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Understanding coronary artery bypass transit time flow curves: role of bypass graft compliance

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Abstract

OBJECTIVES: Low mean bypass graft flow (*Q*) and high pulsatility index (PI) measured by the transit time flow measurement method are not specific for anastomotic stenosis, but occur with competitive flow and poor coronary run-off. We hypothesized that graft compliance is responsible for these changes and that flow measured at the proximal end of the coronary bypass can be viewed as a sum of the graft capacitive flow and flow that passes through the distal anastomosis.

METHODS: Transit time flow measurements (TTFMs) of 15 left internal thoracic artery (LITA) to LAD bypass grafts and 10 saphenous vein grafts (SVGs) to either the right coronary artery (RCA) or posterior descending artery (PDA) were analysed. The TTFM was performed on the proximal and distal end of the graft, and proximally with distal occlusion of the graft. Low mean bypass graft flow PI and diastolic filling (DF) measured distally and proximally were compared, and graft compliance was estimated.

RESULTS: Diastolic filling was higher distally in every single case (LITA–LAD: distal DF 76 ± 12% vs proximal 66 ± 13%, $P = 0.005$; SVG–RCA/PDA: distal 72 ± 15% vs proximal 63 ± 12%, $P = 0.018$). There were no significant differences in *Q* and PI. Subtracting the distal from the proximal flow gave a result identical to the proximal TTFM in distally occluded grafts, confirming the presence of graft capacitive flow. Graft compliance estimated from the flow of distally occluded grafts was 0.99 ± 0.47 μl/mmHg for LITA grafts and 0.78 ± 0.42 μl/mmHg for SVG grafts.

CONCLUSIONS: The study confirmed that the TTFM measured at the proximal end of the coronary bypass could be viewed as a sum of graft capacitive flow and the flow that passes through the distal anastomosis. Graft capacitive flow increases the systolic and decreases the diastolic TTFM when measured at the proximal end of the graft. It explains the higher DF when the TTFM is measured at the distal end of the graft and the increase in the PI at the proximal end when *Q* decreases. As the influence of graft capacitive flow on the PI in low Q can be eliminated by performing the TTFM at the distal end of the graft, we believe that the value of PI is clinically irrelevant.

Keywords: Coronary artery bypass • Transit time flow measurement • Coronary bypass graft compliance

INTRODUCTION

Transit time flow measurement (TTFM) is a commonly used method of quality control in coronary artery bypass surgery. It has been shown that good flow in all grafts is associated with a lower rate of postoperative myocardial infarction, lower mortality, shorter intensive care unit stay, lower rate of intra-aortic balloon pump use and lower rate of re-revascularizations [1–3]. Low graft flow was predictive of early and mid-term graft failure [4, 5]. In a study by D'Ancona *et al.* [6] 3.2% of bypass grafts in 7.6% of patients were revised for both low flow and a high pulsatility index. In only 2 of the 34 grafts, there were no significant findings; however, all flow values and patterns improved after re-anastomosing the bypass. The TTFM also has severe limitations. In a study by Jaber *et al.* [7], 19 international surgeons were asked to interpret TTFM flow curves. All surgeons were able to reliably identify only the nearly occluded anastomoses with more than 90% stenosis, whereas 72% accepted anastomoses with severe stenosis and 24% would redo a fully patent stenosis. We can conclude that the TTFM is a functional method, and that the changes in the flow curve occur when stenosis at the anastomosis reaches haemodynamic significance. Therefore, it cannot reliably detect moderate to severe stenoses. Furthermore, a low mean flow and high PI are not specific to anastomotic stenosis, but are similar or identical in competitive flow, poor run-off and possibly other conditions. The literature offers no explanation of these changes in the flow curve. Furthermore, none of the studies dealing with the TTFM explicitly defines the site of the TTFM along the graft. Typically, we perform the TTFM on the proximal end of the graft, but we know from clinical experience that, when TTFM is performed on the distal end of the same graft, the PI is usually lower, whereas the mean flow is the same.

