Evaluation of a New Device for the Intraoperative Assessment of Coronary Artery Bypass Grafting

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Purpose: The aim of this study was to evaluate a new flow analyze device that can intraoperatively measure compliance and resistance of coronary artery bypass grafting (CABG) by the parameter identification method.

Methods: Subjects were 95 patients who underwent CABG. Angiography soon after surgery confirmed patency in 90 grafts and graft failure in 5 grafts. Variables of Aortic pressure and the graft flow were entered into this new device that includes a mathematical coronary circulation model to extrapolate other information the data; thus, we can estimate intraoperative flow rate, resistance, and compliance. Flow rate, resistance, and compliance were compared between patent and failed graft groups and among three different type grafts.

Results: There were no differences in flow rate, resistance, and compliance among the three grafts types. Between the patent and failed graft groups, there were statistically significant differences in flow rate and resistance, and compliance tended to be lower for the failed graft group.

Conclusions: By measuring graft resistance and compliance, this new device is useful for evaluating graft performance during CABG.

Key words: ischemic heart disease, coronary artery bypass grafting, coronary bypass graft assessment

Introduction

A blood flowmeter measuring flow rate and waveform during coronary artery bypass grafting (CABG) is used to assess graft performance.1, 2) An ultrasonic flowmeter can quickly, conveniently, and noninvasively measure not only flow rate, but also graft flow waveforms; thus, it is useful in the prevention of graft failure during and after surgery.

At present, blood flowmeters measure mean blood flow, pulsatility index (PI), and index of diastolic phase filling, all of which determine the ratio of blood flow rates during the diastolic phase.3)

However, there are other factors that might be involved in graft failure: 1) physiological graft properties: graft diameter, vascular wall thickness, endothelial hyperplasia, and spasm, 2) physiological coronary artery properties: vessel diameter, stenosis degree, vascular wall properties, peripheral runoff, graft resistance, and graft compliance, 3) risk factors for coronary artery diseases: hyperlipidemia, diabetes, and hypertension, 4) surgeon skills, and 5) drug-related factors: anti spasm drugs and antiplatelet agents.4)
Bypass graft flow rate is controlled by various factors. We thought that bypass graft performance should be assessed not only by the flow rate but also by graft resistance and compliance, since graft resistance, area of myocardial perfusion, and graft stenosis are interdependent. Also, graft compliance and condition of the graft wall (such as spasm) are interrelated. For these reasons, we developed a new blood flow analysis device which can estimate the bypass graft by flow rate, resistance and compliance. This new devise includes two electronic circuits with a programmed function for calculating coronary circulation using a parameter identification method. By using this mathematical model and parameter identification method, we were able to measure graft resistance and compliance in vivo.

Methods

Subjects were 95 patients (59 men, 36 women; average age, 66 ± 9 years) who underwent coronary artery bypass grafting between January 2001 and July 2005. The coronary angiography for graft assessment was performed within two months of surgery. In each of 95 patients, we investigated one graft that was anastomosed to the left coronary artery. In coronary artery bypass grafting, extracorporeal circulation was performed on 85 of 95 patients. Off-pump CABG was performed on 10 of 95 patients. A left internal thoracic mammary artery graft was used in 60 patients, a right internal mammary artery graft in 26 patients, and a great saphenous vein graft in 9 patients. When all patients had stable hemodynamics and a spontaneous heartbeat after the peripheral and central anastomoses, we measured graft flow rate, resistance, and compliance.

Radial artery pressure was measured with a pressure transducer (Nihon KOHden Corp., Tokyo, Japan), and at the same time, coronary artery blood flow was measured with an ultrasonic blood flowmeter (Transonic System Inc., New York, USA). Data were entered into the new flow analyze device at a sampling rate of 200 Hz.

Under physiological conditions accompanied by frequency components, a mathematical model of blood pressure, flow rate, compliance, and resistance was prepared according to the method of Taylor et al.\(^3\)

The formula for model preparation is as follows:

\[
\frac{d}{dt} p(t) = -\frac{1}{RC} p(t) + \frac{1}{C} F(t)
\]

Where \(p(t)\) is pressure, \(F(t)\) is flow rate, \(R\) is resistance, and \(C\) is compliance. Here, \(p(t)\) represents arterial pressure (radial artery pressure), flow rate represents bypass flow rate, resistance represents vessel resistance and compliance represents extension of the blood vessel.

Sankai, Kosaka et al. conducted chronic animal studies and measured arterial compliance and resistance by the same parameter identification method used in an online tool.\(^6\) To confirm the sensitivity, specificity and reliability of this device, we calculated estimated flow and pressure by a reverse calculation from the estimated value of resistance and compliance. Comparing the data sets of animals, we found no statistical difference in measured pressure, flow data and estimated flow and pressure, suggesting that the calculation is mathematically correct. Also, the results suggest that estimated resistance and compliance are correct values.

