Comparison of Blood-Flow Velocity Waveforms in Different Coronary Artery Bypass Grafts

Sequential Saphenous Vein Grafts and Internal Mammary Artery Grafts

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Characteristics of blood-flow velocities were investigated at different sites in two types of coronary artery bypass grafts, sequential saphenous vein grafts (SSVG) and internal mammary artery grafts (IMAG). The latter appear to have the longest life span. The patency rate of the side-to-side anastomosis of the SSVG is better than that of the end-to-side anastomosis. The SSVG was anastomosed to the major diagonal branch by side-to-side anastomosis and to the left anterior descending coronary artery (LAD) by end-to-side anastomosis in 13 patients who had 75–100% and 75–90% stenoses in the LAD and major diagonal branch, respectively. IMAG anastomoses were performed to the LAD in 10 patients with 75–100% stenoses of the artery. The blood-flow velocities were measured by the 20-MHz, eighty-channel ultrasound pulsed Doppler method during surgery. In six patients in the SSVG group, we investigated the configuration of velocity profiles at the region just proximal to the side-to-side anastomosis and at the bridge portion between the side-to-side and end-to-side anastomosis. In the other seven patients, we measured the blood-flow velocity at several centimeters proximal to the side-to-side anastomosis and compared it with that in the IMAG. At the region just proximal to the side-to-side anastomosis, the velocity profile skewed toward the anastomosis side wall in all patients, and the flow velocity near the wall opposite to the side-to-side anastomosis was reversed in five of six patients. In the bridge portion, directional changes in skewing of the velocity profile were recognized, that is, a skewed pattern toward the wall opposite to the anastomosis (four patients) or a symmetric pattern (two patients). The peak diastolic velocity in the region was 25.4 ± 5.8 cm/sec, significantly lower than that (46.6 ± 12.3 cm/sec) just proximal to the side-to-side anastomosis. The velocity profile across the IMAG several centimeters proximal to the graft-coronary anastomosis showed a parabolic configuration with a narrow spectrum. The velocity profile in eight of 10 patients was statistically parabolic. In the SSVG, however, only two of seven patients were parabolic at the region several centimeters proximal to the side-to-side anastomosis. The peak diastolic velocity in the IMAG (26.2 ± 2.0 cm/sec) was almost the same as that in the SSVG (26.3 ± 5.5 cm/sec), but the estimated graft diameter of the IMAG (2.3 ± 0.2 mm) was significantly smaller than that of the SSVG (3.4 ± 0.5 mm), indicating a relatively high shear rate in the IMAG. These findings may provide insight into the underlying mechanisms of graft viability because the patterns of blood flow seem to be a contributory factor in determining the fate of the graft. (Circulation 1988;78:1210–1217)
viability for the internal mammary artery graft (IMAG).1–5 One variation in the surgical procedure of the SVG is a sequential saphenous vein graft (SSVG) in which a side-to-side anastomosis of the vein graft into a coronary artery is performed in addition to the end-to-side anastomosis. In cases of SSVG, the patency rates of side-to-side anastomoses have been reported to be better than those of end-to-side anastomoses.6,7

Several factors, including technical problems, determine the early fate of coronary bypass surgery grafts.8 However, atherosclerosis is emerging as the major determinant of long-term vein graft viability.9,10 Its development may be influenced not only by such global factors as abnormal lipoprotein levels but also by local blood-flow patterns.11,12 The possibility that differences in blood-flow velocity waveforms and velocity profiles across the graft are implicated in the fate of the graft has encouraged us to study the blood-flow velocities in different types of grafts (SVG and IMAG) and in different portions of the grafts (side-to-side and end-to-side anastomoses). Studies on velocity profiles across the graft have been few because of technical difficulty with measurements. Recently, we developed a 20-MHz eighty-channel pulsed Doppler velocimeter13–15 and used it for measurements.

Methods

Pulsed Doppler Velocimeter and Its Validity for Measurements of Velocity Profiles Across a Vessel

The pulsed Doppler system used in this study has been previously described.13–15 In brief, the transducer consists of a $\pi \times 0.5 \text{mm}^2$ piezoelectrical crystal with a 20-MHz carrier frequency. The pulse repetition period is 20 $\mu$s, and the sampling pulse width is 0.25 $\mu$s. The sample volume is discoid with a diameter of 1 mm and a thickness of 0.2 mm because the depth resolution is 0.2 mm. The system has 80 sampling gates, and Doppler signals from the multigate circuit are analyzed by a zero-cross method. In addition, a fast Fourier transform is performed for an optional channel by the hardware to detect the spectrum broadening seen in disturbed velocity fields. These procedures are performed in real time.