We hypothesized that graft compliance is responsible for the observations listed above and that the TTFM on the proximal end of the graft can be considered as a sum of two flow curves. First is the capacitive flow of the graft. This flow is a consequence of graft expansion and retraction that occur with arterial pressure changes. Second is the flow that actually passes through the graft to the coronary artery and can be measured at the distal end of the graft.

MATERIALS AND METHODS

Analysis of 25 intraoperative coronary bypass TTFMs from 17 consecutive patients operated in 2013 was performed. All patients provided their written informed consent. The study and consent form were approved by the local ethics committee. Four surgeons (IK, NL, BG, TK) performed the surgeries with or without the use of cardiopulmonary bypass. Only elective primary coronary bypass cases were included. The approach was a full median sternotomy in all patients. The left internal thoracic artery (LITA) was harvested in a skeletonized fashion. The TTFM was performed intraoperatively by using the VeriQ flowmeter (Medistim, Oslo, Norway). We included only the LITA to LAD and SVG to either RCA or PDA bypass grafts as they allow distal measurement of flow without any major manipulation of the heart. All bypass grafts had a single distal anastomosis and SVG grafts had the proximal anastomosis on the aorta. Three measurements were performed on each bypass: proximal (Q_p), distal (Q_d) and proximal with distal occlusion of the graft (Q_{pdo}). The proximal TTFM (Q_p) was measured at the aortic anastomosis for the SVG or as proximal as possible for the LITA grafts. The distal TTFM (Q_d) was performed at the distal anastomosis. The distal occlusion of the graft for the third measurement was made with forceps or digitally at the distal anastomosis for 5–10 s to perform the TTFM. The TTFM included the flow curve, mean flow, pulsatility index (PI), diastolic filling (DF) and heart rate (HR). At each TTFM, systolic and diastolic radial arterial pressure was recorded, and the length in centimetres between the sites of proximal and distal TTFMs was measured.

The TTFM performed proximally and distally were compared in terms of mean flow, PI and DF. The graft compliance was calculated in two ways. The first estimate of graft compliance was obtained from the flow measured at the proximal end of the graft with distal occlusion (Q_{pdo}). An example is shown in Fig. 1C. Here, only the flow that enters or leaves the graft at the proximal end is responsible for changes in the graft volume (V) over time:

$$Q_{pdo} = \frac{dV}{dt} \tag{1}$$

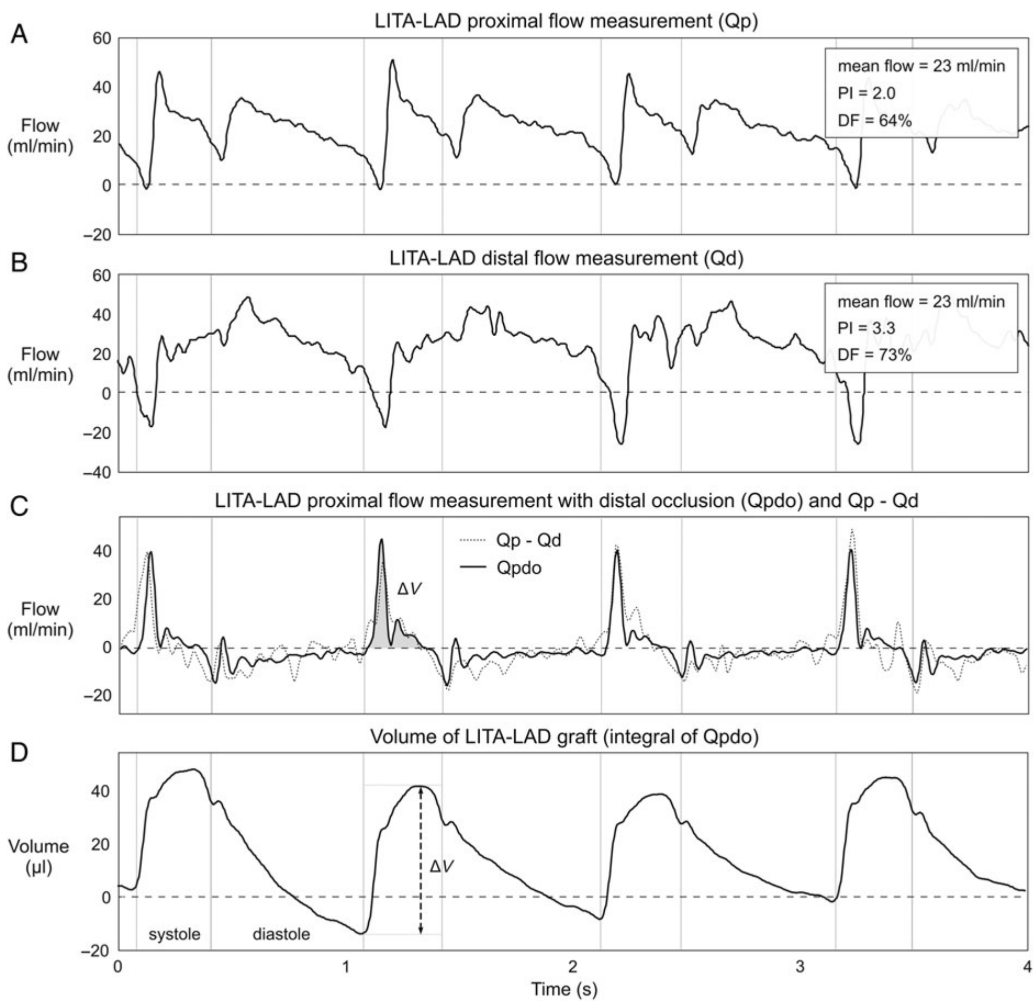

Figure 1: Example of flow measurements on a left internal thoracic artery (LITA) to LAD bypass graft. (**A**) Proximal flow measurement. (**B**) Distal flow measurement. (**C**) Capacitive flow of the LITA–LAD graft, which was either measured by occluding the graft distally (Q_{pdo}) or calculated by subtracting the distal from the proximal flow (Q_p – Q_d). Both methods produced very similar results in terms of the shape and amplitude of the flow curve, which shows high positive flow in early systole and low negative flow throughout the rest of the cardiac cycle. (**D**) Integrating the graft capacitive flow gives the bypass graft volume as it changes over time—the curve is almost identical to the arterial pressure curve.

Integrating Q_{pdo} over time gives the volume of the graft as it changes over time following the arterial pressure changes in each cardiac cycle. As shown in Fig. 1D, the fluctuations in graft volume give the shape of arterial pressure curve. Dividing the difference between maximal and minimal graft volume (ΔV) with the difference between systolic (P_s) and diastolic pressure (P_d) gives the estimate of linear graft compliance (C_g):

$$C_g = \frac{\Delta V}{P_s - P_d} \tag{2}$$

In the example shown in Fig. 1, the graft volume increased on average by 56 µl during each cardiac cycle (ΔV). At a heart rate of 58 bpm, the volume of blood that entered the graft per cardiac cycle was 396 µl, so that the change in graft volume represented 14% of that volume. At the time of flow measurement, the arterial pressure in the radial artery was 118/54 mmHg, thus giving a pulse pressure of 64 mmHg. Dividing the volume change with pulse pressure gave an estimate of the linear graft compliance, which in this case was 0.88 µl/mmHg.

The second estimate of graft compliance was obtained from the proximal (Q_p) and the distal flow (Q_d). The raw binary data for the two flow curves obtained from the VeriQ flowmeter were imported into Matlab R2009b (MathWorks, Inc., Natick, MA, USA) and further analysed. Assuming that there is no bleeding from the graft, the difference in the flow that enters the graft (Q_p) and the flow that leaves the graft (Q_d) results in the change of the volume of the graft (V):

$$Q_p - Q_d = \frac{dV}{dt} \tag{3}$$

An example of Q_p, Q_d and their difference ($Q_p - Q_d$) are shown in Fig. 1A–C. Similarly to the first method, the graft compliance was calculated from the graft volume and radial arterial pulse pressure. All estimates of graft compliance were then normalized to 10 cm length of the graft.