Postoperatively between weeks 4 and 8, bypass grafts were assessed by conventional coronary angiography or Multi slice-CT (Toshiba Corp., Tokyo, Japan). A more than 50% narrowing of the luminal diameter in two projections of bypass grafts was considered a stenosis. A 100% narrowing of the luminal diameter in two projections of bypass grafts was considered to be an obstruction.

Intraoperative coronary arterial flow rate, resistance, compliance, and PI of patients with graft failure: stenosis and obstruction, with were compared to those of patients with a patent graft. The PI was calculated using the following formula.\(^3\)

\[
PI = \frac{\text{Maximum flow rate} - \text{Minimum flow rate}}{\text{Mean flow rate}}
\]

Also, left internal mammary artery, right internal mammary artery, and great saphenous vein grafts were anastomosed to the left anterior descending branch, and among these graft types, coronary artery flow rate, resistance, compliance, and PI were compared. All data are expressed as mean ± SD. Comparisons between the groups with patent and failed grafts were statistically analyzed using the Mann-Whitney U-test, and \(P < 0.05\) was regarded as significant. Flow rate, resistance, compliance and PI among the three graft types were compared by one-way analysis of variance. Relationships among resistance, flow rate and compliance were examined using Spearman’s correlation coefficient (\(P < 0.05\)). All statistical analyses were conducted using StatView ver 5.0 software (SAS Inc., Cary, NC).
Results

Figure 1 shows flow waveforms of a left internal thoracic artery graft anastomosed to the left anterior descending artery, in which favorable patency was confirmed by postoperative angiography. Postoperative angiography showed favorable patency in 90 of 95 bypass grafts to the left coronary artery and graft failure in 5; anastomotic stenosis was evident in 3 failed grafts, and obstruction in 2.

Of 90 patent grafts, 58 were left internal mammary artery, 24, right internal mammary and 8, artery and vein grafts. The mean flow rate, resistance, compliance, and PI are shown in Table 1.

Flow rate, resistance, compliance and PI did not significantly differ among the three groups.

The mean flow rate, resistance, compliance and PI of the 5 graft failures are shown in Table 2. In the statistical

<table>
<thead>
<tr>
<th>Patient Number</th>
<th>Flow (ml/min)</th>
<th>Resistance (mmHg sec/ml)</th>
<th>Compliance (ml/mmHg)</th>
<th>Pulsatility index</th>
<th>Result of angiography</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. LIMA-LAD</td>
<td>2.9</td>
<td>19.6</td>
<td>0</td>
<td>10</td>
<td>obstruction</td>
</tr>
<tr>
<td>2. LIMA-LAD</td>
<td>14.2</td>
<td>4.4</td>
<td>0</td>
<td>1.9</td>
<td>obstruction</td>
</tr>
<tr>
<td>3. RIMA-LAD</td>
<td>1.2</td>
<td>24</td>
<td>0.2</td>
<td>37.6</td>
<td>stenosis</td>
</tr>
<tr>
<td>4. RIMA-LAD</td>
<td>0.92</td>
<td>22.4</td>
<td>0.3</td>
<td>43</td>
<td>stenosis</td>
</tr>
<tr>
<td>5. SVG-LAD</td>
<td>12.2</td>
<td>24.5</td>
<td>0.01</td>
<td>5.1</td>
<td>obstruction</td>
</tr>
<tr>
<td>Mean</td>
<td>6.2 ± 6.3</td>
<td>18.9 ± 8.3</td>
<td>0.1 ± 0.1</td>
<td>19.5 ± 19.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 1  Flow rate resistance compliance and power index of patent grafts

<table>
<thead>
<tr>
<th></th>
<th>Flow (ml/min)</th>
<th>Resistance (mmHg sec/ml)</th>
<th>Compliance (ml/mmHg)</th>
<th>Pulsatility index</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIMA-LAD</td>
<td>26.2 ± 18.8</td>
<td>3.1 ± 3.3</td>
<td>0.2 ± 0.1</td>
<td>3.3 ± 5.6</td>
</tr>
<tr>
<td>RIMA-LAD</td>
<td>26.0 ± 19.2</td>
<td>2.6 ± 2.8</td>
<td>0.2 ± 0.3</td>
<td>2.4 ± 1.3</td>
</tr>
<tr>
<td>SVG-LAD</td>
<td>42.5 ± 22.2</td>
<td>1.6 ± 1.2</td>
<td>0.3 ± 0.3</td>
<td>2.0 ± 0.9</td>
</tr>
<tr>
<td>Mean</td>
<td>27.6 ± 19.5</td>
<td>2.7 ± 0.0</td>
<td>0.2 ± 0.5</td>
<td>4.3 ± 2.9</td>
</tr>
</tbody>
</table>

