surgery included the length of the vein graft (cm), the inflow level (femoral/popliteal), and the outflow level (popliteal/tibial/pedal). Combined preoperative and intraoperative arteriograms were graded for the presence or absence of a plantar arch and by the Society for Vascular Surgery/International Society for Cardiovascular Surgery (SVS/ISCVS) scoring of outflow resistance.

Duplex scan technique and postoperative management. Patients enrolled in this study received routine postoperative care. Patients were seen in the noninvasive vascular laboratory for a baseline, postoperative duplex scan examination of the vein graft at 3 to 4 weeks after surgery. In uncomplicated cases, a 3-week interval before the first study has been routine on our service to allow the wounds to heal and to avoid the effects of immediate postoperative hyperemia on graft hemodynamics.

Duplex scan examinations were all performed with color-assisted duplex ultrasonography with an ATL Ultramark 9 (Advanced Technology Laboratories, Inc., Bothell, Wash.), HDI scanner with a L10-5 MHz linear array transducer (Advanced Technology Laboratories, Inc.). An image of each graft was obtained with the patient in the supine position with the knee slightly flexed and externally rotated. Studies were performed with the transducer in a longitudinal orientation beginning at the proximal anastomosis of the graft. The entire length of the graft was surveyed to assess for localized stenotic areas manifested by flow acceleration or disturbance. When graft abnormalities were ruled out, Doppler-derived PSFV measurements and ultrasound-derived vein graft diameters (VGD) were measured over the distal vein graft (4 to 6 cm from the distal anastomosis) and recorded. PSFVs were measured by placing the sample volume in midstream and the Doppler angle of incidence at 60 degrees. Luminal diameters were measured with electronic calipers placed at opposing luminal margins.

Statistical analysis. All continuous variables are expressed as mean value ± one standard error of the mean. Comparisons between continuous variables were made with a two-tailed Student's t test. Because of the small number of popliteal grafts in this study (n = 6), and because of our previous demonstration that popliteal and tibial grafts share similar hemodynamic properties, popliteal and tibial bypass grafts were combined for the purposes of comparison in this study.

Correlation coefficients were determined for the univariate analysis of factors significantly influencing vein graft PSFV. Significant factors so identified were analyzed by stepwise multiple regression analysis. All statistical calculations were conducted with the SAS program (SAS Institute Inc, Cary, N.C.) for personal computers.

RESULTS

General characteristics. Of 46 vein grafts initially evaluated in this study, two were withdrawn and not considered in the data analysis. One graft was in a patient who had a fatal myocardial infarction 1 week after discharge before his duplex scan evaluation. The second graft was withdrawn when the duplex scan evaluation performed 3 weeks after operation identified an unanticipated high-grade graft stenosis that required graft revision. Three additional grafts, included in the study, developed new graft stenoses 4 to 6 months after operation and were detected and revised as part of our routine surveillance protocol. One of these grafts ultimately failed. The remaining 41 vein grafts have remained patent for periods varying between 6 to 12 months.

The SVS/ISCVS outflow resistance score is a numeric grading of outflow resistance based on arteriography which ranges from 1 (low resistance) to 10 (high resistance). The SVS/ISCVS scores in this series ranged from 2.5 to 10 with a mean value of 42 ± 2.8. Vein graft length averaged 53.7 ± 3.5 cm and ranged from 20.5 to 80 cm.
Table I. Vein graft characteristics for different outflow level bypass grafts

<table>
<thead>
<tr>
<th></th>
<th>Pedal bypasses</th>
<th>Popliteal/tibial bypasses</th>
<th>p Value</th>
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<tbody>
<tr>
<td>PSFV (cm/sec)</td>
<td>64 ± 10</td>
<td>89.5 ± 5</td>
<td>0.02</td>
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<tr>
<td>VGD (mm)</td>
<td>4.5 ± 0.3</td>
<td>4.7 ± 0.2</td>
<td>0.5</td>
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<tr>
<td>MOR (RUs)</td>
<td>1.01 ± 0.19</td>
<td>0.72 ± 0.06</td>
<td>0.06</td>
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<tr>
<td>MOR(PAP) (RUs)</td>
<td>0.86 ± 0.06</td>
<td>0.51 ± 0.05</td>
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Table II. Results of the univariate analysis of the factors influencing vein graft peak systolic flow velocity

