

A comparison of transit-time flowmetry and intraoperative fluorescence imaging for assessing coronary artery bypass graft patency

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Background: Intraoperative graft patency assessment during coronary artery bypass grafting enables detection and immediate correction of graft failure. Currently transit-time flowmetry is used to assess graft patency on the basis of mean graft flow and derived values, such as the pulsatility index. Intraoperative fluorescence imaging, based on the fluorescence of indocyanine green dye, provides direct visual images to confirm graft patency.

Methods: We performed a prospective observational study to assess intraoperative graft patency in patients undergoing coronary artery bypass grafting, by using an intraoperative fluorescence imaging system (SPY) and transit-time flowmetry (BF 2004). Poor flow with the intraoperative fluorescence imaging system was defined if there was an absence of fluorescence or if it did not appear within 15 seconds in the graft. A persistent mean graft flow value less than 5 mL/min and a pulsatility index greater than 5 with transit-time flowmetry were considered unacceptable and prompted graft revision.

Results: We assessed the intraoperative patency of 266 grafts in 100 coronary artery bypass grafting patients. Intraoperative fluorescence imaging and transit-time flowmetry confirmed adequate flow in 241 (91%) grafts in 75 patients (75%). Transient poor flow was detected with both intraoperative fluorescence imaging and transit-time flowmetry in 7 (2.6%) grafts in 7 (7%) patients. This subsequently proved to be adequate on repeat testing and hence did not necessitate graft revision. Both intraoperative fluorescence imaging and transit-time flowmetry confirmed persistent poor flow in 8 (3%) grafts in 8 (8%) patients that necessitated graft revision. However, in a further 10 (3.8%) grafts in 10 (10%) patients, transit-time flowmetry indicated persistently poor flows on the basis of mean graft flow and pulsatility index values, whereas the intraoperative fluorescence imaging system demonstrated satisfactory flow. These grafts were not revised.

Conclusions: In most patients, both intraoperative fluorescence imaging and transit-time flowmetry are useful to confirm intraoperative graft patency. However, in a small proportion of patients (10%), graft patency assessment with transit-time flowmetry alone might prompt unnecessary graft revision.

Intraoperative graft failure is a potentially avoidable major cause of cardiac morbidity and mortality and occurs in up to 3% of grafts (8% of patients) after coronary artery bypass grafting (CABG).¹ It is the most common cause of perioperative myocardial infarction and occurs in up to 9% of patients before hospital discharge.² CABG ideally mandates the use of objective technology to evaluate graft patency. In addition, the increase in the use of arterial grafts³ and off-pump CABG (OPCABG)⁴ has further emphasized the need to confirm intraoperative graft patency.

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The most common method of intraoperative CABG patency assessment is based on flow measurements obtained with transit-time flowmetry (TTFM). TTFM provides a mean graft flow (MGF), a flow waveform, and derived values such as the pulsatility index (PI). Although higher MGF values (>40 mL/min) with a predominant diastolic profile are easy to interpret as adequate graft patency, in situations with low MGF, graft patency interpretation depends on derived values, which can introduce uncertainty. This allows the potential for erroneous interpretation of graft failure. D'Ancona and colleagues¹ reported the necessity to revise 3% of grafts on the basis of TTFM and emphasized the crucial feature of flow value interpretation as an index of graft patency.

We recently described the use of an intraoperative fluorescence imaging (IFI) system (SPY; Novadaq Technologies Inc, Mississauga, Ontario, Canada), which provides direct visual images to assess graft patency.⁵ Using this system, we prospectively studied 200 patients undergoing mainly off-pump total arterial grafting and demonstrated a natural graft failure incidence of 1.5% (8/533 grafts). This occurred in 4% (8/200) of patients and prompted revision.⁶ We have now used the information simultaneously provided by IFI and TTFM to assess graft patency in patients undergoing CABG with the same strategy.

