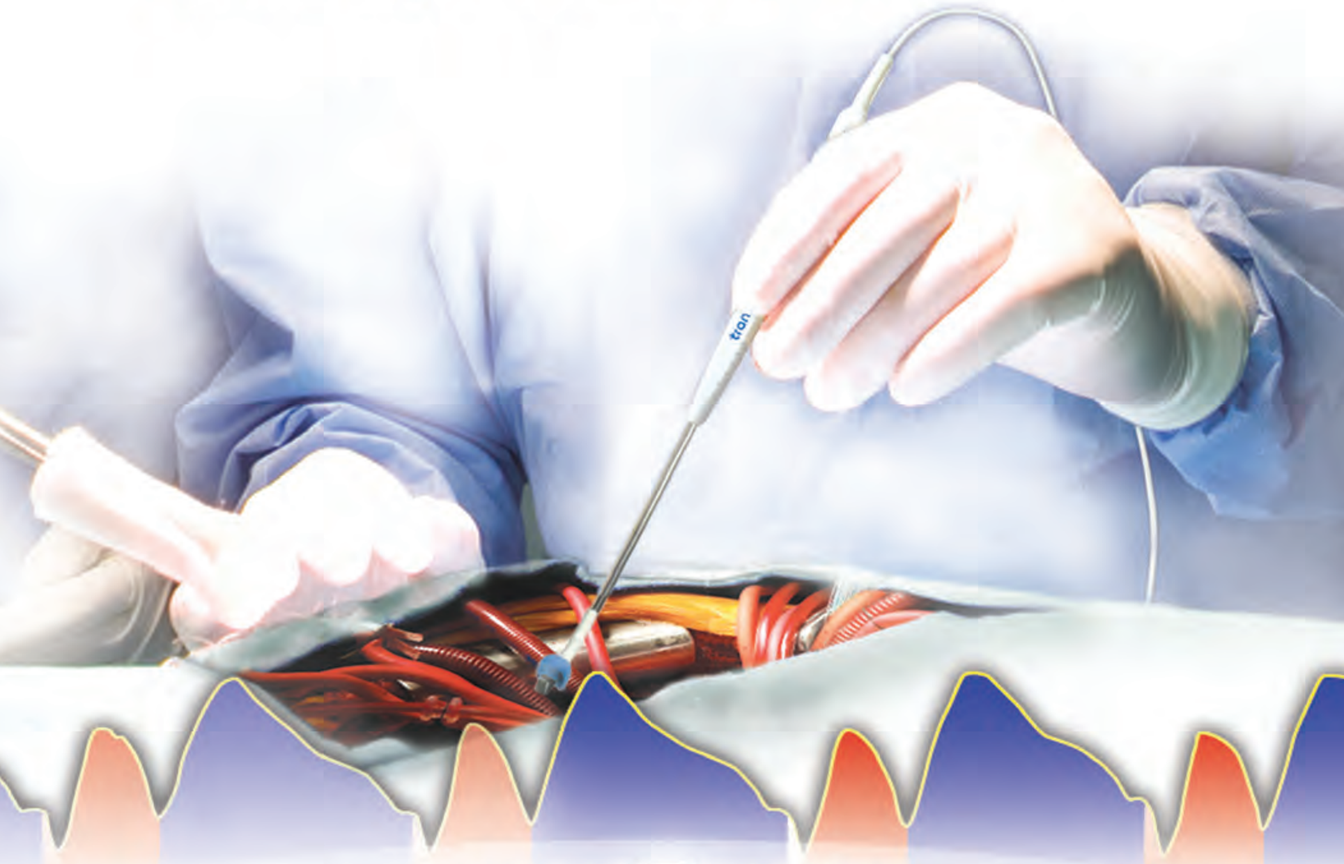
20th Anniversary

Flow-based Intraoperative Coronary Artery Bypass Patency Assessment



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This edition of the Flow-based Intraoperative Coronary Artery Bypass Patency Assurance handbook celebrates the 40th anniversary of Transonic Systems Inc. It presents flow-based intraoperative graft patency assessment with transit-time ultrasound technology updated with knowledge gleaned from decades of experience with coronary artery bypass graft (CABG) flow measurements.

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We continue to acknowledge the invaluable early collaboration with Dr. Bruce Mindich, retired Chief of Cardiac Surgery at The Valley Hospital, Ridgewood, NJ. Dr. Mindich culled through hundreds of cases in 2002 to provide representative case examples of CABG flow measurements. His expertise performing routine intraoperative flow measurements and interpretating its data form the basis of this handbook.

We also acknowledge Sita Drost, PhD, whose collaboration with Dr. Takahashi of the Department of Cardiovascular Surgery, Nippon Medical School, Tokyo, Japan, has led to some of the more recent coronary flow insights documented in this updated handbook.

Printed in the United States of America

Print copies of this handbook may be ordered from Transonic Systems Inc.
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Glossary of Terms

CABG: Coronary Artery Bypass Grafting

Coronary Arteries:

Right Heart
- RCA: Right Coronary
- RVB: Right Ventricular Branch
- AM: Acute Marginal
- PDA: Posterior Descending.
- LVB: Left Ventricular Branch

Left Heart
- LCA: Left Coronary
- LAD: Left Anterior Descending
- DIAG: Diagonal
- RI: Ramus intermedius
- Cx: Circumflex
- OM1: Obtuse Marginal 1
- OM2: Obtuse Marginal 2
- PLA: Posterior Laterall

Coronary Bypass Graft Conduits
- GEA: gastroepiploic artery (right)
- LITA/LIMA: left internal thoracic artery (left internal mammary artery)
- RITA/RIMA: right internal thoracic artery (right internal mammary artery)
- RAD: Radial artery
- SVG: saphenous vein

CPB: Cardiac Pulmonary Bypass
- On-Pump (on CPB) CABG
- Off-pump (off CPB) CABG

Diastolic Filling Percentage (DF%): the average diastole flow to total flow (systolic plus diastolic) times 100 or a comparison of blood volume delivered during diastole versus blood volume delivered during diastole plus systole.

Diastolic Resistance Index (DRI): Diastolic-to-systolic arterial graft pressure-to-flow ratios.

Diastolic/Systolic Ratio (D/S): The ratio of total diastolic graft flow to total systolic graft flow or a direct comparison of blood volume delivered during diastole versus blood volume delivered during systole.

Flow: the amount of fluid passing a certain point during a defined time frame (mL/min, L/min).

FlowSound®: proprietary Transonic technology that translates volume flow into an audible pitch that allows assessment of bypass graft patency without looking away from the surgical field.

FlowTrace®: proprietary Transonic software for data collection of coronary artery bypass grafts.

Pulsatility Index (PI): A flow derived calculation that is arrived at by subtracting the minimum flow value from the maximum flow value and dividing the result by mean flow.

Transit-time Flow measurement (TTFM): Measurement of intraoperative flow using transit-time ultrasound technology.

Transit-time Ultrasound Technology (TTUT): A technology that integrates the time of flight of ultrasound signals over a fixed distance into a volume flow measurement.

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I. Why Measure Bypass Graft Flow

A. Introduction

"I measure flow, but I don't know what the flows mean."

This 2001 remark by a surgeon who routinely performed coronary artery bypass grafting (CABG) surgery, along with a treasure trove of case reports from The Valley Hospital in Ridgewood, NJ, sparked publication of the first edition of this handbook in 2002. The goal of the handbook at that time was to familiarize cardiac surgeons, particularly those performing off-CPB procedures, with intraoperative flow measurements of bypass grafts as a quantitative quality assurance tool for CABG grafts.