The first method of estimating compliance is simpler, faster and can be performed directly on the VeriQ flowmeter machine. This method was used in all cases; however, as it estimates compliance from distally occluded grafts, it needed to be validated by the second method, which is performed on a functioning graft. The second method, however, requires much more work and was only performed for five LITA–LAD grafts and five SVG–PDA grafts.

Statistical methods

Data were compiled and analysed with Microsoft Access 2007 (Redmond, WA) and SPSS Statistics 11.5 (SPSS, Inc., Chicago, IL, USA). Because of small sample sizes, the continuous variables were compared by using the Mann–Whitney *U*-test or the Wilcoxon signed-ranks test when comparing related data. Categoric variables were compared by using χ^2 or Fisher's exact test. Results for the continuous variables are reported as the mean ± standard deviation in the text and tables.

RESULTS

We operated 17 patients; 11 (65%) were male; the mean logistic EuroSCORE was 3.1%. We performed 2.9 ± 0.5 distal anastomoses per patient, cardiopulmonary bypass was used in 4 cases. We analysed measurements performed on 15 LITA to LAD grafts and 10 SVG to either PDA (7) or RCA (3) (Table 1).

Mean graft flow and PI were not significantly different proximally and distally; however, DF was significantly higher distally. When looking at individual data, DF was higher distally in every single case. Results of estimating linear graft compliance for a 10-cm-long segment of the bypass graft by two different methods are presented in Table 2. Linear graft compliance for a 10-cm-long segment of the bypass graft estimated from flow of distally occluded grafts was 0.99 ± 0.47 µl/mmHg for LITA grafts (n = 15) and 0.78 ± 0.42 µl/mmHg for SVG grafts (n = 10).

To further illustrate the impact of graft compliance on graft pulsatility index, flow measurements were performed proximally and distally on a LITA–LAD graft, while gradually occluding the graft with two fingers near the distal anastomosis, thus mimicking stenosis at the distal anastomosis (Fig. 2). When flow was measured proximally, a systolic spike appeared with a decrease in the mean flow, whereas the diastolic flow decreased and was negative with complete graft occlusion causing a rapid increase in the pulsatility index (PI) (Fig. 2A). The Medistim software erroneously calculated a DF of 40% in complete distal occlusion when diastolic flow was negative and thus directed away from the coronary artery. When flow was measured distally, the shape of the flow curve remained relatively constant regardless of the mean flow and resulted in minor changes in the PI. Only in complete occlusion when there

Table 1: Comparison between flow measurements performed on the proximal and distal ends of bypass grafts

	Proximal	Distal	P*
LITA–LAD (n = 15)			
DF (%)	66 ± 13	76 ± 12	0.005
PI	3.2 ± 1.7	2.9 ± 0.8	0.363
Mean flow (ml/min)	33 ± 18	35 ± 21	0.330
SVG–RCA/PDA (n = 10)			
DF (%)	63 ± 12	72 ± 15	0.018
PI	2.1 ± 0.9	1.9 ± 0.4	1.000
Mean flow (ml/min)	34 ± 13	32 ± 11	0.426

LITA-LAD: left internal thoracic bypass graft to left anterior descending artery; DF: diastolic filling; PI: pulsatility index; SVG-RCA/PDA: saphenous vein graft to either right coronary artery or posterior descending artery.
*Wilcoxon's signed-ranks test.

Table 2: Linear graft compliance (C_g) normalized to a 10-cm-long graft segment estimated from the flow of distally occluded grafts (Q_{pdo}) and from the difference between the proximal and the distal flow ($Q_p - Q_d$)

	C_g (Q_{pdo}) (µl/mmHg)	C_g ($Q_p - Q_d$) (µl/mmHg)	P*
LITA–LAD (n = 5)	0.89 ± 0.22 (0.56–1.19)	0.86 ± 0.13 (0.66–1.01)	0.500
SVG–RCA/PDA (n = 5)	0.95 ± 0.42 (0.53–1.51)	1.11 ± 0.52 (0.57–1.78)	0.068

*Wilcoxon's signed-ranks test.