<table>
<thead>
<tr>
<th>Variable</th>
<th>r Value</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOR(PAP)</td>
<td>-0.69</td>
<td>0.0001</td>
</tr>
<tr>
<td>MOR</td>
<td>-0.59</td>
<td>0.0001</td>
</tr>
<tr>
<td>Inflow level</td>
<td>-0.47</td>
<td>0.0002</td>
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<tr>
<td>Outflow level</td>
<td>-0.35</td>
<td>0.03</td>
</tr>
<tr>
<td>SVS/ISCVS Score</td>
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<td>VGD</td>
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<td>Systolic pressure</td>
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<td>0.17</td>
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<tr>
<td>Graft length</td>
<td>0.11</td>
<td>0.58</td>
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<tr>
<td>Ankle pressure</td>
<td>0.10</td>
<td>0.53</td>
</tr>
<tr>
<td>Ejection fracture</td>
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<td>0.60</td>
</tr>
<tr>
<td>Patent plantar arch</td>
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<td>0.89</td>
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<td>ABI</td>
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Table III. Results of the multiple regression analysis of factors influencing vein graft peak systolic flow velocity

<table>
<thead>
<tr>
<th>Variable</th>
<th>r²</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOR(PAP)</td>
<td>0.51</td>
<td>0.0001</td>
</tr>
<tr>
<td>VGD</td>
<td>0.14</td>
<td>0.0001</td>
</tr>
<tr>
<td>Combined model</td>
<td>0.65</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Only MOR(PAP) and VGD influenced peak systolic flow velocity in this model.

Vein graft characteristics. Comparisons of various vein graft characteristics between pedal and popliteal/tibial grafts are included in Table I. Vein graft PSFVs ranged from 22 to 148 cm/sec and averaged 83.4 ± 4.8 cm/sec. Pedal bypass grafts had significantly lower PSFVs (64 ± 0.10 cm/sec) than did popliteal or tibial grafts (89.5 ± 5 cm/sec, p = 0.02). The mean vein graft diameter (VGD) over the distal graft segment did not differ between pedal (4.5 ± 0.3 mm) and popliteal/tibial grafts (4.7 ± 0.2 mm, p = 0.5).

MOR without papaverine ranged from 0.26 to 2.10 RUs. MOR(PAP) ranged from 0.17 to 1.47 RUs. The MOR in every graft decreased after papaverine infusion (p = 0.0001). As anticipated pedal bypasses had higher resistances than did popliteal/tibial bypasses (1.01 ± 0.19 RUs vs 0.72 ± 0.06 RUs, p = 0.06, without papaverine and 0.86 ± 0.15 RUs vs 0.51 ± 0.05 RUs, p = 0.05, after papaverine).

Univariate analysis of factors influencing PSFV. The correlation coefficients (r values) and associated p values between the various factors and graft PSFV is shown in Table II. The factors that correlated with PSFV included MOR (r = -0.59, p = 0.0001), MOR(PAP) (r = -0.69, p = 0.0001), inflow level (femoral vs popliteal, r = -0.35, p = 0.03), SVS/ISCVS resistance score (r = -0.34, p = 0.04), and outflow level (pedal vs popliteal/tibial, r = -0.47, p = 0.002). VGD approached statistical significance with an r = -0.3, p = 0.06). Factors that did not correlate with vein graft PSFV included cardiac ejection fraction, the presence or absence of a patent pedal arch, conduit length, absolute ankle blood pressure (or ankle-brachial index), and systolic blood pressure at the time of PSFV measurement.

Multiple regression model. When the significant factors for univariate analysis were introduced into a multivariate analysis (Table III) the optimal model included only MOR(PAP) (r² = 0.51, p = 0.0001) and VGD (r² = 0.14, p = 0.001). The MOR(PAP) correlated significantly with all of the
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Fig. 2. Graphic representation of multiple regression analysis of factors affecting vein graft peak systolic flow velocity.

other univariate predictors (except VGD) and overwhelmed their significance in the multivariate model. Consideration of MOR\textsubscript{(PAP)} along with VGD in the multivariate model significantly improved the correlation of VGD with PSFV over that identified in the univariate analysis. The overall model predicts vein graft PSFV as PSFV = 176 + VGD\textsubscript{(mm)} (−11.7) + MOR\textsubscript{(PAP)} (−63.4). The overall model had an \( r^2 = 0.65 \) and \( p = 0.0001 \). The relationship of MOR\textsubscript{(PAP)} and VGD to PSFV is demonstrated graphically in Fig. 2.