B. Intraoperative Assessment Guidelines

Since then, off-pump CABG procedures have stabilized at 17% of all CABG procedures in the US, with higher percentages in some other countries. As accountability has increased in all areas of medicine, intraoperative graft patency measurement has become more accepted, especially in Europe and Japan where graft patency assessment has been included in the 2010 and 2019 European Guidelines for Myocardial Revascularization[1,2] and the 2018 Japanese Guidelines[3]. The 2018 European Guidelines state: *"Besides continuous ECG monitoring and transoesophageal echocardiography immediately after revascularization, intraoperative quality control may also include graft flow measurement to confirm or exclude a technical graft problem. Transit-time flow measurement is the most frequently used technique for graft assessment and has been able to detect 2-4% of grafts that require revision. In observational studies, the use of intraoperative graft assessment has been shown to reduce the rate of adverse events and graft failure, although interpretation can be challenging in sequential and T-graft configurations."* The Japanese Guidelines state, *"Combining quantitative analysis by TTFM with a modality that allows morphological assessment enables accurate graft evaluation and helps achieve consistent quality of care for CABG."*

1 Neumann FJ et al, "2018 ESC/EACTS Guidelines on myocardial revascularization," Eur Heart J. 2019 Jan 7;40(2):87-165.

2 The Task Force on Myocardial Revascularization of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS) Kohl G (Chair) (Belgium), Wijns W (Chairperson) (Belgium)*, Danchin N (France), Di Mario C (UK), Falk V (Switzerland), Folliguet T (France), Garg S (The Netherlands), Huber K (Austria), James S (Sweden), Knuuti J (Finland), "Guidelines on Myocardial Revascularization," Eur J CardiothoracSurg 2010; 38, S1 S52

3 Nakamura, M, Yaku, H, Ako, J, Arai, H, Asai, T, Chikamori, T et al. JCS/JSCVS 2018 Guideline on Revascularization of Stable Coronary Artery Disease. Circ J 2022; 86:477-588. 4 Di Giammarco G, Rabozzi R, "Can transit-time flow measurement improve graft patency and clinical outcome in patients undergoing coronary artery bypass grafting?" Interact Cardiovasc Thorac Surg. 2010 Nov;11(5):635-40.

B. Intraoperative Assessment Guidelines cont.

Despite widespread adoption of intraoperative graft patency assessment in Europe and Japan, and more than a hundred publications that attest to its value, no comparable United States guidelines for graft patency assessment yet exist.

In a coronary graft assessment review, Dr. Michael Mack noted, *"Coronary artery bypass grafting (CABG) is the only major vascular procedure currently performed that does not routinely undergo an assessment of patency at the end of the procedure."*[4] He said that this is based on a false assumption that a large majority of grafts produce good clinical outcomes, but data from the PREVENT IV trial of 22,400 saphenous vein grafts showed a failure rate at one year of 25%.[5] In 2019, Dr. KB Kim *et al,* from Seoul National University Hospital, Seoul, Korea reported on his 20-year experience of flow-guided CABG (TTFM) in 2919 patients who underwent off-pump CABG.[6] After TTFM introduction, patency of arterial conduits became significantly higher (97.2% vs 99.2%). Dr. Kim concluded that TTFM-guided revision of abnormal grafts improved early arterial graft patency (see Publication Brief, bottom of next page).

C. Flow — the Quintessential Vital Sign

Flow, the amount of fluid passing a certain point during a defined time frame (mL/min, L/min), is life's quintessential vital sign. By delivering oxygen and nutrients to cells for metabolism and removing metabolic wastes, blood flow is life giving. When blood flow fails, life ends.

Whether a CABG is performed minimally-invasively, off-pump, on-pump, or hybrid using a robot to harvest the left internal mammary/thoracic artery (LIMA/LITA), the surgeon's end goal is to know that blood is flowing through newly created anastomoses. Intraoperative flow measurements offer this assurance. While a measurement takes only seconds to perform, its quantitative result augments a surgeon's other standard clinical observations of a patient's condition.

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4 Mack, MJ, "Intraoperative Coronary Graft Assessment," Current Opinion in Cardiology 2008, 23: 568-572.

5 Magee MJ, Mack MJ, *et al.,* PREVENT IV Investigators. "Coronary artery bypass graft failure after on-pump and off-pump coronary artery bypass: findings from PREVENT IV," Ann Thorac Surg 2008; 85(2): 494-9

6 Kim KB, Choi JW, Oh SJ, Hwang HY, Kim JS, Choi JS, Lim C "Twenty-year experience with off-pump coronary artery bypass grafting and early postoperative angiography," Ann Thorac Surg. 2019 Sep 6.

C. Flow — the Quintessential Vital Sign cont.

Yet, flow measurements as a quality assurance tool is underused. Because precise flow measurement technologies and devices were unavailable until the mid-twentieth century, surrogate measurement modalities such as pressure and pulse gained precedence in assessing hemodynamics and are, in fact, surrogates for absolute volume flow, precisely measured by transit-time ultrasound, a volume flow technology that was refined and adapted for biomedicine by Transonic founder Cornelis Drost while a senior researcher at The NYS College of Veterinary Science at Cornell University[7].

[7] Drost CJ, "Vessel Diameter Independent Volume Flow Measurements Using Ultrasound," Proceedings San Diego Biomedical Symposium 1978; 17: 299-302. US Patent 4,227,407, 1980.

Twenty-year experience with off-pump coronary artery bypass grafting and early postoperative angiography.

Kim KB, Choi JW, Oh SJ, Hwang HY, Kim JS, Choi JS, Lim C, Ann Thorac Surg. . 2020 Apr;109(4):1112-1119.

PURPOSE

To report off-pump coronary artery bypass grafting performance and early postoperative angiography for assessing anastomosis accuracy in surgical revascularization patients.

METHOD

- 3083 patients who underwent isolated CABG (1998-2017), 2919 (94.7%) underwent OPCAB.
- Distal anastomoses conduits were: left ITA (n=2764), right ITA (n=866), right gastroepiploic artery (n=997), radial artery (n=16), and saphenous vein (n=1505).
- After transit-time flow measurement (TTFM) introduction in 2000, abnormal grafts were revised intraoperatively. Early (≤7days) angiography was performed in 2820 patients (96.6%) at 1.5±1.2 postoperative days; surgical intervention was based on angiography.

RESULTS

- Operative mortality: 1.1%. Average number of distal anastomoses per patient was 3.2±1.0.
- TTFM-guided revision was performed in 1.3% (109 of 8,585) distal anastomoses failures.
- Angiography showed patency of 98.2% (99.0%, arterial; 96.9%, venous conduits).
- Venous conduit patency was 87.2% for free grafts and 97.7% for composite grafts.
- After TTFM introduction, arterial conduit patency increased significantly (97.2% vs 99.2%).
- Patency of free venous grafts did not improve significantly (86.0% vs 91.4%).
- Early re-intervention due to angiographic findings was performed in 76 patients (2.7%).
- Re-evaluation of graft patency before discharge in 31 patients who underwent revision of distal anastomoses showed improved patency (65.1% vs 95.3%).

CONCLUSION

- Intraoperative TTFM revision of abnormal grafts improved early arterial graft patency.