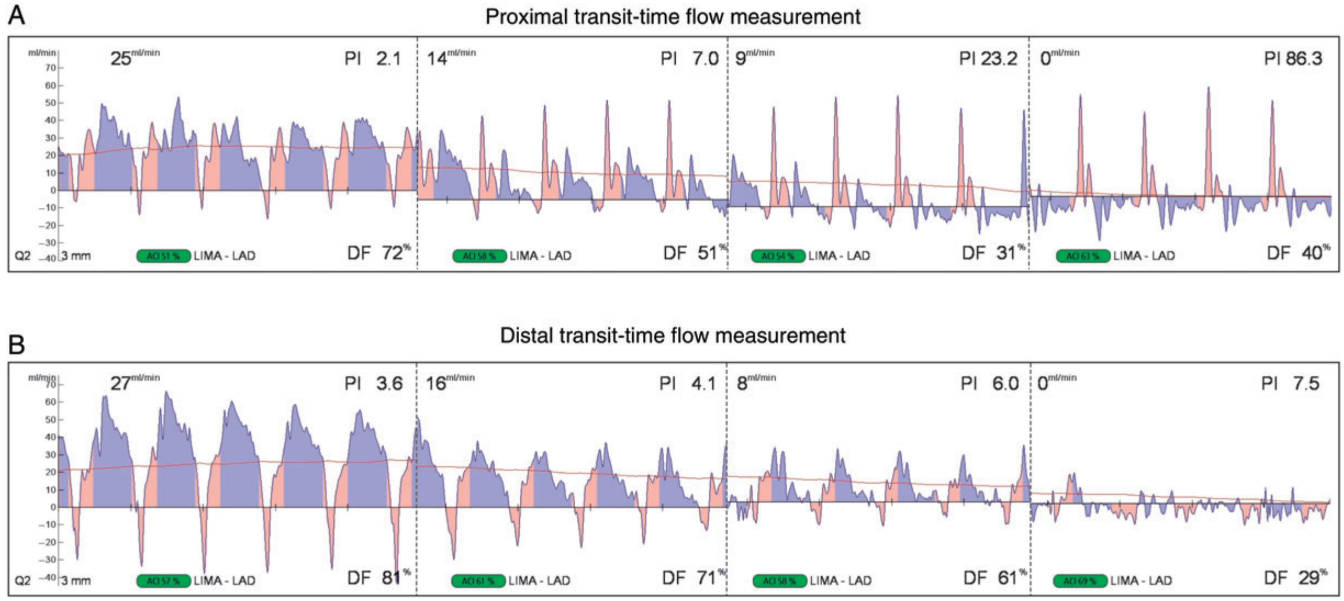

Figure 2: (**A**) Changes in the transit time flow curve (TTFM) measured on the proximal end of the left internal thoracic artery (LITA) to LAD bypass graft that occurred with gradual distal occlusion of the bypass graft. (**B**) The TTFM measured on the distal end of the LITA–LAD graft in the same setting.

should have been a straight line of zero flow, the artefacts produced by motion of the heart showed an irregular pattern (Fig. 2B).

DISCUSSION

The graft compliance calculated by the two methods was very similar. A study by Glineur *et al.* [8] has shown that in the resting conditions the pressure drop along the LITA is 2.9 ± 2.2 mmHg and along the SVG only 0.4 ± 0.7 mmHg. Thus, the pressure along the graft is nearly identical in open and occluded grafts and the volume changes of the graft due to the changes in arterial pressure in each cardiac cycle are similar regardless of the flow rate, at least in the resting conditions.

