Novel Device Accurately Measures Graft Resistance and Compliance to Ensure Quality of Coronary Artery Bypass

Kinichi Nakata, MD, PhD;1 Yukihiko Orime, MD, PhD;1 Kenji Akiyama, MD, PhD;1 Hayato Koba;2 Yoshiyuki Sankai, PhD;2 and Motomi Shiono1

1Department of Cardiovascular Surgery, Nihon University School of Medicine, Tokyo, Japan
2Graduate School of Systems and Information Engineering, University of Tsukuba, Tsukuba, Tsukuba, Japan

Introduction: The purpose of this study is to know the influence of coronary artery bypass grafting (CABG) on coronary circulation. In the present study, we evaluated CABG by using a novel flow analyzer that can calculate bypass graft resistance (Ra), resistance of the peripheral bed to which graft connects (Rp), the inertia of blood flow through the graft (L) and vascular wall compliance (C).

Methods: We performed off-pump CABG surgery on fifteen pigs assigned to the following groups (n = 5 each): normal CABG, competitive flow grafts and constrictive grafts.

Results: The wave pattern of 3 groups showed a clearly different form. In normal CABG and competitive flow group, we accepted a statistical difference in Rp and flow. In normal CABG and constrictive grafts. We accepted a statistical difference in Ra and flow.

Conclusion: We can know the relationship between CABG and coronary circulation by this device in detail. This device will be useful for evaluating graft performance during CABG.

Keywords: ischemic heart disease, coronary arterial bypass grafting, off pump CABG

Introduction

We performed this study to know the mutual relation between CABG and coronary circulation.

We developed a new device to ensure high quality CABG. We considered that CABG should be evaluated using not only flow rate but also other factors. This is because the following might be involved in graft failure: 1) physiological graft properties, such as graft diameter, vascular wall thickness, endothelial hyperplasia and spasm; 2) physiological coronary artery properties, such as vessel diameter, degree of stenosis, vascular wall properties, peripheral runoff, graft resistance and compliance; 3) risk factors for coronary artery diseases, such as hyperlipidemia, diabetes and hypertension; 4) surgical skill and 5) medical factors such as antispasmodic and antiplatelet drugs.1) In this manner, bypass graft flow rate is controlled by various factors. We thought that the bypass graft should be estimated not only by flow rate but also by graft resistance and compliance because there will be a relationship between graft resistance and area of myocardial perfusion. However, sometimes there will be a situation where even a low flow rate might be enough. Also, there will be a relationship between graft compliance and wall condition of graft, such as spasm. For these reasons, we developed a new flow analysis device, which can estimate the bypass graft not only the flow rate but also the resistance and the compliance, the inertia (L) of blood flow through the graft.

Our novel device can be used to calculate bypass graft resistance (Ra), resistance of the peripheral bed to which
the graft is connected (Rp), the inertia of blood flow through the graft (L) and vascular wall compliance (C).²,³)

We performed off pump CABG surgery on 15 pigs, placed into 1 of 3 groups 1) normal CABG 2) grafting under competitive flow 3) stricture in an anastomotic region.

### Methods

Fifteen pigs underwent off-pump CABG surgery under the following conditions: standard CABG, competitive flow and anastomotic stricture. Two occluders were attached at the bypass graft and at the proximal part of the LAD to generate the different conditions. We measured bypass graft flow rate (LITA) and the left descending artery (LAD) segment at the proximal part of the LAD using flowmeters (Transonic System Inc., Ithaca, NY, USA) placed on the tip side of the occluders (Fig. 1). We inserted two catheters into the ascending aorta and left ventricle from the femoral artery to measure pressure using a pressure transducer (DT-XX; Becton Dickinson , USA).

