Transit-Time Flow Measurement is Essential in Coronary Artery Bypass Grafting

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Background. Patent bypass grafts are fundamental to successful coronary artery bypass grafting. Intraoperative flow measurement through newly constructed grafts is a test of patency. We studied the use of transit-time flow measurement to determine its ability to detect technical errors in grafts, to measure the mean flow norms for Asian patients, and to compare arterial and vein grafts.

Methods. From January 1, 2001, to June 30, 2002, 116 patients underwent isolated primary coronary artery bypass grafting. Sixty-seven patients underwent conventional coronary artery bypass grafting and 49 patients underwent off-pump coronary artery bypass grafting. There were 125 arterial and 197 vein grafts. Transit-time flow measurement was carried out on all completed grafts. Graft patency was assessed using flow curves, mean flow, and pulsatility index. Average of mean flows was calculated to determine mean flow norms. Arterial and vein grafts were compared by statistical analysis between the variables mean flow and pulsatility index.

Results. In 6 patients with seven grafts, intraoperative graft assessment detected technical errors, which were corrected. Average mean flow was 37.4 ± 23.5 mL/min for left anterior descending coronary artery–to–left internal mammary artery grafts, and values ranging from 21.2 to 36.0 mL/min for the rest. There were no statistically significant differences in mean flow or pulsatility index between arterial and vein grafts.

Conclusions. Transit-time flow measurement enables technical problems to be diagnosed accurately, allowing prompt revision of grafts. It should be mandatory in coronary artery bypass grafting to improve surgical outcomes.

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Early graft failure may occur after coronary artery bypass grafting (CABG). It is a complication that can lead to refractory angina, myocardial infarction, arrhythmias, and even mortality. Although most surgeons believe that it is a rare occurrence, studies using intraoperative and early postoperative coronary angiography to assess graft patency have demonstrated significant variations in patency and an incidence of early graft failure of approximately 5% for internal mammary artery (IMA) grafts and 11% for vein grafts [1–7]. These findings strongly suggest the need for intraoperative assessment of bypass grafts that will allow early detection and correction of technical problems.

Transit-time flow measurement (TTFM) is a recently revived technology that allows quick and easy assessment of graft flow. We studied the use of TTFM in 116 consecutive patients undergoing primary isolated CABG to determine the ability of TTFM to detect technical errors in coronary artery anastomoses, the incidence of this problem, the mean flow norms for various coronary artery anastomoses in Asian patients, and whether native coronary runoff can be used as a predicator of intraoperative mean flow in coronary artery anastomoses.

Patients and Methods

From January 1, 2001, to June 30, 2002, 116 patients underwent primary isolated CABG within a single surgical service. Sixty-seven patients (58%) underwent conventional CABG, and 49 (42%) underwent off-pump CABG. There were 84 men and 32 women, of which there were 17 Malays, 11 Indians, 85 Chinese, and 3 Eurasians. Mean age was 60.7 ± 9.5 years, and mean body surface area was 1.69 ± 0.18 m^2. There were 125 IMA grafts and 197 saphenous vein grafts (SVGs). The mean number of grafts was 2.9 per patient. As the patients are disconnected from cardiopulmonary bypass, we use inotropic agents to maintain the systolic pressure at 100 to 120 mm Hg when measuring blood flow using the transit-time flowmeter (multichannel Medi-Stim Butterfly Flowmeter Doppler transit-time flow measurement system; Medi-Stim ASA, Oslo, Norway).

Measurements were taken in the proximal portions for SVGs and in the middle portions for IMA grafts. The measurements were taken after all grafts were completed, after reversal of heparin, and before closure of the chest. The 3-mm probe was most commonly used. The 4-mm probe was only used for large-caliber vein grafts.

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Abbreviations and Acronyms

CABG	= coronary artery bypass grafting
IMA	= internal mammary artery
LAD	= left anterior descending coronary artery
LIMA	= left internal mammary artery
OM	= obtuse marginal branch
PI	= pulsatility index
SVG	= saphenous vein graft
TTFM	= transit-time flow measurement

Target vessel name; type of graft; flow rate in milliliters per minute for maximum flow, minimum flow, and mean flow; and flow curves were recorded. Pulsatility index (PI) was calculated according to the following formula:

$$PI = \frac{(\text{max flow} - \text{min flow})}{\text{mean flow}}$$

and recorded.

The patency of the grafts was assessed using three variables: diastolic flow curve, mean flow, and PI. For a patent graft, the flow curve will show a small backflow during early systole and a predominantly forward flow during diastole [8]. Mean flow should be cautiously interpreted, as its value is not necessarily a good indicator of the quality of the anastomosis. Mean flow is largely dependent on the quality of the native coronary artery, and low mean flow can be expected in fully patent anastomoses whenever the target territory has a poor runoff [9]. We considered mean flows of less than 15 mL/min to be questionable. The PI is a good indicator of the flow pattern and, consequently, of the quality of the anastomosis. This number is obtained by dividing the difference between the maximum and minimum flows by the value of the mean flow. The PI value should ideally be between 1 and 5. The possibility of a technical error in the anastomosis increases for higher PI values [10].