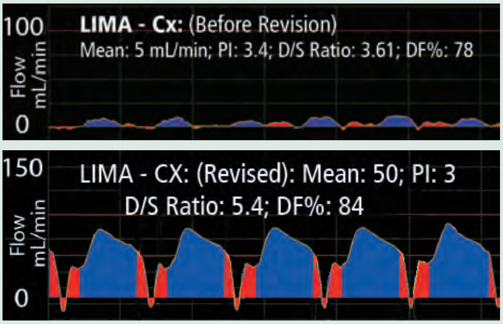
D. To Measure Is to Know

If it is worth taking the time to construct a graft, then it is also worth taking the time to measure flow in the graft to make sure that it is patent. By measuring flow, one quantifies the blood flow that will reach myocardial territories. Rather than relying on subjective impressions or qualitative images, real data provide valuable functional information. Just as a pilot must learn to fly by instruments to avoid crashing, so should the clinician learn to rely on quantitative data to help make objective clinical decisions.

Example: Revision of LIMA - Cx Graft with PI < 5

A 67-year-old male patient with single-vessel coronary artery disease underwent off-CPB CABG. LIMA-Cx graft flow first measured 5.2 mL/min (D/S Ratio; 3.61, DF%: 78, PI: 3.4). The patient's pulse and pressure were normal and the graft appeared functional, but the waveform exhibited a damped profile with atypical diastolization. The surgeon decided to revise the graft.

After revision, LIMA-Cx graft flow improved to 50 mL/min (D/S Ratio: 5.4, DF%: 84, PI: 3). The flow waveform (bottom) exhibited a classic LIMA-Cx profile. Note that the first PI was 3.4, the revised PI was 3.



The top waveform demonstrates a damped profile with atypical diastolization. This supported the surgeon's decision to revise the LIMA-Cx graft. Flow improved dramatically after revision and the waveform exhibited a classic LIMA-Cx profile (bottom waveform).

Summary: Off-CPB CABG; LIMA - Cx graft; 67-year-old male, multi-vessel coronary artery disease						
Flow Measurement	Mean Flow (mL/min)	PI	D/S Ratio	DF%	Waveform	Analysis
Post-bypass	5.2	3.4	3.61	78	Atypical diastolization	Revision indicated
After revision	48 - 50	3	5.4	84	Classic LIMA-Cx profile	Revision successful
Example demonstrates that a PI < 5 (in this instance 3.4 before revision) doesn't always mean that the graft is good. Mean flow is the key indicator.						

Case example courtesy of Dr. B.P.Mindich, Valley Hospital, Ridgewood, NJ.

Best Evidence – Coronary: Can Transit-time Flow Measurement Improve Graft Patency and Clinical Outcome in Patients Undergoing Coronary Artery Bypass Grafting?

Di Giammarco A, Rabozzi R, Interact Cardiovasc Thorac Surg 2010; 11(5): 635-40.

PURPOSE

A best evidence topic in cardiac surgery was written according to a structured protocol. The question addressed was if transit-time flow measurement (TTFM) can improve graft patency and clinical outcomes in patients undergoing coronary artery bypass grafting surgery.

METHOD

One hundred two papers were found using the reported search, of which ten represented the best evidence to answer the clinical question. The authors, journal, date, country of publication, patient group studied, study type, relevant outcomes, and results of these papers were tabulated. The papers considered for the analysis focused attention on three major topics: intraoperative graft verification with the aim of improving immediate graft patency; predictive power of early- and mid-term graft patency, and clinical outcome. Among TTFM parameters, according to different authors, mean graft flow is set at 10 or 15 mL/min; pulsatility index is set at 3 or 5; insufficiency ratio is set by 3 or 4%.

RESULTS

The studies demonstrated the usefulness of intraoperative TTFM as a method to improve intraoperative graft patency.

CONCLUSION

TTFM is a reliable method to verify intraoperative graft patency. There is some evidence that checking graft patency intraoperatively may improve mid-term outcomes.

> "The intraoperative use of flow measurements provides invaluable information in a timely, accurate, cost-effective manner allowing for the surgical correction of a surgical problem. This has significantly reduced the complications related to early technically induced graft failure ... and provides documentation of the *sine qua non* of the operation: patency." B.P. Mindich, MD

Frequently Asked Questions

Why should I bother measuring flow if the grafts are working OK?

If it was worth taking your time to construct a graft, then is also worth taking the time to measure flow in the graft to make sure that it is patent for the best outcome for your patient.

I am used to palpating the graft. What advantage is there to measuring flow?

Palpation gives a qualitative indication of the presence of a pulse, but does not detect an occlusion downstream from the point of palpation (i.e., the distal anastomosis). Some surgeons have developed a "feel" for flow by partially occluding the graft — the thrill of turbulence provides a sense that something is passing through the graft. Flow measurement provides an unique opportunity to "look inside" the graft and make a quantitative, not qualitative, assessment of graft patency. Surgeons with ample case experience continue to rely on intraoperative flow measurement to test the quality of their work.

Do studies demonstrate better outcomes when graft flows are measured?

CABG surgery seeks positive outcomes for the patient. Non-functional grafts sabotage this goal. Many studies report that intraoperative flow measurement can detect technical error[1-4]. Flow-based intraoperative patency was confirmed by post-op angiography and/or Doppler[5-6].

While intraoperative graft patency assessment serves the short-term purpose of helping the surgeon accomplish his immediate goals of constructing patent grafts that guarantee early graft patency, long-term outcomes are determined by many more factors than just graft patency at the end of surgery.

Indisputable evidence from more than a hundred publications over the last two decades supports the value of intraoperative flow assessment. This prompted the The Task Force on Myocardial Revascularization of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS) to include intraoperative assessment of coronary artery bypass grafts in their 2010 and 2018 European Guidelines, and the Japanese Circulation Society (JCS) to include it in their 2018 Guideline of coronary artery revascularization.[7-9]

One must also be mindful that it has been reported that intraoperative graft flow assessment can only detect stenoses that occlude over 75% of a graft area.[10-11] Grafts constructed with sub-acute stenosis that are not detectable with intraoperative flow measurement likely have a significant influence on long-term outcomes as well.

References on next page.

I. Why Measure Bypass Graft Flow cont.

Graft quality verification in coronary artery bypass graft surgery: how, when and why?

Kieser TM, University of Calgary, Calgary, Alberta, Canada.

Curr Opin Cardiol. 2017 Nov;32(6):722-736.

BACKGROUND: Coronary artery bypass graft (CABG) surgery is one of the few remaining operations/interventions on diseased arteries that are not routinely verified during or immediately after the procedure.

- Quality assurance of CABG is becoming increasingly important;
- Reports (Freedom Trial, SYNTAX Trial) suggest that CABG is superior to percutaneous coronary intervention (PCI) for improved mid-term and long-term outcomes.
- Perhaps the era of better and better stents has leveled off and CABG is now considered important using improved tools and techniques.

OBJECTIVE: To answer 'how', 'when' and 'why' use intraoperative CABG assessment with transit-time ultrasound.