Fig. 1 Measurements of graft resistance, graft compliance, flow rate and pressure waveforms in vivo.
analysis, the flow rate, resistance, and PI between the failed and patent grafts differed significantly. Although compliance did not significantly differ between the groups, the vascular wall tended to be harder in the group with failed grafts. Resistance correlated with flow rate $-0.64$ ($P < 0.001$) (Fig. 2) and compliance $-0.41$ ($P < 0.001$) (Fig. 3) in the group with patent grafts.

**Comment**

Ultrasonic blood flowmeters such as transit time flow meters are popular, convenient, and noninvasive, and blood flow is commonly assessed during surgery. Graft performance is generally assessed from results of waveform, flow rate, and PI. Appropriate values of PI reported by D’Ancona et al. were $\leq 5$, those of DiGiammarco were $\leq 3$, and those of Leong et al. ranged from 1 to 5. The mean PI values for groups with patent and failed grafts in the present study were $3.3 \pm 4.8$ and $19.5 \pm 19.2$, respectively, suggesting that appropriate PI values were around 3.0 in the present study. While PI is thought to be useful in graft assessment, the formula indicates changes in flow rate per unit flow rate, and as a result, PI strictly indicates pulsation intensity and does not directly reflect...
resistance and compliance, which are the essential determinants of blood flow. The mean flow rate from LIMA to LAD is 37.4 ± 23.5 ml/min according to Leong et al. and 37.4 ± 24.7 ml/min according to DiGiammarco et al.\(^2\) The mean flow rate here was 27.6 ± 19.6 ml/min and as a result, the average bypass graft flow rate to the left coronary artery appeared to be 30–40 ml/min. Walpoth et al. reported that a mean flow rate of ≥20 ml/min was sufficient.\(^2\) However, Takami et al. documented that even if the flow rate were ≤20 ml/min, postoperative angiography could still occasionally confirm favorable patency.\(^10\) Figure 2 shows that even at a mean flow rate of ≤20 ml/min, the postoperative graft had not always failed, thus suggesting that graft performance cannot be assessed based solely on flow rate. Furthermore, statistical correlations were identified between flow rate and resistance, and between resistance and compliance (Figs. 2 and 3). Figure 2 showed the relations that resistance decreased if the flow rate rose.

Figure 3 shows the relations that compliance decreased if resistance rose at the same time. We considered flow rate, resistance and compliance to be related mutually. These results suggest that the bypass graft should be estimated not only by flow rate but also by resistance and compliance. Among the three graft types, flow rate, resistance and compliance did not significantly differ. These results suggest that the three graft types do not physically differ at the acute stage during surgery.

The values of mean resistance for the patent and failed grafts were 2.7 ± 0.0 and 18.9 ± 8.3 mmHg sec/ml. Thus, about 3.0 mmHg sec/ml seemed to be the normal value in the present study. Greater compliance means a softer vessel, and the values of mean compliance for the patent and failed grafts were 0.2 ± 0.5 and 0.1 ± 0.1 ml/mmHg, respectively; the vascular wall tended to be harder in the group with failed grafts. We considered approximately 0.3 ml/mmHg as the normal value in the present study. The values for flow rate, resistance and compliance in patient number 2 with graft failure were 14.2 ml/min, 4.4 mmHg sec/ml and 0.0 ml/mmHg. We supposed that a spasm obstructed this graft, because even with a resistance within the normal range, the value for compliance was very low.

Here, we evaluated bypass grafts using a new device that can calculate vascular resistance and vascular compliance from aortic pressure and the flow rate. This device comprises a mathematical circulatory organ model for the heart and CABG, and it can be used to estimate a bypass because the graft flow rate is determined by multiple factors such as blood pressure, vessel resistance, heart rate and vascular compliance. These factors always change, are related to one another, and make up a single coronary circulation system. The mathematical model can measure not only flow rate during coronary artery bypass grafting, but also blood pressure, vascular resistance peripheral to the bypass graft and bypass graft compliance, thus allowing more accurate assessments of graft performance.

**Conclusion**

Measuring dynamic vascular resistance and compliance in vivo is challenging. However the present results showed that these parameters can be measured as physical values in actual patients. Hence, the new assessment method is apparently useful for evaluating graft performance during CABG.

**Acknowledgement**

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**References**


8) D’Ancona G, Karamanoukian HL, Ricci M, Salerno...