As for the accuracy of our method, we have measured the known velocity of water seeded with starch particles in the circular groove of a turntable rotating at various speeds. We reported that the correlation coefficient between the known and measured velocities was significantly high ($r = 0.998$).14 The validity of measurements of the velocity profile across a vessel has been evaluated by measuring the velocity profile of water flow in a model tube with a length of 80 cm and an inner diameter of 7 mm, the wall of which was made from silicon resin.15 We found that the measured and calculated velocity profiles were in good agreement for different flow rates, indicating the validity of our method for the evaluation of velocity profiles.

Measurements of Blood-Flow Velocity Profiles in Coronary Bypass Grafts During Cardiac Surgery

Blood-flow velocities in coronary bypass grafts were measured by our method during cardiac surgery. A total of 23 patients (16 men and seven women) who had been admitted to the Department of Thoracic Surgery, Kawasaki Medical School, Kurashiki, Japan, were studied (Table 1). All patients underwent coronary arteriography and opacification of the left ventricle within 2 months before the surgical procedure. The SSVG was anastomosed to the major diagonal branch by side-to-side anastomosis and to the left anterior descending coronary artery (LAD) by end-to-side anastomosis in 13 patients (aged 47–82 years) who had 75–100% and 75–90% stenoses in the LAD and diagonal branch, respectively. The anastomosis angle between the graft and the coronary artery was small (quasi-parallel) for both side-to-side and end-to-side anastomoses. In six patients (patients 1–6), the blood-flow velocity in the SSVG was measured at three sites, that is, 2–3 cm distal to the aorto-graft anastomosis, just proximal to the graft–diagonal branch anastomosis (side-to-side), and at the bridge portion between graft–diagonal branch and graft-LAD (end-to-side) anastomoses (1, 3, and 4 in Figure 1). In seven patients (patients 7–13), the blood-flow velocity in the SSVG was measured only at a site several centimeters proximal to the diagonal anastomosis (2 in Figure 1). IMAG anastomoses were performed to the LAD in 10 patients (aged 45–73 years) with 75–100% stenoses of the artery. The blood-flow velocity was measured at two sites, that is, several centimeters proximal and just proximal to the graft-LAD anastomosis. A specially designed pencil-type probe holder with a slight curvature was used to measure blood-flow velocities in the graft (Figure 2). This holder was made of Teflon, and a transducer was mounted in it with an angle of 60° to the central axis of the cuff. The size of the cuff is controlled by the sliding of a knob with the operator’s index finger. The holder is slightly curved to obtain better accessibility to the graft. A plate-type probe holder was also used,15 when necessary. The holder was placed perpendicular to the myocardial surface. Blood-flow velocity measurements were performed when hemodynamic variables became stable after the completion of bypass grafting and weaning from the cardiopulmonary bypass. The maximum diameter of a graft during a cardiac cycle was roughly estimated by disappearance of the Doppler signals.

Statistical Analysis

Data are reported as mean ± SEM. The differences between two means were compared by paired and unpaired $t$ tests. The differences between two ratios were compared by Fisher’s exact test. The criterion for statistical significance was $p < 0.05$. As a quantifiable index of the velocity profile, we used an information theoretical criterion (AIC),16,17 which repre-
TABLE 1. Patient Characteristics

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (yr)</th>
<th>Sex</th>
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<th>Diag</th>
<th>RCA</th>
<th>LMT</th>
<th>LCx</th>
<th>Procedure</th>
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M, male; F, female; LAD, left anterior descending coronary artery; Diag, diagonal main branch; RCA, right coronary artery; LMT, left main trunk; LCx, left circumflex coronary artery; SSVG, sequential saphenous vein graft; SVG, saphenous vein graft; IMAG, internal mammary artery graft.