When to Measure	On-Pump CABG	Off-Pump CABG
1.	With cross-clamp on, to check distal anastomoses	As soon as the distal anastomosis is completed with stabilizer in place
2.	With cross-clamp off, but still on-pump, to check distal anastomoses	With snare on proximal coronary to occlude competitive flow
3.	Off-pump, pre-protamine, to check body of conduit, i.e., twist, graft too short	Heart in normal position without the stabilizer to check correct conduit lie and length.
4.	Off-pump, post-protamine, to check flow through the graft before closing	Post-protamine, to check flow through the graft before closing

POINTS OF INTEREST

- Approximately 2 - 4% of bypass grafts are revised by surgeons who routinely use transit-time flow measurement intraoperatively.
- Eleven studies show that 4 - 12% of bypasses occlude within 3 weeks after surgery, usually due to technical errors or poor conduit choice.
- Flow measurement basics are easy to learn, but the more one uses it, the more one learns. Flow measurement helps surgeons become better surgeons.

CONCLUSION: In order to reduce technical errors, it is best practice to perform intra-operative assessment of bypasses.

References:

Farkouh ME, FREEDOM Trial Investigators *et al*, "Strategies for multivessel revascularization in patients with diabetes," N Engl J Med. 2012 Dec 20;367(25):2375-84.

Mohr FW *et al*, "Coronary artery bypass graft surgery versus percutaneous coronary intervention in patients with three-vessel disease and left main coronary disease: 5-year follow-up of the randomised, clinical SYNTAX trial," Lancet. 2013 Feb 23;381(9867):629-38.

Techniques and standards in intraoperative graft verification by transit time flow measurement after coronary artery bypass graft surgery: a critical review

Niclauss L, Dept. of Cardiovascular Surgery, University Hospital of Lausanne, Lausanne, Switzerland, Eur J Cardiothorac Surg. 2017 Jan;51(1):26-33.

BACKGROUND
Transit-time flow measurement (TTFM) is a quality control tool for intraoperative graft evaluation in coronary artery bypass graft (CABG) surgery.

OBJECTIVE
To present a critical review of the available literature using TTFM in CABG surgery that details precise parameters for flow evaluation, shows TTFM limitations, and proves its predictive impact on postoperative graft failure rate.

METHOD
PubMed database publications were reviewed, searching for intraoperative graft verification in coronary surgery by TTFM, with postoperative imaging follow-up (FU) modality. A special focus was on publications released after the 2010 European guidelines.

RESULTS
- Nine publications revealed an overall graft failure rate of 12%.
- Mean graft flow had a positive predictive value in the largest study. Cut-offs were proposed of at least 20 mL/min for internal mammary artery (IMA) grafts (partially confirmed guidelines) and 30-40 mL/min for saphenous venous grafts (SVGs).
- A correlation between graft flow, patency rate and severity of coronary stenosis, by indicating the fractional flow reserve, was found for IMA grafts.
- Increased pulsatility index and increased systolic reverse flow probably predict worse outcomes and may help identifying competitive flow.
- Diastolic filling, rarely indicated, could not be confirmed as the predictive marker.
- No significant correlation of TTFM and graft failure rate for radial and other arterial grafts could be found, partially due to the small number of these types of grafts analysed.
- Low TTFM sensitivity to reliably detect graft failure, as found in randomized analyses, is a major issue.

CONCLUSION
- Methodical limitations and varying threshold values for TTFM make a general consensus difficult.
- Influence of quantity (vessel territory distribution) and quality (myocardial scar) of the graft perfusion area, on TTFM and FU outcome, was not included by anyone and should be part of future research.
- TTFM is probably not the tool of choice to detect progressive late graft failure of SVG.
- TTFM values should be correlated with the type of conduit, and differentiated between early and late graft failure, to precisely confirm threshold values.

II. Flow-based Graft Patency Assessment

A. Introduction

Patent, functioning bypass grafts are necessary for successful CABG. Measurement of flow intraoperatively through newly constructed bypass grafts sets the stage for this surgical success. When inadequate graft flow indicates a problem, a surgeon can perform immediate revision, avert complications, and thereby ensure early graft patency.

The purpose for this handbook is twofold. It is to provide:

1) Basic flow measurement techniques to ensure successful measurements;
2) To relay best practices that have been demonstrated in clinical settings so that optimal patient outcomes can be obtained.

Successful flow-based graft patency assessment during CABG requires skillful surgical technique coupled with astute on-the-spot decisions during the course of the surgery. Moreover, it is important to follow an established graft patency assessment protocol to ensure correct interpretation of the measurements.

Flow measurements are technique dependent. Therefore, this chapter begins with a step-by-step procedure on pages 11 and 12 describing how to perform correct graft flow measurements with transit-time ultrasound flowmetry. A surgical team must be comfortable with the flow measurement technique and procedure to achieve successful measurements.

Secondly, the key components for successful patency assessment of coronary artery bypass grafts are delineated including all the conditions that must be taken into consideration for accurate graft assessment. Using clinical data, we provide a summary of flow analyses. Addressed are: the primary importance of mean flow, consideration of competitive flow, determining if a graft is in trouble, reasons (both physiologic and technical) for less than expected flows, and other factors that can be taken into consideration.

To measure is to know! Measuring bypass flow offers the surgeon a tool to detect otherwise undetectable flow restrictions before leaving the operating room.

B. Measuring Coronary Bypass Graft Flow

Pioneered by Cornelis Drost, transit-time ultrasound technology is the recognized gold standard for repeatable volume flow measurements.

Measurements are Technique Dependent

A surgical team must first be familiar and comfortable with the correct procedure for measuring coronary bypass graft flow. A correct-sized Flowprobe should be used with adequate ultrasound couplant to produce a good ultrasonic signal. Motion artifacts should be avoided by holding the Flowprobe still on the graft during the measurement.

Anatomy of a Transonic Coronary Flowprobe

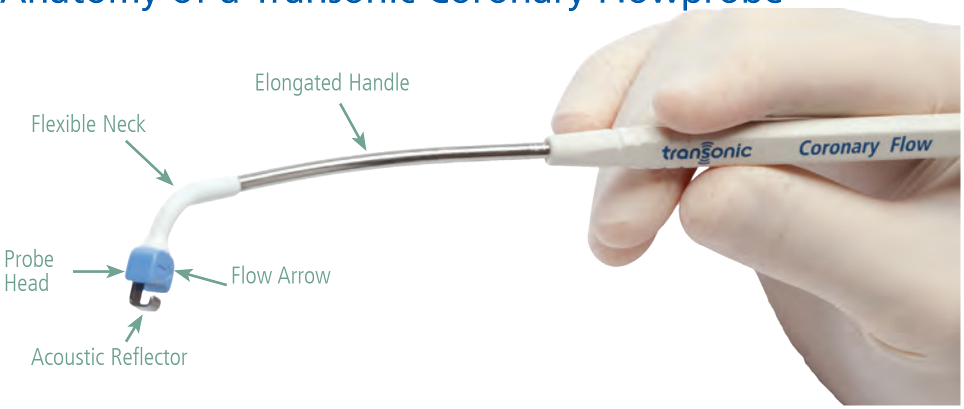


Fig. 2.1: A measurement tool used for CABG patency assessment, a Transonic Coronary Flowprobe's pliable neck bends as needed for positioning on a bypass graft. Its elongated handle allows convenient application of the Probe around any coronary artery bypass graft..

*Flow-Assisted Surgical Techniques ("F•A•S•T") and Protocols are drawn from surgical experiences by transit-time flow measurement users and passed along by Transonic for educational purposes. They are not intended to be used as sole basis for diagnosis. Clinical interpretation of each patient's individual case is required.