In an attempt to arrive at a more clinically applicable model for predicting vein graft PSFV (which doesn’t depend on MOR determinations) the multiple regression analysis was repeated leaving MOR and MOR\textsubscript{(PAP)} out of the analysis. In this analysis inflow level (\( r^2 = 0.23, p = 0.003 \)), outflow level (\( r^2 = 0.07, p = 0.09 \)), and VGD (\( r^2 = 0.08, p = 0.05 \)) contributed to the overall model. Unfortunately, although statistically significant, this model is considerably less predictive (\( r^2 = 0.37, p = 0.002 \)) than models including MOR or MOR\textsubscript{(PAP)}. The inclusion of inflow level in this particular model most likely does not reflect inherent differences in PSFV related to inflow level but more likely the fact that popliteal inflow grafts are generally to the pedal outflow level and hence have lower PSFVs.

DISCUSSION

Routine postoperative surveillance of femorodistal vein grafts has gained widespread acceptance as a method of enhancing long-term graft patency and limb salvage.\textsuperscript{1,8} Serial evaluation of the graft with duplex scanning has emerged as the best available technique for this purpose. Early studies by Bandyk et al.\textsuperscript{1,2} established a PSFV of 45 cm/sec or less as a marker of a low flow graft at risk for failure. Subsequent arteriography of the vein grafts generally confirmed a hemodynamically significant stenosis. Others have confirmed the utility of this threshold value.\textsuperscript{8} More recently, a number of series have found measurement of PSFV to be a fairly nonspecific and insensitive marker of vein graft stenosis.\textsuperscript{4,5,8} In our practice we have followed a number of extremely distal bypass grafts that have remained patent despite PSFVs less than 45 cm/sec on serial examinations. Furthermore, significant segmental vein graft stenoses have been identified and repaired in grafts with PSFVs greater than 45 cm/sec. We speculated that vein grafts with different diameters and varying outflow levels should have widely variable flow characteristics and that routine application of a single threshold abnormal PSFV to all vein grafts would be inherently inaccurate. In a previous study we established that vein graft PSFV was inversely correlated to vein graft diameter for tibial (\( r = −0.49, \)
outflow grafts. We also found significantly lower PSFVs in extremely distal tibial and pedal outflow grafts (59.1 ± 3.4 cm/sec) than more proximal tibial (77.2 ± 5.6 cm/sec) and popliteal bypass grafts (71.0 ± 5.6 cm/sec, p = 0.04). We hypothesized that a more complete understanding of the factors influencing individual vein graft hemodynamics would allow more accurate identification of grafts that have abnormal hemodynamics and thus harbor significant abnormalities. This prospective study was thus undertaken to identify and quantify the measurable factors impacting on vein graft hemodynamics.

In this study a number of possible factors were evaluated for their relationship with vein graft PSFV. Although a number of variables were significantly correlated to PSFV in the univariate analysis (Table II), only VGD and MOR(PAP) contributed to the overall multiple regression model (Table III). The other factors including MOR, SVS/ISCVS score, and outflow level are all related to outflow resistance but are not as informative as MOR(PAP). This suggests that intraoperative papaverine infusion "corrects" for the variable amounts of vasospasm between different patients. Ascer et al.11 also found that intraoperative papaverine infusion enhanced the accuracy of outflow resistance measurements. Other parameters including systolic blood pressure, cardiac ejection fraction, vein graft length, ankle pressure, and the patency of the plantar arch, were not demonstrated to relate to PSFV. Although it is possible that these factors may exert subtle influences on graft hemodynamics it is unlikely they have a major impact on PSFV. It is noteworthy that the patency of the plantar arch did not correlate with PSFV. The influence of the patency of the plantar arch on PSFV may have been obscured by the relatively small minority of patients with completely intact arches in this study (8 patients). Other factors not assessed in this study, such as vein graft compliance and blood viscosity, may also impact on PSFV.

For a two component, non-designed regression model, the combination of VGD and MOR(PAP) demonstrated a highly significant relationship to PSFV (r² = 0.65, p = 0.0001). Unfortunately, the combination of these two factors can only account for 65% of the variation in PSFV with 35% relating to a combination of other less significant factors. Thus it is unlikely that this model will have significant clinical utility. Furthermore, this model depends on the measurement of MOR(PAP), which is not routine, and the model became much less predictive when MOR was eliminated (r² = 0.37).