Materials and Methods

Study Approval

This study was approved by the Oxfordshire research ethics committee, and informed consent was obtained from all patients included in the study.

Patients

All patients undergoing CABG performed by a single surgeon (D.P.T.) between April 2003 and January 2004 were included in the study unless, for technical reasons, the equipment was not available. Intraoperative graft patency data were prospectively recorded in 100 patients, simultaneously using an IFI system (SPY) and TTFM (BF 2004; Medistim AS, Oslo, Norway) after construction of the grafts and before chest closure.

Surgical Technique

All patients underwent CABG via a median sternotomy. Both internal thoracic arteries (ITAs) were harvested as skeletonized conduits. The skeletonized ITA was bathed in a swab containing topical papaverine. The radial artery was harvested and stored in heparinized blood containing phenoxybenzamine in the earlier patients⁷ and additional verapamil in the later patients before the anastomosis was performed. The long saphenous vein was harvested with a minimally invasive technique.

Our strategy for construction of anastomoses and the surgical technique for performing OPCABG and on-pump CABG (ONCABG) have been previously described.⁶ Some of the later patients in the ONCABG group with poor ventricular function had

CABG with cardiopulmonary bypass, but on a beating heart without the use of the aortic crossclamp to avoid any ischemic period.

Data Collection

Intraoperative fluorescence imaging. IFI is a technique based on the fluorescence of indocyanine green (ICG). We have described this technique previously.⁵ In brief, ICG rapidly binds to plasma proteins when injected intravenously and fluoresces (emits light at 830 nm) when illuminated with a monochromatic laser light source at 806 nm. The fluorescence is captured on a charge-coupled device video camera. The low-intensity laser, with a total output of 2.7 W and a 1-mm depth of penetration over an area of 7.5×7.5 cm, at a distance of 30 cm above the heart, has an excellent safety profile for both the patient and the operating room staff. The system has CE approval in Europe; this allows patient use in the European community. ICG has an excellent safety profile, with a reported 1:40,000 incidence of allergic reaction, especially in patients allergic to iodine.⁸ The risk is strongly dose dependent and is greatest with doses more than 0.5 mg/kg body weight.

The sterile draped camera head, guided by a range-detector diode, was positioned at 30 cm above the heart. On completion of the distal coronary anastomosis, 1 mL (0.03 mg/kg) of ICG dye was injected into the oxygenator in ONCABG or was injected through the central venous line and flushed through with 10 mL of normal saline in OPCABG. Screening was started at the time of injection, and the grafts were imaged as the fluorescent dye passed through them. Images were then recorded on the computer hard drive. The procedure took approximately 3 minutes per graft. Skeletonized conduits provided better visualization than pedicled ones. The appearance of fluorescent images as the dye passed through the bypass grafts confirmed graft patency.

Transit-time flowmetry. The technique for use of TTFM has been described by D'Ancona and colleagues.¹ In brief, the TTFM QuickFit flow probes (Medistim AS, Norway) were sterilized with Tristel sterilizing solution (The Tristel Company, Snailwell, United Kingdom) and prepared for intraoperative use. Patient data were entered into the transit-time flowmeter (BF 2004), and the integrated chart recorder on the monitor displayed the flow waveform and its analysis and simultaneously recorded the electrocardiogram and systemic arterial pressure. The ultrasound couplant (gel) was applied to the flow probe lumen before it was positioned on the graft such that the graft occupied at least 75% of the flow probe lumen. TTFM provides a flow waveform profile and MGF values. MGF values more than 40 mL/min indicate satisfactory flow, and values less than 5 mL/min are considered unsatisfactory and prompt revision.⁹ Certain derived values, such as PI and diastolic flow index, are also displayed. PI is an absolute number (defined as the difference between maximum and minimum flow divided by the mean flow) that indicates the resistance to graft flow, and a value more than 5 is considered unsatisfactory.¹⁰ A diastolic flow index value more than 50% indicates a predominantly diastolic graft flow profile and is recognized as normal, akin to native coronary artery blood flow.¹¹