Also, the average of the mean flow was calculated for all types of grafts. This was to determine mean flow norms for various coronary artery conduits for Asian patients. The sample sizes were 40 diagonal 1–SVG grafts, 53 obtuse marginal branch (OM)-SVG grafts, 32 right coronary artery–SVG grafts, 72 right posterior descending coronary artery–SVG grafts, 14 right posterior lateral–SVG grafts, 9 OM-IMA grafts, and 100 left anterior descending coronary artery (LAD)–left IMA (LIMA) grafts.

In addition, IMA grafts and SVGs to the OM and the LAD were compared. Statistical analysis was performed using the Student's t test analysis between the variables mean blood flow and PI. A p value of less than 0.05 was defined as statistically significant.

Results

Of the 116 patients, 6 patients had seven grafts in which a high PI, low mean flow, unsatisfactory flow curve, or all of them were detected using the transit-time flowmeter. Problems included IMA that was occluded or stretched, or SVGs that were kinked, twisted, or stenosed at anastomotic sites. In all cases the problems were corrected at the time of surgery, resulting in satisfactory flows. When an unsatisfactory flow was observed in the vein graft, the graft was carefully inspected for the lie and to check whether there was kinking. If no obvious cause was found then a small venotomy was performed approximately 1 cm from the anastomosis, and a small 1-mm probe was used to probe the anastomosis. In one graft it was obvious that the anastomosis was not patent, and the anastomosis was taken down and revised using interrupted 7-0 polypropylene (Prolene; Ethicon, Somerville, NJ) sutures. In 4 patients the grafts were patent but appeared kinked in 3 and twisted in 1. The grafts were transected and shortened in the case of the graft that was too long, and placed in the correct orientation in the one that was twisted. In the other 2 patients with IMA flows that were unsatisfactory, the right IMA-LAD graft was too short in 1 patient, and the proximal IMA was transected and then anastomosed to the LIMA-OM graft as an end-to-side anastomosis. In the other patient, the LIMA anastomosis was taken down and reconstructed using interrupted sutures. No electrocardiographic changes were noted in those patients in whom unsatisfactory graft flow was noticed and the anastomosis had to be corrected. In another patient, there was difficulty in weaning off cardiopulmonary bypass. Flowmeter measurement showed that all grafts were patent with good flow. The assumption was that the difficulty in weaning could be caused bu myocardial stunning. After a short additional period of cardiopulmonary bypass, the patient was weaned from cardiopulmonary bypass without problem. So TTFM is also useful in situations of low cardiac output in which knowing the patency of the graft will influence further management.

Table 1 shows mean flows and PI before and after correction. In the grafts that were revised, the mean graft flow increased significantly after correction from 5.4 ± 3.7 mL/min to 26.4 ± 8.2 mL/min ($p < 0.05$). The PI decreased significantly after correction from 11.3 ± 5.9 to 3.1 ± 1.3 ($p < 0.05$).

Table 2 shows the mean flows of various grafts for our patients. The average LAD-IMA mean flow for the patients operated on with conventional CABG was 35.0 ± 24.4 mL/min, whereas that for patients operated on with off-pump CABG was 39.6 ± 21.9 mL/min. However, the difference between the two average mean flows did not reach a level of statistical significance. The average LAD-IMA mean flow for male patients was 34.2 ± 19.7 mL/min and that for female patients was 43.6 ± 30.8 mL/min. The difference between these two average mean flows also did not reach a level of statistical significance.

The average mean flow of OM-IMA grafts is 32.2 ± 21.2 mL/min and that for OM-SVG grafts is 21.2 ± 6.0 mL/min. The average PI of OM-IMA grafts is 3.2 ± 2.1 and that for OM-SVG grafts is 2.4 ± 1.0.

The average mean flow of LAD-IMA grafts is 37.4 ± 23.5 mL/min and that for LAD-SVG grafts is 35.5 ± 19.9

Table 1. Flow and Pulsatility Index

Cause of Obstruction	Flow Before Correction (mL/min)	Flow After Correction (mL/min)	PI Before Correction	PI After Correction
IMA occluded	5	18	5.6	1.7
Vein graft kinked	4	21	7.9	4.7
Vein graft occluded	0	18	23	2.8
Vein graft kinked	2	30	14	3.9
Vein graft rotated	8	34	8.7	4.1
Vein graft kinked	9	25	7.8	3.5
IMA stretched	10	39	12	1.2

IMA = internal mammary artery; PI = pulsatility index.

mL/min. The average PI of LAD-IMA grafts is 2.5 ± 1.0 and that for LAD-SVG grafts is 3.7 ± 4.3.