The TTFM flow curve measured at the proximal part of the bypass graft can be interpreted as the sum of two flow curves. First is the flow curve that can be measured at the distal end of the bypass graft and has the shape of the normal coronary flow curve with low systolic and high diastolic flow as dictated by the myocardial contractions [9]. The shape of this curve is relatively independent of the absolute value of the mean flow. Therefore, the PI of this flow curve is low and within normal range. The second flow curve is the one that is observed in occluded grafts and represents the flow due to changes in compliant bypass graft volume that occur with changes in arterial pressure. Here, the flow is always positive when the arterial pressure is rising (first part of the systole), and negative throughout the rest of the heart cycle, when the arterial pressure is falling. The net flow is zero and the peak positive and negative values depend on the graft compliance and arterial pulse pressure. A slightly different pattern is observed when the patient has intra-aortic balloon pump inserted [10]. Then, the arterial pressure rises twice in each cardiac cycle, which produces two positive peaks in the flow curve of a distally occluded bypass graft. This second flow curve has a distinct influence on the flow measured by the TTFM probe on the proximal part of the bypass graft. It always increases the systolic and decreases the diastolic flow, but it has no influence on the mean flow. The shape of the TTFM curve measured by the probe depends on the relative sizes of both flow curves as can be seen in Fig. 2. In case of good run-off or very low graft compliance, the mean flow is high and the PI is low. Reducing the mean flow and augmenting the graft compliance results in a high PI. When the graft is occluded, the mean flow is zero and the PI is infinite.

The LITA and SVGs were shown to have similar compliance. Also, the capacitive flow of both types of grafts exhibited the same influence on flow measurements. However, proximal TTFM measurement with distal occlusion may not always be adequate for estimation of graft compliance in SVGs, as they may contain functioning venous valves, which prevent emptying of the graft through its proximal anastomosis. This is probably the cause of a trend towards lower SVGs compliance when estimated from distally occluded grafts (Table 2).

Limitations of the study

The same probe size was used for distal and proximal TTFMs. The diameter of the LITA usually decreases distally. At the beginning, we chose the size of the probe to fit the distal diameter. As a result, when performing the TTFM on the proximal end, the LITA graft was slightly compressed by the probe, which resulted in a somewhat lower mean flow when compared with the TTFM at the distal end. To avoid this problem, we started using larger probes of sizes 4 and 5 and added sterile ultrasound or Xylocaine gel to improve the contact between the graft and the probe at the distal end of the graft.

The best way to measure the proximal and the distal flow would be to use two probes simultaneously, which was not done in our study due to the increased cost of the procedure.

Clinical implications

The size of the probe can significantly affect the mean graft flow, even if the probe only gently compresses the graft. The stenosis produced by the probe is probably not haemodynamically

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significant; however, the graft flow decreases due to the competition between the graft and native coronary flow for the relatively constant run-off [11]. A better way to measure the graft flow more accurately is to use a large probe and add sterile ultrasound gel or lidocaine gel to provide adequate contact.

The capacitive flow of the bypass graft always increases systolic flow and decreases diastolic flow when the TTFM is performed proximally. As a result, the distal DF is always higher than the proximal DF, regardless of the type of the graft or mean graft flow. The PI, on the other hand, depends on the shape of the distal flow curve. In LITA grafts, there is often a short period of low or negative flow at the beginning of systole, which probably occurs due to a short delay in the pressure wave between the aorta and the left subclavian artery, and is not present in aorto-coronary bypass grafts. Left ventricular hypertrophy, which occurs in the setting of aortic stenosis, hypertrophic cardiomyopathy or long-standing arterial hypertension, is also associated with reduced or negative systolic coronary blood flow [12, 13]. The increase in systolic flow that occurs with a compliant graft may actually decrease the PI in this setting (as demonstrated in Fig. 1). However, further lowering of the mean graft flow eventually leads to a rapid increase in the PI.

Graft compliance significantly influences TTFM. As a result, the PI cannot be used as a measure of graft patency as it only reflects the ratio of capacitive to mean graft flow. It depends on the position of measurement along the graft, graft compliance, graft length, arterial pulse pressure and mean graft flow. As the mean graft flow decreases, the capacitive flow becomes more apparent and it increases the PI; however, this effect can be eliminated by measuring the flow at the distal anastomosis (Fig. 2), which makes the PI value clinically irrelevant.

We conclude that only the value of mean flow should be used to judge the function of the bypass grafts. Adding proximal coronary snaring to exclude the competitive flow and adenosine to induce maximal coronary vasodilation could probably add some value to this measurement; however, only imaging methods can reliably detect stenosis at the distal anastomosis.

Conflict of interest: none declared.

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