Definition of Graft Flow

The graft flow was assessed on the basis of simultaneous IFI images and TTFM flow values recorded with the heart in the same

TABLE 1. Configuration of conduits used to perform distal anastomosis in all patients (266 grafts)

Variable	LAD	OM	PDA	RCA	IM	D1	LVBR
LITA (n = 98)	44	48	—	—	3	3	—
RITA (n = 50)	49	—	—	—	—	1	—
RA (n = 48)	2	7	20	3	6	10	—
SVG (n = 70)	4	21	24	11	1	7	2

LITA, Left internal thoracic artery; RITA, right internal thoracic artery; RA, radial artery; SVG, saphenous vein graft; LAD, left anterior descending coronary artery; OM, obtuse marginal coronary artery; PDA, posterior descending branch of the right coronary artery; RCA, right coronary artery; IM, intermediate artery; D1, first diagonal branch of the left anterior descending coronary artery; LVBR, left ventricular branch of the right coronary artery.

position and with the same mean arterial blood pressure (MAP). Using IFI as the gold standard, we defined flow on the basis of IFI and TTFM as good or poor.

For IFI, good flow was defined as the appearance of fluorescence in the graft within 15 seconds, and poor flow was defined if there was an absence of fluorescence or if it did not appear within 15 seconds. For TTFM, good flow was defined as an MGF value greater than 5 mL/min with a PI value less than 5, and poor flow was defined as an MGF less than 5 mL/min or a PI value greater than 5.

On the basis of IFI and TTFM, we differentiated 4 categories (Table 1):

1. Category GG: good flow with IFI and good flow with TTFM
2. Category GP: good flow with IFI but poor flow with TTFM
3. Category PG: poor flow with IFI but good flow with TTFM
4. Category PP: poor flow with IFI and poor flow with TTFM

In cases in which poor flow values were initially documented with either IFI or TTFM, graft flow was subsequently reassessed after MAP increased to 80 mm Hg or more and 10 to 20 minutes later while other grafts were completed. We revised grafts for which there was persistent poor flow with both techniques (PPp) despite adequate systemic MAP and did not revise those for which flow had improved. This latter category was defined therefore as transient poor flow (PPt).

Statistical Analysis

Results for categorical variables are expressed as number (percentage of total). Continuous variables are presented as mean \pm SD. The χ^2 test was used for comparison of categorical variables. The continuous variables were compared by using the Student *t* test. Nonparametric data were compared by using the Mann-Whitney *U* test.

Results

We obtained intraoperative graft flow values and images in 266 grafts performed in 100 patients. The mean number of distal anastomoses was 2.7 per patient. Of these patients, 80 (80%) underwent OPCABG, and 20 (20%) underwent ONCABG. The ONCABG group included 3 patients with simultaneous aortic valve replacement.

TABLE 2. Categories based on graft patency assessment in 266 grafts (100 patients) with intraoperative fluorescence imaging (IFI) and transit-time flowmetry (TTFM)

Flow variable	Good TTFM flow	Poor TTFM flow
Good IFI flow	GG	GP
No. grafts	241 (91%)	10 (3.8%)
No. patients	75 (75%)	10 (10%)
Poor IFI flow	PG	PPt
No. grafts	0	7 (2.6%)
No. patients		7 (7%)
		PPp
No. grafts		8 (3%)
No. patients		8 (8%)

GG, Good flow with IFI and good flow with TTFM; GP, good flow with IFI but poor flow with TTFM; PG, poor flow with IFI but good flow with TTFM; PPt, grafts with initial poor flow with IFI and TTFM that were subsequently adequate; PPp, Grafts with persistent poor flow with both IFI and TTFM that were revised.