Comment

Transit-time flow measurement gives important and accurate intraoperative information about the status and patency of each individual graft. It enables technical problems such as kinked, twisted, or stenotic grafts to be diagnosed accurately, thereby allowing prompt revision of the constructed grafts before the patient leaves the operating room. Thus, hemodynamic instability during the early postoperative period is possibly prevented and the probability of early graft failure is minimized significantly, improving the outcome of CABG and off-pump CABG surgery. Internal mammary grafts compared with SVGs do not show significant differences early after operation in mean blood flow or PI. This is consistent with the literature [11]. Further studies are needed to evaluate long-term performance of the grafts. However, it has already been proven that the rate of restenosis in SVGs is much higher than that in IMA grafts [11, 12].

Knowledge of graft patency through the use of TTFM is important because early graft failure owing to technical problems, which are potentially correctible, can be catastrophic. Current techniques of graft testing with syringes, fingertips, and direct probing of the anastomoses are insufficient to monitor flow in bypass grafts and detect technical errors [13].

Table 2. Patient Flows Versus Flows From Literature

N	Grafts	Mean Flow of Patients (mL/min)	Mean Flows Reported in Literature (mL/min)
40	D1-SVG	22.6 ± 11.0	
53	OM-SVG	32.2 ± 21.1	
32	RCA-SVG	32.2 ± 20.8	66.0 ± 5.0 [24]
72	RPDA-SVG	36.0 ± 27.4	
14	RPL-SVG	26.2 ± 13.6	
			44.0 ± 25.4 [23]
103	LAD-LIMA	37.4 ± 23.5	69.9 ± 2.5 [24]

D1 = diagonal 1; LAD = left anterior descending coronary artery; LIMA = left internal mammary artery; OM = obtuse marginal; RCA = right coronary artery; RPDA = right posterior descending artery; RPL = right posterior lateral; SVG = saphenous vein graft.

Many surgeons argue against the use of TTFM, saying that TTFM is difficult to use and is time-consuming. However, the TTFM device is very easy to use and requires no more than 30 seconds per measurement. Many surgeons also believe that TTFM is unnecessary, arguing that incidences of surgical mistakes are extremely low. Today, the modern techniques of exposure and stabilization of the different coronary artery branches in off-pump CABG provide very stable conditions and excellent surgical exposure comparable to cases using conventional CABG with cardiopulmonary bypass. In spite of this, surgical mistakes are still possible. However, it is true that TTFM is less important in off-pump procedures because in on-pump procedures, the chance of anastomotic mistakes is very low.

A limitation of TTFM is the lack of standard curves and flow values for different types of grafts and revascularized vessels. Standardization of TTFM findings is difficult because of large biologic variability among different patients, as well as within the same patient. Interpretation of flow curves and TTFM findings is largely dependent on the surgeon's personal experience. The ability to correctly interpret TTFM findings develops with clinical and experimental experience and, thus, surgeons who have not been exposed to TTFM technology cannot easily accord it the proper level of importance. Another limitation of TTFM is the high cost of the equipment. Many surgeons' and hospitals' hesitation in adopting TTFM technology mainly stems from this factor. However, we believe that as the push toward better patient care becomes increasingly important, the use of TTFM during CABG will become imperative.

In this study, we also determined the mean flows for our predominantly Asian patient population, as many studies of mean flows in whites are not applicable to Asians. However, there are some limitations in this present study, as the number of some grafts such as right posterior lateral–SVG and OM-IMA was too small to produce a representative mean flow for the general Asian population. We also did not divide our patients into the various ethnic groups. For all these reasons, further investigations are needed. In conclusion, we believe that there is sufficient evidence to suggest that TTFM should be mandatory and adopted routinely in all CABG and off-pump CABG procedures to improve patient care and surgical results.

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INVITED COMMENTARY

Transit-time flow measurement (TTFM), a new quantitative volume-flow Doppler technique, has been used for the last 10 years in clinical revascularization procedures. In vitro and in vivo validation studies have described good accuracy and high precision for clinical use [1]. TTFM enables the surgeon to obtain immediate quality control of bypass surgery. The technique is simple and rapid to use, and is certainly less costly and cumbersome than other methods such as intraoperative coronary angiography. In addition, TTFM allows the measurement of the quantity of blood passing through a newly grafted vessel to the myocardium at risk. Data obtained from flow measurements are dependent on several factors that all interact, such as cardiac output, arterial pressure, peripheral vascular resistance, residual antegrade coronary artery flow, size of the myocardium at risk, microvascular tonus, type of grafts used, length and diameter of grafts, hematocrit, and temperature, just to name a few. Thus, normal values may vary considerably. In my view, the most important result for the surgeon, and consequently for the patient, is a mean basal flow value above a certain limit, ie, 20 mL per minute with a diastolic filling pattern and a pulsatility index below 5. All the modern measuring devices calculate automatically these measurements online. A major dilemma arises when graft flow is below 10 mL per minute, with an elevated pulsatility index and a predominant systolic flow pattern. This suggests technical failure at the distal anastomosis. In

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