The new devise was composed from a mathematical model that represents the characteristics of vascular dynamics. Here, Ra, Rp, and C, parameters in the model, were estimated using the least squares method applied to measured blood pressure and flow rate. This mathematical model was prepared according to the Navier–Stokes equations. The formula for model preparation is as follows:

\[
- \frac{1}{\rho} \frac{\partial}{\partial z} \rho V_z + \frac{\partial}{\partial r} V_r + \frac{\partial}{\partial z} V_z + V_z \frac{\partial}{\partial z} V_z - \nu \left( \frac{\partial^2 V_z}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} V_z + \frac{\partial^2 V_z}{\partial z^2} V_z \right)
\]

- \( V_z \) : Velocity of Axial element
- \( V_r \) : Velocity of Radial element
- \( t \) : Time
- \( p \) : Pressure
- \( \rho \) : Density of Blood
- \( \nu \) : Coefficient of Dynamic Viscosity

We initially measured these parameters under normal CABG conditions as standard values and then compared the values among all three groups. Relationships among Ra, Rp, L and C 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).
1) Standard CABG

The occluder around the LAD was tightened to cause approximately 75% stenosis at the proximal part of the LAD. The flow wave pattern is shown in Fig. 2.

In clinically a more than 75% narrowing of the luminal diameter in two projections of bypass grafts is considered to be stenosis, in standard angiography. However in this study, the level of stenosis was determined by using a flowmeter. The flow rate at the proximal part of the LAD decreased from 61.3 ± 7.3 to 22.2 ± 8.7 ml/min, by using an occluder.

2) Competitive flow

The absence of a stenotic lesion in the LAD resulted in competitive flow. Backflow occurred in the bypass graft. The flow wave pattern is shown in Fig. 3.

3) Stricture in an anastomotic region

The flow wave pattern is shown in Fig. 4.

The occluder around the LAD was tightened to cause approximately 75% stenosis at and an anastomotic region was constricted to 80% using the occluder. We decide the stricture in comparison with flow quantity before tying it up.

Before surgical procedures, we measured the flow rate at the proximal part of the LAD, resistance of the LAD, inertia (L) of blood flow through the LAD, and compliance (C) of the LAD vascular wall.

Results

1) Standard CABG

The flow rate measured at the proximal part of the LAD decreased from 61.3 ± 7.3 to 22.2 ± 8.7 ml/min; Ra decreased from 1.4 ± 0.3 to 1.1±0.6 mmHg·s /ml; C increased from 0.7 ± 0.7 to 0.7 to 1.7 ± 1.4 ml/mmHg; L increased from 0.1 ± 0.2 to 0.9 ± 0.3 mmHg·s·s/ml; and Rp decreased from 1.6 ± 0.4 to 0.8 ± 0.4 mmHg·s /ml. The bypass graft flow rate was 37.2 ± 13.6 ml/min after standard CABG.

2) Competitive flow

The flow rate of the bypass graft decreased from 37.2 ± 13.6 to 9.8 ± 13.6 ml/min; Ra increased from 1.1 ± 0.62 to 1.8 ± 2.5 mmHg·s /ml; and C decreased from 1.7 ± 1.4 to 0.3 ± 0.6 ml/mmHg. The L increased from 0.9 ± 0.3 to 1.9 ± 1.9 mmHg·s·s/ml under conditions of competitive flow. Inertia of blood flow through the graft reflects the
Fig. 3  Flow wave of competitive flow graft (Seg. #6, 0%; LITA, 0%).
LITA: left internal thoracic artery.

Fig. 4  Flow wave of constrictive graft (Seg. #6, 75%; LITA, 75%).
LITA: left internal thoracic artery.
indicate flow, Ra, Rp, C and L.

Bypass flow rate and Rp significantly differed (p <0.05).

3) Constricted anastomotic region
The bypass graft flow rate decreased from 37.2 ± 13.6 to 9.8 ml/min; Ra increased from 1.1 ± 0.6 to 4.6 ± 0.41 mmHg·s /ml; C increased from 1.7 ± 1.4 to 0.8 ± 0.9 ml/mmHg; L increased from 0.9 ± 0.3 to 2.1 ± 1.9 mmHg·s/ml; and Rp increased from 0.8 ± 0.4 to 1.8 ± 2.4 mmHg·s /ml.

Flow rate and Ra significantly differed (p <0.05).

The schema, shown in Figure 5, that composed from indicate flow, Ra, Rp, C and L.

Discussion
Flow rate and waveforms have been quickly, conveniently and noninvasively evaluated using ultrasonic blood flowmetry, which has proven useful in preventing graft failure during and after surgery.