In patients with triple-vessel disease, the mean number of grafts for the OPCABG and ONCABG groups was similar (OPCABG, 3.2 ± 0.4 ; ONCABG, 3.4 ± 0.6). Overall, 57 (57%) patients had total arterial grafting; of these, composite arterial grafting was performed in 33 (33%) patients. Excluding those with single-vessel disease, bilateral ITA conduits were used in 49 (49%) patients. The configuration of conduits used to perform distal coronary anastomoses is detailed in Table 1.

On the basis of information obtained from the IFI and TTFM techniques, we assessed intraoperative graft patency in 266 grafts and identified 4 categories based on graft patency interpretation (Table 2). Good flow with both IFI and TTFM (category GG) was seen in 241 (91%) grafts in 75 (75%) patients. In 10 (3.8%) grafts in 10 (10%) patients, good flow was confirmed by IFI, but persistent poor flow values were recorded with TTFM (category GP), and these grafts were not revised (Table 3). No grafts demonstrated poor IFI flow but good TTFM flow (category PG).

Poor flow with both IFI and TTFM (category PP) was initially observed in 15 (5.6%) grafts in 15 (15%) patients and was subsequently subclassified as transient (category PPt) or persistent (category PPp). Of the 15 grafts initially classified as PP, 7 (2.6%) grafts in 7 (7%) patients subsequently demonstrated good flow with IFI and TTFM and were therefore classified as PPt and did not undergo graft revision (Table 4). In these cases, the MGF increased significantly, from the initial measurement of 4.1 ± 4.3 mL/min to 16.3 ± 10.3 mL/min ($P = .02$), and this was accompanied by a significant decrease in PI from 9.6 ± 3.7 to 3.1 ± 0.9 ($P = .001$).

However, of the 15 grafts initially classified as PP, persistent poor flow on repeat assessment was seen with both IFI and TTFM in 8 (3%) grafts in 8 (8%) patients, thus

TABLE 3. Details of cases that demonstrated good flow with intraoperative fluorescence imaging (IFI) but poor flow with transit-time flowmetry (TTFM) and that were not revised

Patient no.	Age (y)	Sex	No. diseased vessels	Suspected graft	Good flow seen on IFI	TTFM	
						MGF (mL/min)	PI
1	73	F	2	LITA-OM	Yes	3	8.2
2	58	M	3	LITA-OM	Yes	5	2.4
3	49	M	3	RA-PDA (proximal-end RA to LITA-OM)	Yes	3	5.4
4	62	M	3	Recycled LITA-D1 (proximally to LITA-LAD)	Yes	4	5.6
5	65	M	2	RITA-LAD	Yes	3	2.7
6	64	M	3	LITA-OM	Yes	4	7.4
7	73	F	2	LITA-LAD	Yes	1	5.2
8	58	M	3	LITA between D1 and distal LAD (sequential LITA to D1 and distal LAD)	Yes	2	2.4
9	69	M	3	Proximal LITA (sequential LITA-LAD and D1)	Yes	5	8.4
10	75	M	2	LITA-D1	Yes	4	2.6

MGF, Mean graft flow; PI, pulsatility index; LITA, left internal thoracic artery; RITA, right internal thoracic artery; RA, radial artery; SVG, saphenous vein graft; OM, obtuse marginal coronary artery; LAD, left anterior descending coronary artery; D1, first diagonal branch of the left anterior descending coronary artery; PDA, posterior descending coronary artery.

prompting graft revision (category Ppp). None of these patients showed any electrocardiographic or significant hemodynamic changes to indicate graft compromise. Re-exploration of the anastomosis in these failed grafts showed 3 likely causes for poor flow (1 intimal flap, 1 thrombosis, and 1 kink) but showed no definite cause in the remaining 5. The functional status of the revised grafts was reassessed with both IFI and TTFM in all cases but 1 (because of equipment failure) and was confirmed to be acceptable

(Table 5). In these cases, the MGF increased significantly from 2.0 ± 1.2 mL/min to 12.9 ± 9.3 mL/min ($P < .005$), and there was a simultaneous decrease in PI values from 29.8 ± 22.1 to 6.9 ± 9.9 ($P < .01$).