AIC represents a measure of the fitness of a model to a given set of statistical data. In our study, AIC is expressed as

\[ \text{AIC} = -n[\log(n/2\pi)-1] + n\log SS + 2K \]  

(1)

where \( n \) is the number of data, \( SS \) is the sum of squares of residuals, and \( K \) is the degree of the polynomial equation. The conceptual schema of model selection is as follows. 1) Estimate the polynomial equations (\( K=2, 3, \text{etc.} \)) to fit a velocity profile by the least-squares method and calculate \( SS \). 2) Calculate the AIC value for each \( K \), and select the number of \( K \) corresponding to the minimum AIC as the optimal one. If the selected number of \( K \) is 2, the velocity profile is recognized as parabolic. We examined the velocity profile corresponding to the peak central axial velocity.

**Results**

**Velocity Profiles in a Sequential Saphenous Vein Graft**

Figure 3 shows a typical example of the waveform just proximal to the side-to-side anastomosis. The velocity profile skewed toward the anastomosis side wall in all patients (Table 2), especially during diastole, but the spectrum of the peak velocity was narrow in this region. The flow velocity near the wall opposite the anastomosis was reversed (dark shading) during diastole in five of six patients and close to the zero-velocity line in one patient. The early systolic reverse flow seen in this patient was frequently observed. In the bridge portion, the shape of the profile showed a symmetric (two of six patients) or a skewed pattern (four patients) toward the wall opposite the anastomosis (Figure 4). A reverse flow was noticeable in early systole. The spectrum of the peak velocity was narrow as in the region just proximal to the side-to-side anastomosis. The peak diastolic velocity in the bridge portion was 25.4±5.8 cm/sec, significantly lower than that (46.6±12.3 cm/sec) just proximal to the side-to-side anastomosis (\( p<0.05 \)). The estimated maximum graft diameter at the bridge region was 4.4±0.4 mm, which was not significantly different from that just proximal to the side-to-side anastomosis (3.8±0.3 mm).

A typical recording of the SSVG flow velocities at several centimeters proximal to the diagonal branch is shown in Figure 5. Compared with the velocity
profiles at the portion just proximal to side-to-side anastomosis and the bridge portion, the velocity profile in this region showed a more symmetric configuration. However, only two of seven patients were judged by AIC to have a parabolic velocity configuration. The peak diastolic velocity was 26.3 ± 5.5 cm/sec, and the estimated graft diameter was 3.4 ± 0.5 mm. The velocity waveform at the region 2–3 cm distal to the aorto-graft anastomosis showed a relatively high systolic flow. Two of six patients were recognized by AIC to have a parabolic velocity profile.

**Velocity Profiles in the Internal Mammary Artery Graft**

Figure 6 shows a representative recording of the IMAG flow velocity in the region several centimeters proximal to the graft-LAD anastomosis. The velocity waveform had a normal coronary artery flow pattern, that is, diastolic predominant, and the velocity spectrum was narrow. The AIC analysis indicated that eight of 10 patients had a parabolic velocity configuration. This ratio of parabolic to total patients (eight of 10) was higher than that (two of seven) at a region several centimeters proximal to the diagonal branch anastomosis in the SSVG, although the difference was not significant statistically (p = 0.052). When we included the data (parabolic/total = 2/6) at the region 2–3 cm distal to aorto-graft anastomosis, the difference in the ratios (eight of 10 vs. four of 13) was significant statistically (p = 0.026). The peak diastolic velocity in IMAG was 26.6 ± 2.0 cm/sec. The velocity differences between IMAG and SSVG several centimeters proximal to the side-to-side anastomosis were not significant statistically. The estimated graft diameter at this region was 2.3 ± 0.2 mm. This was significantly smaller than that of the SSVG. The velocity profile in the region just proximal to the graft-LAD anastomosis was almost the same as that in the region several centimeters proximal to it. An early systolic reverse flow was frequently observed at both measuring sites.

**Discussion**

The longer-term patency of the IMAG compared with that of the SVG has been well documented in carefully designed follow-up studies.\(^1\)\(^-\)\(^5\) Lytle et al\(^2\) and Campeau et al\(^10\) noted the susceptibility of SVG to late atherosclerotic changes in 50–60% of grafts implanted for 10–12 years. The long-term follow-up study of SSVG by Kieser et al\(^6\) showed that the side-to-side anastomosis had a much better patency rate than the end-to-side anastomosis. It has also been indicated that development of atherosclerosis is the major determinant of the long-term viability of grafts.\(^9\)\(^,\)\(^10\)
Our studies have resulted in the first detailed description of the characteristics of the SSVG and the IMAG blood-flow velocities. This may be very important because it has been suggested that interactions between the blood and the vessel wall are related to the development of atherosclerosis. For our studies, we used the eighty-channel 20-MHz dual-mode (zero-cross and fast Fourier transform) pulsed Doppler velocimeter developed in our department. Eighty channels were used to allow evaluation of a detailed blood-flow velocity across the graft, and the Fourier transform was indispensable to the analysis of flow disturbance. Freed et al. have also shown the usefulness of the 20-MHz pulsed Doppler velocimeter for graft velocity measurements, although in their studies, no Fourier analysis was performed, and the number of channels of measurement was limited.