B. Measuring Coronary Bypass Graft Flow cont.

Step-by-Step Measurement Procedure

The following techniques are the result of 35 years of our users' best practices in flow measurement techniques and are necessary for proper measurement results. Flow-assisted patency tests are performed once the patient is off-pump:

1. If using an internal mammary artery graft, skeletonize a 1.5 cm segment of its distal end before performing the anastomosis. Vein grafts require no additional preparation.
2. Select a Flowprobe sized so that the graft will fill at least 75% of the window of the Flowprobe. Do not undersize the probe for the graft. Compressing a graft can cause changes in measurement accuracy.
3. Apply ultrasound couplant into the window of the Flowprobe. At this moment the meter will show the Flowprobe's 'zero offset." Confirm that this is appropriately low (under +1mL/min for the 1.5 and 2 mm probe, under +1.5 mL/min for the 3 mm probe, under +3 mL/min for the 4 mm probe). One of the following graft patency criteria relies on the Flowprobe's capability to perform within specifications under very low flow conditions.
4. Turn on FlowSound®. A low-pitch hum flow sound indicates that the Flowprobe is properly connected to the Flowmeter and that there is adequate ultrasound couplant within its flow-sensing window.
5. Place the Flowprobe on the graft, bending its flexible neck as needed for perpendicular placement. Avoid stretching, compressing, or kinking the graft. Do not place the Flowprobe over surgical clips or sutures. The measurement should be done about 1 cm proximal to the anastomosis. (Especially PI, but also D/S-ratio depend on distance to anastomosis.) The ultrasound's signal quality is indicated on the Monitor's display.
6. Observe the contraction of the heart while listening to FlowSound: a higher pitch indicates greater flow. Listen for a strong diastolic flow component.
   - Diastolic-dominant Left Heart Flow Sounds: Contracted muscle resists inflow. Therefore, on a good graft to the left heart, one would expect low flow (a pitch within one's vocal range) during systole, and a far higher pitched FlowSound (above one's vocal range) during diastole

Continued on next page.

B. Measuring Coronary Bypass Graft Flow cont.

Step-by-Step Measurement Procedure cont.

for a "Diastolic-dominant Flow Profile."

- Systolic/Diastolic Balanced Right Heart FlowSounds: The right side of the heart contracts less forcefully than the left heart. Therefore, bypass graft flow to a right heart coronary is less impeded during systole. Both systolic and diastolic FlowSounds to a good right heart graft will be above one's vocal range.

7. The average (mean) flow will display on the Flowmeter screen or its front panel.

8. If competitive flow is suspected, graft patency must be tested at its greatest graft flow. Temporarily occlude the native coronary artery proximal to the anastomosis and note any changes in the pitch and pattern of FlowSound®. An increase in FlowSound pitch or mean flow indicates the presence of competitive flow. If no competitive flow is observed, the occlusion may be released; otherwise maintain the occlusion during the patency test.

9. When flow waveform and mean flow have stabilized, press snapshot, print, or export buttons on the Flowmeter.

C. On-the-Spot Quality Assessment

Look for highly repetitive flow as shown in the SVG - RCA waveform (Fig. 2.2) and listen for repetitive pitches (flows) with FlowSound®.

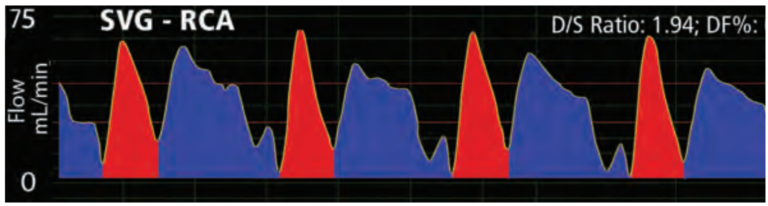


Fig. 2.2: Each flow beat should be a replica of the previous, without undue "noise" in the printout, without "jitter" in FlowSound.

If this is not the case, look for one of the following:

Motion Artifacts (Figs. 2.3a, 2.3b)

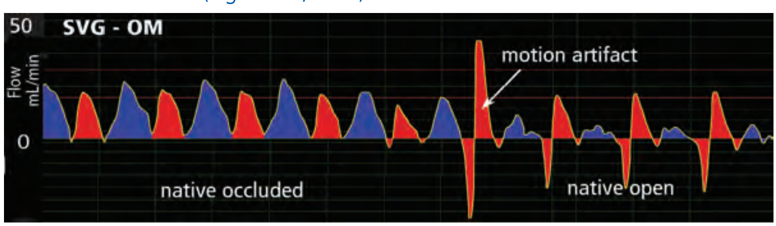


Fig. 2.3a: The left half of this trace is less repetitive due to motion caused by manual occlusion of the native coronary. A motion artifact (and change to repetitive flow pattern) is observed when the occlusion is released.

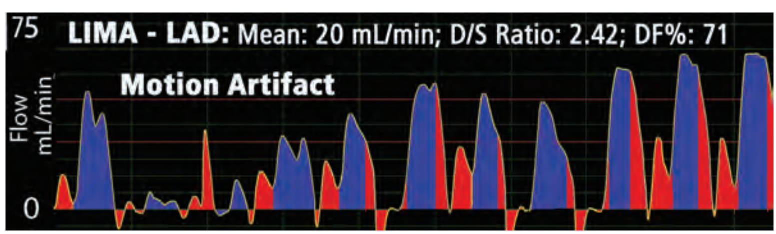


Fig. 2.3b: The non-repetitive left half of this LIMA - LAD waveform illustrates a motion artifact due to motion of the Flowprobe on the graft. As the Flowprobe is held steady on the graft, the waveform becomes more repetitive as shown on the right..

C. On-the-Spot Quality Assessment cont.

Probe Window Too Small for Vessel

A Flowprobe which compresses the graft induces its own waveform distortions with errors in mean flow and other metrics. A probe size must be selected for a nonconstrictive fit. Adequate acoustic coupling is attained through the use of couplant, rather than by forcing an over-sized vessel into the probe window. Do not to measure over surgical clips or suture material.

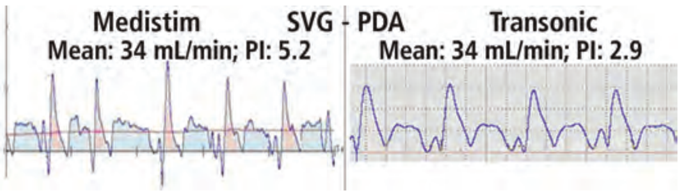


Fig. 2.4: These archival waveforms show a Medistim SVG - PDA waveform, on the left, recorded simultaneously with a Transonic SVG - PDA waveform. The pair exemplify how Pulsatility Index (PI) is affected by waveform integrity. Both waveforms record identical average flows of 34 mL/min, but the difference in PI (Meditim's 5.2 PI vs. Transonic's 2.9 PI) is therefore the result only of the spikiness of the Medistim waveform in comparison to the signature smooth repetitive profile of the Transonic waveform. Waveforms courtesy of R. Poston

Frequently Asked Questions

Will flow measurement detect an air bubble in a vein graft or in the distal vessel?

If the Probe is placed over an air bubble, it will not measure flow because air obstructs ultrasound transmission. The Flowmeter display will indicate "NO SIGNAL." Air bubbles elsewhere reduce mean flow and produce abnormal flow patterns. A sudden dip in an otherwise good waveform is typical in the event of a transient bubble.

How do you know the direction of graft flow?