Discussion

Verification of patency after most vascular procedures, such as percutaneous coronary intervention, is standard practice. However, although the rationale for routine intraoperative

TABLE 4. Details of cases that demonstrated transient poor intraoperative fluorescence imaging (IFI) flow and transit-time flowmetry (TTFM) flow but that improved after pharmacologic manipulation and did not require revision

Patient no.	Age (y)	Sex	No. diseased vessels	Suspected graft	Good flow on repeat IFI	TTFM initial flow value		TTFM subsequent flow value	
						MGF (mL/min)	PI	MGF (mL/min)	PI
1	75	M	3	LITA-LAD	Yes	8	7.6	27	1.9
2	74	F	3	Proximal limb of LITA-OM (RA-D1 from LITA)	Yes	2	4.9	7	2.3
3	61	F	3	RITA-LAD (proximal RITA attached to LITA)	Yes	2	8.4	8	3.3
4	53	M	2	RITA-LAD	Yes	3	6.8	30	3
5	50	M	3	LITA-IM	Yes	2	12	11	4.1
6	63	F	3	LITA-OM	Yes	0	12	7	4.3
7	69	M	3	SVG-PDA	Yes	12	15.4	24	3

MGF, Mean graft flow; PI, pulsatility index; LITA, left internal thoracic artery; RITA, right internal thoracic artery; RA, radial artery; SVG, saphenous vein graft; OM, obtuse marginal coronary artery; LAD, left anterior descending coronary artery; D1, first diagonal branch of the left anterior descending coronary artery; PDA, posterior descending coronary artery; IM, intermediate artery.

TABLE 5. Details of the cases that demonstrated persistent poor flow with both intraoperative fluorescence imaging (IFI) and transit-time flowmetry (TTFM) and that were revised

Patient no.	Age (y)	Sex	No. diseased vessels	Culprit anastomosis	Postrevision good flow seen on IFI	Prerevision TTFM		Postrevision TTFM	
						MGF (mL/min)	PI	MGF (mL/min)	PI
1	68	M	3	LITA-OM	Yes	3	55	12	3
2	72	M	3	RA-D1 (RA proximal end to LITA-LAD)	Yes	0	9.8	2	3.2
3	69	F	2	LITA-OM	Yes	3	4.4	11	1.1
4	69	M	3	SVG-PDA	Yes	3	33	9	29
5	50	M	3	RITA-LAD	Yes	1	47	32	3.2
6	64	F	3	SVG-OM	Yes	2	58	—	—
7	51	M	2	LITA-LAD	Yes	1	26	9	7.1
8	73	F	2	RITA-LAD	Yes	3	4.7	15	1.6

MGF, Mean graft flow; PI, pulsatility index; LITA, left internal thoracic artery; RITA, right internal thoracic artery; RA, radial artery; SVG, saphenous vein graft; OM, obtuse marginal coronary artery; LAD, left anterior descending coronary artery; D1, first diagonal branch of the left anterior descending coronary artery; PDA, posterior descending coronary artery.

assessment of CABG grafts is overwhelming, this frequently does not occur in practice. Furthermore, although several randomized controlled trials have compared the clinical outcome of OPCABG and ONCABG,^{12,13} none has evaluated intraoperative graft patency. This is somewhat surprising, because OPCABG—especially when performed with arterial grafts¹⁴—is often considered to be technically more challenging.

Several techniques are available for intraoperative graft patency assessment.¹⁵⁻²⁰ We have previously reported the value and simplicity of IFI in assessing graft patency,^{5,6} but TTFM is currently the most commonly used technique. Whereas IFI interpretation depends on immediate visual feedback, interpretation of TTFM relies not only on MGF, but also on flow waveform analysis and calculated derivatives, such as PI. Although a high MGF and low PI value provide good confirmation of graft patency, lower MGF and higher PI values, in the absence of visual feedback, can be difficult to interpret because there are no absolute values to determine when grafts should be revised.