One of the prominent features of the velocity profile just proximal to the side-to-side anastomosis in the SSVG was the skewing of the profile toward the anastomosis side wall, suggesting high velocities into the diagonal branch. Despite the skewing, the configuration of the velocity profile was smooth, and the velocity spectrum was narrow. Watts et al. studied the velocity patterns in distensible model tubes with different types of anastomoses by using a blood-flow visualization technique. They observed that the flows at a kiss anastomosis (side-to-side) were less agitated than those at end-to-side anastomosis, supporting our present results. These flow configurations may contribute to the better patency rate of side-to-side anastomosis.

The reverse flow near the wall opposite the anastomosis suggests the existence of flow separation and recirculation in this region, which dissipates energy. The change in the shape of the velocity profile between side-to-side and end-to-side anastomosis was another characteristic of the velocity pattern in the SSVG; that is, the skewed pattern toward the anastomosis side wall at the region just proximal to the side-to-side anastomosis changed to a skewed pattern toward the wall opposite the anastomosis (four of six patients) or a symmetric pattern (two patients) in the bridge portion. This directional change in the velocity profile also suggests a complex flow field. Such alterations in the velocity patterns may contribute to the poor patency rate of the end-to-side anastomosis. The entry region of flow in the graft, which is the distance required to develop the velocity profile, will be approximately 10–20 vascular diameters in the coronary artery graft. The complex flow field near the bridge portion may be because this measuring point is within the entry region. In the present study, the angle of the graft-artery anastomosis was made small. However, it was shown in the above-mentioned model experiment that the angle had considerable effect on the flow condition.

**TABLE 2. Characteristics of Blood-Flow Velocity Profile in Sequential Saphenous Vein Bypass Graft**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Just proximal to SSA</th>
<th>Bridge portion*</th>
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</table>

SSA, side-to-side anastomosis.

*Bridge portion between side-to-side and end-to-side anastomosis.

†Symmetric pattern.

‡Transient and small reverse flow.

§Double-peaked (M-shaped) pattern.

**FIGURE 3.** Tracings of blood-flow velocities just proximal to side-to-side anastomosis in the sequential saphenous vein graft. Top: Velocity waveform at the central axial region of the vessel by fast Fourier transform. Bottom: velocity profiles in a three-dimensional display composed of coordinates of velocity (zero-cross), radial position, and cardiac cycle. Value of the maximum diameter during one cardiac cycle, which was estimated by Doppler signals, is indicated by the position of the inner walls of the graft. Reverse flow velocities during diastole near the probe side wall (opposite to the side-to-side anastomosis [SSA]) are indicated by the dark shading. Note the skewing of the velocity profile toward the SSA side wall during diastole.
in the artery, that is, the strength of the helix being proportional to the increase in the angle. Therefore, further study will be required to determine the optimal angle for obtaining a better flow condition. But, at present, we suspect that too large an angle may not be desirable because it may strengthen the helical flow too much.

The higher flow velocity in the proximal segment of the sequential graft observed in this study was compatible with the data of O’Neill et al. They also reported that the proximal segment of the double sequential graft had a higher velocity of blood flow than that seen in a single bypass graft, although the diameters of single and sequential grafts were nearly equal. The importance of higher velocity for longer patency of the graft has been suggested by earlier studies; for example, Rittgers et al found an inverse correlation between the flow velocity in long-term vein grafts and the amount of intimal proliferation. Earlier clinical studies also suggest a tendency toward intimal proliferation in regions of low shear rate, although the cause of such lesions has not yet been well established. Accordingly, higher velocity may also be related to the better patency rate of side-to-side anastomosis.