Measuring graft flow does not reveal the direction of flow inside the native coronary artery. This is not an issue if the distal anastomosis is placed downstream from the coronary stenosis. Graft flow can only flow toward the distal myocardium. If a question exists in a mid-vessel anastomosis, occlude proximally, then distally, and measure both flows. The ratio between these two readings establishes the distribution of graft flow. If such measurements are unacceptable, they will be spotted in the Flow-QC® protocol.

D. Coronary Artery Bypass Grafting Protocol Overview[1]

Mean Flow is Primary (see pages 18-21).

Mean graft flow is the most important consideration to confirm graft patency or to alert the surgeon to an undesirable condition.

Mean Flow Assessment Rules of Thumb are simply: an adequately high flow indicates a patent graft; a very low flow indicates a potential problem with the graft.

1. Mean Flow ≥ 25 mL/min (small patients, >20 mL/min) = Patent Graft: If mean flow is less than expected, first consider the presence of competitive flow.
2. Mean Flow < 5 mL/min = Graft has a potential problem and demands further investigation including the consideration of other factors.

Competitive Flow

First and foremost, the presence of competitive flow must be considered (pages 25-28). If competitive flow is ruled out as the cause of the low flow reading, a variety of conditions can limit bypass graft flow. Consider the following:

- Mean graft flow can vary over a wide range. It is influenced by, and should be evaluated with respect to:
  - The patient's size, weight and physical condition;
  - The size and quality of the graft;
  - The size and quality of the target vessel;
  - Mean arterial pressure (MAP);
  - State of disease in the myocardial run-off.

> "Only a very low mean graft flow (e.g. 3 mm LAD with flow of less than 5 mL/min) can, in and of itself, imply poor graft performance. Conversely, a very high mean flow should be accepted as evidence of good graft patency, irrespective of other factors. Questionable mean flows should be further examined with waveform analysis."
>
> BP Mindich, MD

[1] Mindich BP *et al.*, "Reduction of Technical Graft Problems Utilizing Ultrasonic Flow Measurements," NY Thoracic Society, 2001.

D. Coronary Artery Bypass Grafting Protocol Overview cont.[1]

Low or Zero Flows Indicate a Graft in Trouble

If flow is still less than expected after flow is measured with the native coronary temporarily occluded to assess competitive flow, the surgeon can consider various other factors that could influence and possibly limit flow. These include:

1. Physiologic Factors:
   - Vasospasm of arterial grafts;
   - Mean arterial pressure;
   - Run-off quality of the myocardium;
   - Size of target coronary vessel;
   - Size and quality of the bypass graft;
   - Size and health of the patient.
2. Technical Problems
   - Thrombus;
   - Twists or kinks in the graft;
   - Run-off quality of the myocardium;
   - Misapplied stitch at the anastomosis;
   - Kinking of graft during chest closure.
3. Other Considerations
   - Use of IABP for ventricular support.

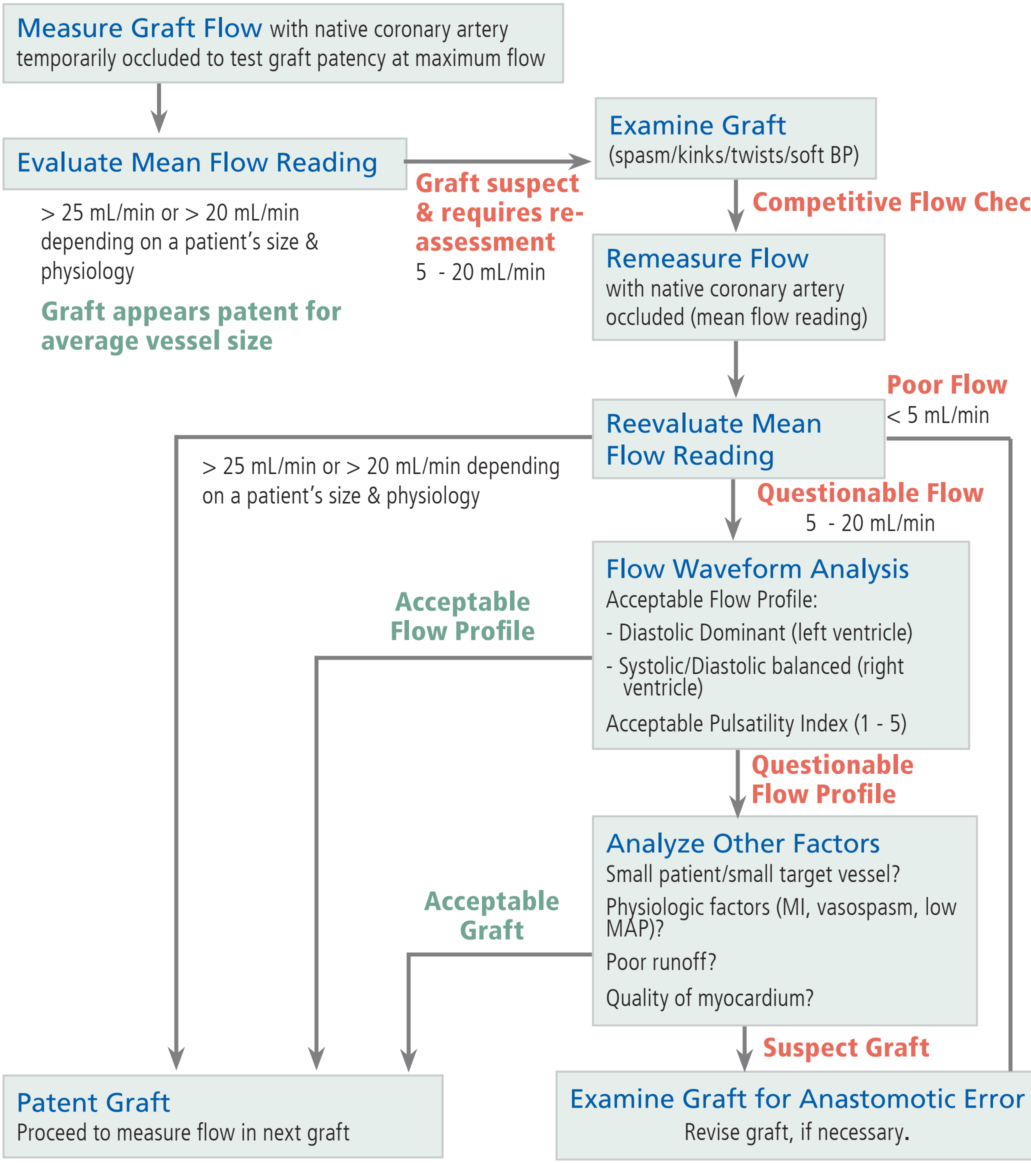
Waveform Analysis for Medium Range Mean Flows

If flow values fall in the medium range (more than 5 mL/min but less than 20-30 mL/min), flow waveform analysis can shed light on a possible problem. Flow waveforms should be first evaluated to see if they exhibit a repetitive flow pattern characteristic for the target ventricle it is supplying (left ventricle: diastolic dominant grafts; right ventricle: more balanced systolic and diastolic waveforms). Does the waveform exhibit competitive flow? If not and the profiles exhibit a stenotic pattern as shown on page 30, the graft should be reexamined to assess other factors that may account for a lowered flow such as small target vessel, small patient, small graft capacity, or poor runoff.