Using TTFM, D'Ancona and colleagues¹ revised 37 (3.2%) of 1145 grafts in 33 (7.6%) of 409 OPCABG patients. They emphasized the reliance on correct analysis of TTFM flow patterns to correct abnormalities and reported a predominantly systolic flow in 34 of the 37 grafts, which had altered to a diastolic pattern after revision. Generally, they accepted a PI less than 5 and stated that MGF alone is not a good indicator of graft patency. However, definitive values were not described to determine graft patency, especially in low flow situations. In our study, although we found that flow patterns are useful to confirm graft patency in conjunction with adequate MGF and low PI values, the systolic and diastolic profiles of the flow waveform are not always evident in low-flow situations, thus compounding

the ambiguity in terms of interpreting PI in the setting of a low MGF.

In practice, in most situations, interpretation of TTFM is straightforward, and we found good correlation between IFI and TTFM for most grafts. Indeed, for the categories GG and PP (both transient and persistent), which accounted for 256 (96%) of 266 grafts, similar information was provided with both techniques. Whereas there was no incidence of PG (ie, poor flow with IFI but good flow with TTFM), there were 10 cases of GP (ie, good flow with IFI but poor flow with TTFM). Although there were only 10 grafts in this category (3.8% of all grafts), because these occurred in different patients, this could have resulted in unnecessary graft revision in 10% of patients.

Of 15 grafts in category PP, 7 were subsequently classified as PPt, thus indicating that the initial poor graft flow was transient and improved after a period of increased MAP. As shown in Table 4, PPt grafts subsequently demonstrated improved mean flows and a lower PI, and these grafts were therefore not revised. It is of particular note that the appearance of fluorescence in these grafts was initially only moderately delayed to between 15 to 25 seconds.

This phenomenon of transient poor flow may be explained by several mechanisms. Luxation and rotation of the heart with the patient in the Trendelenburg position achieves a suitable position for performing the anastomosis and imaging the graft. Restoring the heart to the normal anatomic position usually increases the MAP and possibly results in increased graft flow. Alternatively, arterial graft spasm after immediate handling of the graft may resolve spontaneously with an increased MAP. In some situations, the same effect was achieved by a small dose of vasoconstrictors.

However, category PP contained a further 8 grafts (3%) in 8 (8%) patients classified as PpP, indicating persistent poor flow with both TTFM and IFI, even after the heart was restored to its normal position and MAP was increased for 10 to 20 minutes. These grafts were therefore revised (and there were no deaths or perioperative myocardial infarctions in this group). However, in only 3 cases was a definite reason found for poor flow, and even after revision, as shown in Table 5, most showed only a moderate increase in flow.

Likely mechanisms for persistently poor flow include

1. Competitive flow from the native coronary vessel with a less-than-critical stenosis. The use of a proximal snare can confirm this likelihood, because it results in an increase in graft flow.
2. Poor distal runoff either because of severe distal disease in the grafted coronary vessel or because of a noncompliant distal coronary vascular bed (similar to the no-reflow angiographic phenomenon sometimes seen on angiography after patency is restored in an occluded vessel).

Although it is not our practice to perform routine postoperative angiograms, long-term angiographic patency data would be invaluable in determining the natural history of these grafts.

Limitations

There are 2 limitations to our study. Interpretation of good and poor flow with both techniques is semisubjective, even though it is based on considerable clinical experience, and the lack of angiographic follow-up precludes understanding the fate of the grafts with initial or persistent poor flow.

Conclusion

In most grafts, IFI and TTFM correlate well with each other and provide adequate confirmation of graft patency. However, in a small proportion of grafts (but in up to 10% of patients), TTFM alone might result in unnecessary graft revision.

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