It has become increasingly clear that the long-term patency of IMAG is superior to that of SVG. The improved survival curve of the IMAG group versus that of the SVG group was apparent within 5 years and has increased with time. This is probably due to the relative immunity of the internal mammary artery to atherosclerosis. In this study, we applied AIC to test quantitatively whether or not a velocity profile across a graft is parabolic. AIC

**FIGURE 4.** Tracings of typical blood-flow velocity at the bridge portion in the sequential saphenous vein graft. Top: Velocity waveform at the central axial region of the vessel by fast Fourier transform. Bottom: velocity profiles in a three-dimensional display composed of coordinates of velocity (zero-cross), radial position, and cardiac cycle. Note the directional change in the skewing of the velocity profile between Figures 3 and 4. SSA, side-to-side anastomosis.

**FIGURE 5.** Tracings of typical blood-flow velocity at several centimeters proximal to the major diagonal branch anastomosis in the sequential saphenous vein graft. Top: Velocity waveform at the central axial region of the vessel by fast Fourier transform. Bottom: velocity profiles in a three-dimensional display composed of coordinates of velocity (zero-cross), radial position, and cardiac cycle. Velocity profile in this region showed a more symmetric configuration.
was introduced by Akaike for estimation of the order of linear dynamical systems and has been successfully applied for statistical model identification in a wide range of fields. Compared with the velocity profiles in the SSVG (at several centimeters proximal to the graft-diagonal branch anastomosis and 2–3 cm distal to the aorto-graft anastomosis), those in the IMAG appeared to be more parabolic and regularly based on both the AIC and subjective judgment. Although the peak-diastolic velocities between IMAG and SSVG did not differ, the caliber of the IMAG was significantly smaller than that of the SSVG, indicating relatively high shear in the IMAG. This nondisturbed, well-ordered velocity configuration and relatively high shear may help to explain why the patency of the IMAG is higher than that of the SVG. The distensibility of the vessel wall is an important factor in the hemodynamics of pulsatile blood flow. It has been reported that vein grafts are not as compliant as those of arteries in humans and animals when arterial pressures are applied. A compliant wall acts as an elastic reservoir and absorbs energy during systole, a function of which is especially important in the coronary artery where flow is predominantly diastolic. A less compliant vessel causes the pulse-wave velocity to increase in value, and more energy is lost in pulsatile form, thereby reducing the energy available for distal perfusion. Wave reflection may also reduce the energy. In this sense, the IMAG may be better than the SVG. Vein grafts are known to undergo histological changes after implantation. This process of arterialization results in a medial hypertrophy and intimal hyperplasia, which might change the compliance of the grafts. As a result, the velocity profile might begin to resemble that of an arterial graft. However, Kidson and Abbott reported that compliance of the femoral vein graft in the dog remains unaltered, independent of thickening. It may be possible to study such vessels in the occasional patient returned to surgery for a second coronary bypass.

The location of the vasa vasorum, perfectly formed internal elastic lamina, and intact vascular smooth muscle may contribute to the higher patency of the IMAG. Among these properties, the intact vascular smooth muscle allows the IMAG to retain a flexible caliber and supply a blood flow dictated by myocardial demand. As for the internal elastic lamina, it has been suggested that if it has deficiencies early, progressive intimal thickening will occur. Recent histological study of the vasa vasorum of the internal mammary artery by Landymore et al., however, demonstrated that the vasa vasorum was confined to the adventitia, suggesting that its nutritional role is relatively unimportant.

In summary, the blood-flow velocities in SSVG and IMAG were analyzed by an eighty-channel 20-MHz pulsed Doppler velocimeter during aorto-coronary bypass graft surgery. The velocity profile across the graft in the IMAG was more parabolic with a narrower spectrum than that in the SSVG several centimeters proximal to the graft-diagonal branch anastomosis. Complex flow field including flow separation and directional changes in skewing of the velocity profile were recognized along the SSVG just proximal to the side-to-side anastomosis and the bridge portion between the side-to-side and the end-to-end anastomosis. These characteristics of the blood-flow velocity patterns seem to be a contributory factor in determining the fate of the graft.

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**Figure 6.** Tracings of typical blood-flow velocity patterns in the internal mammary artery graft. Top: Velocity waveform at the central axial region of the vessel by fast Fourier transform. Bottom: Velocity profiles in a three-dimensional display composed of coordinates of velocity (zero-cross), radial position, and cardiac cycle. Parabolic, nondisturbed velocity configuration is characteristic of internal mammary artery graft flow.
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References

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