The use of Duplex scanning as a method of monitoring vein grafts has been an important advance in vascular surgery, which continues to evolve. The original work of Bandyk et al.1,2 on graft surveillance depended on continuous-wave Doppler scanning and gray-scale duplex scanning. The reliance on PSFV as a marker for graft stenosis thus evolved as the most efficient and clinically useful approach. More recently, color-assisted duplex scanning has greatly facilitated the evaluation of vein grafts.6,7,12,13 This technology allows a rapid preliminary screening of the entire conduit identifying areas of stenosis. These areas may then be more carefully interrogated for segmental increases in velocity. Most authors have identified the velocity ratio (the maximal velocity within the stenosis/the velocity in the normal graft above or below the stenosis) as the most sensitive and specific indicator of a significant lesion.5,7,13 A velocity ratio of 2 or greater has been identified as a marker for a hemodynamically significant (>50% diameter stenosis) lesion. Unlike measurements of PSFV, which vary widely between different vein grafts, this approach has the benefit of an "internal control" where flow velocities within a stenosis are compared with normal areas within the same graft.

Another interesting observation is the high outflow resistances and associated low-flow velocities identified in bypass grafts to distal tibial and pedal outflow tracts. Despite these observations, our experience and that of others is that these bypasses exhibit excellent hemodynamic results and durable patency rates. Although outflow resistance has traditionally been considered a factor of fundamental importance in the success of femorodistal bypass surgery, we believe that this factor has been over emphasized. We believe that the quality of the venous conduit is the major factor influencing the patency of bypass grafts. As confirmed in a number of clinical studies, high-quality venous conduits of adequate diameter will remain patent despite very limited outflow tracts as demonstrated by arteriography and measured outflow resistance.14,15 This is consistent with the observations of Peterkin et al.16 who found that a high MOR did not correlate with early vein graft failure. Conversely, Ascer et al.11 did find that a high MOR (≥1.2 RUs) was a risk factor for early graft failure. In Ascer's study, however, 56% of the grafts were completed with polytetrafluoroethylene, and it
is likely that outflow resistance and graft flow velocities assume more significance in prosthetic grafts than in vein grafts.

In summary, vein graft diameter and measured outflow resistance are the most important factors influencing vein graft PSFV in the absence of intrinsic graft stenosis. The wide variation in these parameters among patients contribute to the wide range of PSFVs identified in different vein grafts under normal conditions. This variability makes it difficult to identify a vein graft at risk for failure based on an individual measurement of PSFV. Monitoring techniques that scan the entire graft (with color-assisted duplex scanning) and then focus on areas of stenosis are likely to be more accurate in identifying and assessing vein graft stenosis.

REFERENCES


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DISCUSSION

Dr. Dennis Bandyk (Tampa, Fla.). In 1985 our division at the Medical College of Wisconsin reported that serial measurement of peak systolic velocity after infrarenal vein bypass was a useful adjunct for the detection of failing bypass grafts.1 We found that grafts that developed a stenosis that warranted correction could be recognized by a decrease in peak systolic velocity to less than 45 cm/sec when recorded from a normal 3 to 5 mm diameter in the distal graft segment. Dr. Belkin and his colleagues have emphasized the variation of vein graft flow velocity with luminal diameter and outflow resistance.

In their prospective study of 46 patients undergoing elective infrainguinal bypass for critical ischemia, multiple regression analysis, an appropriate technique, found that postoperative peak systolic velocities most significantly correlated with intraoperative graft outflow resistance measurements followed by vein graft diameter. Bypass
graffs to the pedal arteries had higher outflow resistance and corresponding lower graft flow velocities.

One important limitation of this study was that the hemodynamic measurements were not all performed at the same time. But significant differences were observed with the methods described; no early graft failures occurred, and only one early graft stenosis was found.

The obvious implication of these data on the reliability of graft surveillance is that a single measurement of graft flow velocity is an inadequate predictor of graft failure, and thus serial measurements are necessary to detect deteriorations in graft function.

Because peak systolic velocity varies with diameter, wouldn't it be helpful to use a value recorded from a 4 mm vein segment as the signature value and thus allow follow-up of that graft in comparison with other graft types? This modification may improve this parameter as a marker for graft stenosis or for identifying high graft outflow resistance.

Do you have any hemodynamic parameter that you use during operation to detect technical error? I have found low flow with absent diastolic flow to frequently recognize poor outflow problems or residual technical problems.