Current blood flowmeters are used to measure mean blood flow, pulsatility index (PI) and diastolic filling index, which indicates the ratio of blood flow rates during the diastolic phase. PI was calculated using the following formula.

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. Similarly DFI does not show resistance, compliance.

Again, the direct cause of the bypass law flow rate in PI and diastolic-phase filling index cannot be determined using this technology. Moreover, PI and the diastolic-phase filling index cannot be measured under extracorporeal circulation with low pulse pressure. The PI strictly indicates pulsation intensity and does not directly reflect either resistance or compliance. Here, we applied a novel device that can calculate blood flow and determine the condition of blood vessels.

1) Standard CABG
We reproduced a typical off-pump CABG with approximately 75% stricture at the proximal part of the LAD generated using an occluder and the LITA anastomosed at #7. The flow rate measured at the proximal part of the LAD was decreased from 61.3 ± 7.3 to 22.2 ± 8.7 ml/min.

The bypass flow rate was 37.2 ± 13.6 ml/min, which we considered acceptable, considering that the pigs weighed about 45.5 kg and that the mean flow rate was ≥20 ml/min, which was sufficient [2]. The flow rate measured at the proximal part of the LAD decreased from 61.3 ± 7.3 to 22.2 ± 8.7 ml/min.

We performed CABG to the 75% constricted site at the segment of the proximal part of the LAD. We judged that the model accurately reflected the conditions of CABG.

2) Competitive flow
One cause of insufficient flow rate is competitive flow, which comprises a pre-systolic phase and low or back flow during the diastolic phase. We removed the LITA and coronary stricture to generate competitive flow. Among the measured parameters, Rp significantly increased from 0.8 ± 0.4 to 11.4 ± 15.6 mmHg·s /ml, Ra increased from 1.1 ± 0.62 to 1.8 ± 2.5 mmHg·s /ml, and L increased from 0.9 ± 0.3 to 1.9 ± 1.9 mmHg·s·s/ml. L is the inertia of blood flow through the graft and it reflects the ease of flow. A high value reflects flow difficulties. C, which reflects vascular wall compliance, decreased from 1.7 ± 1.4 to 0.3 ± 0.6 ml/mmHg. This finding indicates that the vascular wall changes hardly. We thought that back flow from the LAD to LITA caused increased tension in the blood vessels and if so, it would explain why L increased and C decreased. Since there is no stenosis and blood streams easily down coronary arteries from the bypass graft, and the graft has the measurement part of the flowmeter, we think that Rp will rise.

In human CABG, high Rp will be considered peripheral bed disease because Rp was resistance of the peripheral bed to which the graft was connected.

3) Stricture in an anastomotic region
The bypass graft flow rate decreased from 37.2 ± 12.5 to 15.7 ± 4.5ml/min; Ra increased from 1.1 ± 0.6 to 15.7 ± 60.3 mmHg·s /ml; and C decreased from 1.7 ± 1.4 to 2.2 ± 60.3 ml/mmHg. L increased from 0.9 ± 0.3 to 1.7 ± 3.4 mmHg·s·s/ml and Rp increased from 0.8 ± 0.4 to 47.7 ± 47.2 mmHg·s /ml. Because blood was pervasive in a graft as for the vascular wall, the vascular wall was tense, and C decreased Therefore, C decreased and L increased. Flow rate and Ra significantly differed (p <0.05).

We think that various factors cooperate to determine blood flow. We calculated flow rate, Rp, Ra, C and L, but we also considered that the measuring of only one parameter might be sufficient during surgery, in the interests of time and feasibility. We made a schema comprised of 5 parameters. A five-cornered top becomes the Ra in a
constrictive graft. A five-cornered top becomes Ra in a constrictive graft A top becomes Rp in competitive flow. A top becomes the flow quantity in normal CABG, immediately (Fig. 5).

**Conclusion**

This novel device can intraoperatively calculate five parameters: resistance (Ra), resistance of the peripheral bed to which graft connects (Rp), the inertia of blood flow through the graft (L) and vascular wall compliance (C). We think that the surgeon can know the state of the graft from these parameters; immediately By doing so, this device will help to increase the quality of CABG and thus improve patient outcomes.

**References**