[1] Mindich BP *et al.*, "Reduction of Technical Graft Problems Utilizing Ultrasonic Flow Measurements," NY Thoracic Society, 2001.

II. Flow-based Graft Patency Assessment cont.

D. Coronary Artery Bypass Grafting Protocol Overview cont.



Flow Chart 1: Flow Chart of Flow-based Bypass Patency Protocol

E. Mean Flow Assessment

1. Assess Graft Mean Flow

Mean graft flow is the first consideration to confirm graft patency or to alert the surgeon to an undesirable condition.

- Normal (or higher) Mean Flow = Patent Graft
  See Table on the next page for a compilation from the scientific literature of the "Normal Flow Range" for various types of coronary grafts. Flows > 30 mL/min indicate a good graft flow. A number of conditions can limit bypass graft flow. First and foremost, the presence of competitive flow must be considered as the cause for less than expected flow (see pages 25-28).
- Occlude the Native Coronary Artery. Compare mean flow with and without occlusion of the native coronary artery to reveal the presence or absence of competitive flow. Occlusion of the native coronary creates optimal conditions for maximal flow through the graft and uncomplicated flow waveforms.
- If flow is still less than expected after the native coronary has been temporarily occluded and flow remeasured, the surgeon must consider other factors that might influence and possibly limit flow.

2. Mean Flow < 5 mL/min; Almost Always Indicates a Graft in Trouble

A very low flow of a coronary artery bypass graft is cause for concern. A Mean Flow under < 5 mL/min indicates that the graft needs to be examined. The low flow may be caused simply by a twisted graft, by competitive flow from the native coronary, or by flow into the third branch of a jump graft. However, it also might be a misplaced anastomotic stitch that creates constriction of the anastomosis.

- Look for kinks, twists in the graft, low MAP, vasospasm.
- Redo the anastomosis if indications point to technical error.

3. Medium Range Mean Flows (5 mL/min - 20 mL/min): Analyze Graft Flow Waveforms

If flow values fall in the medium range (more than 5 mL/min but less than 20-30 mL/min), flow waveform analysis can shed light on a possible problem.

- Evaluate flow waveforms to confirm that they exhibit the expected pattern (see pages 29-30). For left ventricle grafts, look for a

E. Mean Flow Assessment cont.

diastolic dominant waveform. For right-ventricle grafts, look for a systolic/diastolic balanced waveform.

- Assess other factors that may account for a lowered flow: (see pages 37-48) such as small patient, small target vessel, small graft capacity, poor myocardial runoff.

Graft	Mean Flow Readings - Off CPB Cases[1,2]			
	# of Cases	Normal Flow Range (85% of cases)	Questionable Flow (requires further test & diagnosis)	Obstructed Flow (graft with technical error)
LIMA - LAD	175	> 27 mL/min	5 to 27 mL/min	
RIMA - RCA	11	> 26 mL/min	5 to 26 mL/min	
SVG - RCA	117	> 29 mL/min	5 to 29 mL/min	
SVG - Diag	54	> 21 mL/min	5 to 21 mL/min	Any flow < 5 mL/min
SVG - OM$_1$, OM$_2$	125	> 29 mL/min	5 to 29 mL/min	
SVG - PDA	45	> 24 mL/min	5 to 24 mL/min	
SVG - Cx	62	> 48 mL/min	5 to 48 mL/min	

[1] On CPB readings are typically 25% below off-CPB readings.
[2] The normal range is average minus one standard deviation of the reported readings. This captures approximately 85% of observations.

Table 1: Typical mean flow readings of coronary bypass grafts compiled from statistical averages of 589 transit-time flow measurements in the American population. Data courtesy of B. Mindich M.D.

Mean Flow Rules of Thumb

Mean flow is the primary determinant of graft quality and alerts the surgeon to one of three graft conditions

1. Mean flow falls within the normal range (20 mL/min) or above: the graft provides adequate flow and may be considered patent.
2. Mean flow below 5 mL/min: flow is unacceptably low; the graft is compromised and requires further examination.
3. Mean flow between 5 mL/min and normal range: further analysis should be performed to assess whether the graft delivers acceptable flow.

E. Mean Flow Assessment cont.

Mean graft flow can vary over a wide range. It is influenced by, and should be evaluated with respect to:

- The size and quality of the graft;
- The size and quality of the target vessel;
- Mean arterial pressure;
- Run-off quality of the coronary bed.

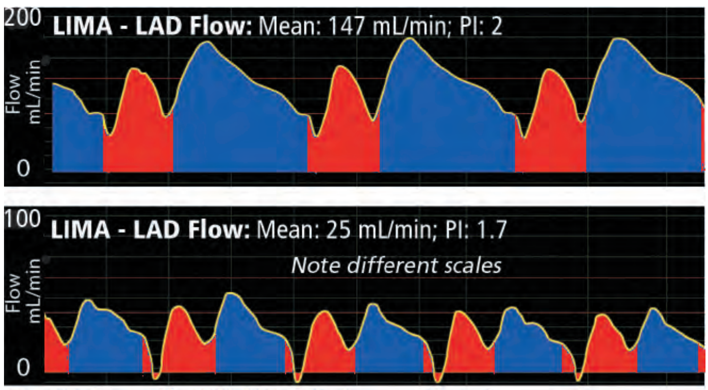


Fig. 2.5: Acceptable LIMA-LAD grafts in two patients demonstrate a range in average flows. The top graft can be considered patent based solely on mean flow (147 mL/min). The bottom graft required waveform analysis because of its questionable mean flow reading (25 mL/min). Its strong diastolic flow component indicates a patent graft.

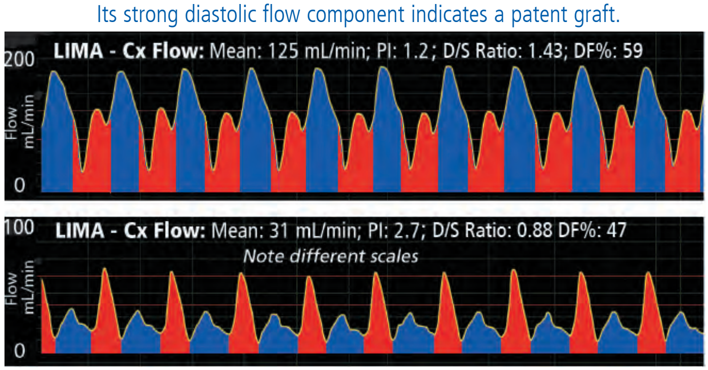


Fig. 2.6: LIMA to LCc (circumflex) grafts in two patients also demonstrate a range of acceptable mean flows.

2023 Refinements to CABG Assessment Protocol

Although the fundamentals of our time-tested quantitative CABG Patency assessment protocol remain intact, recent coronary flow research[1,2] have resulted in the following refinements to the protocol:

Mean Flow: The Transonic current F•A•S•T protocol states that Mean Flow Assessment is primary and is the most important consideration to confirm graft patency or to alert the surgeon to an undesirable condition. We now know that Mean Flow alone (after other causes are ruled out) will identify only the most severe (critical) anastomotic constriction (AHA angiography grading of 75% or more, see table on page 31). Pulsatility Index (PI) is a similar metric that identifies such severely compromised grafts – but PI measures "spikiness" of the flow and therefore, is subject to other errors that generate flow spikes such as motion artifacts and graft wall compliance, and will provide more false positives.