You have recommended scanning the entire graft to identify developing graft stenosis. Do you use peak systolic velocity with other duplex criteria to decide in intervention decision making to correct the stenosis?

It is difficult to calculate the number of true low-flow grafts you had in your study. Do you treat this patient cohort any differently, for example, in terms of recommending anticoagulation?

Mr. Julian Scott (Bristol, United Kingdom). I am surprised that your literature survey failed to highlight the limitations of measuring peripheral resistance with use of saline solution, and perhaps you could comment about that.

I challenge you on the conclusion that the measurement of outflow resistance is an impractical tool. In the United Kingdom, with the Sci-Med operative Doppler flowmeter (Medical Safetec, Inc., Indianapolis, Ind.), it is now well established this is a good predictor of outcome as defined by the SVS/ISCVS criteria.

I have a degree of statistical skepticism about your application of univariate to multivariate analysis in a patient population of less than 100.

Dr. James O. Menzoian (Boston, Mass.). In your technique for measuring intraoperative mean outflow resistance you infused saline solution at 16 ml/min and measured the pressure generated during that period of infusion. Can you tell me how you arrived at 16 ml/min of infusion?

You state that the pedal arch score did not correlate with peak systolic flow velocity. I'm somewhat surprised by this finding because in our own regression analysis of approximately 100 bypass grafts, pedal arch score was very important in predicting the measured intraoperative resistance.

Looking into the physical principles involved in the measurement of blood flow and resistance, the length of the tube is a very important determinant. I'm surprised that the length of your vein graft did not correlate with measurements of outflow resistance of peak systolic flow velocity.

Do you have any information on serial measurements of peak systolic flow velocity where a change in peak systolic flow velocity was predictive of impending vein graft failure?

Dr. Phillip Bendick (Royal Oak, Mich.). Going back to basic physiology, if you combine the parameters of outflow resistance, peak systolic flow velocity, and vessel diameter, you come up with the independent variable of volume flow. Have you considered looking at volume flow, which can, in fact, be measured by duplex ultrasonography, as a parameter that might indicate graft failure?

How do you distinguish the important problem of the graft that is at risk for failure, that is, thrombosis, which is a clinical problem, versus the anatomic defect of something that might require repair, which would be identified by some of the parameters you propose?

Dr. Sergio Salles-Cunha (Toledo, Ohio). Most of the analysis in this study has focused on a single measurement in time. For example, graft velocity is higher or lower than 45 cm/sec. There is another way to analyze Bandyk's data. If a graft velocity is 75 cm/sec and drops to 45 cm/sec, then that change is significant and implies graft failure. The statistical power increases with multiple measurements in an individual as opposed to single measurements in a population.

Our own measurements indicate that a decreasing velocity of 25% is statistically significant. Before adopting other single measurement standards, velocities, or B-mode percent stenosis, we should study changes.

What are the changes in low velocity, high velocity, percent of stenosis, diameter, or peripheral impedance detected from one serial measurement to another in your graft population?

Dr. Michael Belkin. One of the overriding themes is the serial nature of measurements, and whether changes are important. They are important, but I suggest that whenever we find a graft velocity that has dropped from 75 to 45 cm/sec, we can get much more information by scanning the entire graft and finding out exactly why the velocity has dropped by identifying a new stenosis. We measure peak systolic flow velocity, but we only use it as a qualifier to finely tune our evaluation of the overall vein graft.

Our decision to use measurements obtained 3 weeks after operation, as opposed to use of intraoperative numbers is because we are trying to develop a clinically relevant model. If we used flow rates obtained during surgery, our correlations would have been even higher, but
perhaps of a limited relevance to what happens in the vascular laboratory.

Saline solution is a very low viscosity fluid compared with blood and that could have an effect on velocity, but we're just looking for a technique to gauge the resistance, and there are many factors that we didn't account for, and this is just our best effort.

The problem with a small number is that we fail to identify effects, but the results speak for themselves and the statistical significance was quite high.

We used 60 cc because that's what our machine would do. We tried to do 60 and 120 cc but the problem was that if the resistance is 1.8 and we infuse at 120 cc/sec, we would get pressures of over 200, which we just didn't feel comfortable with during this investigation.

Length should be an important factor according to Poisson's law, and it probably is a factor, but more subtle than we could identify in this relatively small group, and I'm sure that length would account for somewhere in that 35% of variance which we can't identify.