Flow Waveform Analysis: For less severely (sub-critical) compromised CABG grafts (AHA grading of 50% stenosis), a flow waveform analysis needs to be performed, with a metric that compares systolic flow versus diastolic flow. A sensitive test is the Transonic D/S Ratio (a direct comparison of blood volume delivered during diastole versus blood volume delivered during systole), followed by DF% (a comparison of blood volume delivered during diastole versus blood volume delivered during diastole plus systole; this somewhat dilutes the direct diastolic-systolic comparison).

Mean Flow Plus D/S Ratio: The combination of Mean Flow and D/S Ratio provides the CABG surgeon with a quick quantitative measurement assessment tool, before the patient is closed, to assess whether a CABG graft is possibly compromised. One drawback of this assessment approach for the on-pump surgeon is that the measurement is performed after the patient is taken off-pump rather than during construction of the graft.

Therefore, the on-pump surgeon should always perform a baseline Mean Flow measurement on-pump after each graft is constructed with which they can compare to the measurements performed after the patient has been taken off pump.

References:

1. Takahashi K, Morota T, Ishii Y, "A novel transit-time flow metric, diastolic resistance index, detects subcritical anastomotic stenosis in coronary artery bypass grafting," JTCVS Tech. 2022 Dec 13;17:94-103.
2. Drost S, Drost C, Flow-based CABG patency evaluation: physical and statistical background. DRI(CV-30-wp)RevA2022A4

Saphenous vein grafts in contemporary coronary artery bypass graft surgery

Caliskan E. *et al*, German Heart Institute Berlin, Berlin, Germany., Nat Rev Cardiol. 2020 Mar;17(3):155-169.

OBJECTIVE

- To present a comprehensive review of saphenous vein graft (SVG) use during CABG;
- To discuss current practices to prevent vein graft disease (VGD) and vein graft failure (VGF).

KEY POINTS

- SVGs are associated with 10-year VGF rates of 40–50%.
- VGD and VGF result from endothelial damage attributable to mechanical harm and ischemia–reperfusion injury to the vein graft. VGD/VGF is characterized: within hours to <1 month post CABG by SVG thrombosis; 1–12 months post CABG, by intimal hyperplasia in the SVG; >12 months post CABG, by atherosclerosis of the SVG.
- A meticulous harvesting strategy to reduce surgical trauma and avoid excessive handling and distension is required to prevent VGD and VGF.
- Traditional intraoperative preservation solutions, such as saline or autologous whole blood, cannot sufficiently preserve the endothelium and might even be harmful to SVGs.
- Intraoperative graft flow assessment (transit-time ultrasound) is important in identifying grafts that have initial low flow. It provides an opportunity to correct an issue intraoperatively and has resulted in major revision of bypass grafts in 2–4% of CABG patients. Mean graft flow should be 15–20 mL/min; pulsatility index (PI) should be between 1 and 3 (between 3 and 5 is also deemed acceptable). Epicardial ultrasonography or thermal imaging can also identify grafts with low flows that can be revised intraoperatively. Combining functional graft assessment TTFM with anatomical epicardial ultrasonography further increases the sensitivity of the graft evaluation process.

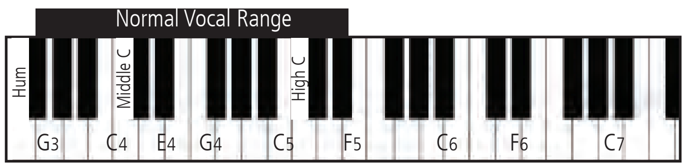
CONCLUSIONS

- SVGs are still used in most CABG patients due to its availability, harvest ease and speed, handling ease during anastomosis, and no increased risk of sternal wound complications.
- A systematic, step-by-step, best practice approach to improve long-term SVG patency rates, should include:
  1) Meticulous SVG harvesting technique to reduce surgical trauma and excessive manipulation of the SVG and its associated long-term complications.
  2) A good intraoperative preservation and storage strategy to minimize ischemia and reperfusion injury to the SVG endothelium.
  3) Intraoperative graft assessment to help identify grafts that might fail early and lead to revision of the low-flow graft, thereby improving graft patency.
  4) A meticulous anastomosis technique, careful anatomical considerations, and optimal postoperative pharmacological treatment are essential in achieving good long-term SVG patency.

F. FlowSound® Volume Flow Analysis

Transonic's proprietary FlowSound translates volume flow into an audible pitch that allows assessment of bypass graft patency without looking away from the surgical field. A musically attuned surgeon, comfortable with the FlowSound tool, can save precious minutes in confirming functionality of his or her grafts following anastomosis.

With FlowSound, the higher the pitch, the higher the volume flow. When the pitch is high, flow is good. When the pitch is low or is dropping, flow is dropping proportionally. At zero flow, the sound is a low hum. Sounds within the normal vocal range are generally too low for a patent CABG graft.



1.5; 2 mm	<0.9	1.5	2.5	3.5	6	10	15	25	50	100
3 mm	<1.8	3	5	7	12	20	30	50	100	200
4 mm	<3.5	6	10	14	25	40	60	100	200	400
Probe	Flow in mL/min									

Transonic Flowprobes' Flow - to - Pitch (FlowSound) Conversion		
Probe Size	Acceptable FlowSound Flow Ranges	Volume Flow
1.5; 2 mm	≥ C6 (an octave above high C)	≥ 25 mL/min
3 mm	≥ F5 (F above high C)	≥ 25 mL/min
4 mm	≥ C5 (High C)	≥ 25 mL/min

Fig. 2:7: FlowSound pitch-to-flow conversion for CABG 1.5 mm - 4 mm Flowprobes. Comparing FlowSound pitches between systole and diastole provides feedback on the systolic/diastolic flow ratio and graft patency.

Frequently Asked Question

I'm reading a low graft flow. How do I know that this is accurate, and not just a problem in the Flowmeter?

Turn on FlowSound® and occlude the graft with the thumb and index finger. By occluding and releasing, you create an intermittent flow, which will be reflected in the change in pitch. A high-pitched FlowSound® indicates that the probe is measuring flow — when there is flow.

II. Flow-based Graft Patency Assessment cont.

F. FlowSound® Volume Flow Analysis cont.

Benefits

- Provides audio feedback on signal quality. A low hum indicates good ultrasonic contact.
- Provides instantaneous feedback on changing flow conditions. Technical errors in a newly created bypass can be heard and corrected by listening to FlowSound. For example, a surgeon can manipulate a kinked vessel or graft and immediately detect an improvement in flow.

FlowSound Pitch

An increase in FlowSound's pitch by one-half tone (E to F [Mi to Fa]) corresponds to a 12.5% increase in volume flow. One full tone increase in pitch (F to G [Fa to So]) corresponds to a 25% volume flow increase. An octave (C to C [Do to Do]) change in pitch equates to a four-fold volume flow increase.

FlowSound

No Sound	=	No Signal
(apply gel or saline inside flowsensing window)		
Low Pitch (Hum)	=	ZERO or Low Flow
Higher pitch	=	Higher flow

FlowSound Pitch Validation

A mathematical equation governs the conversion from flow value to tone pitch. The computer generates these pitches with its oscillator frequency-controlled software that Transonic software designers validate.

Note: For a complete explanation of how to use FlowSound with FAST (Flow-Assisted Surgical Technique), see FlowSound Technical Note (CV-23-tn).

G. Competitive Flow Assessment

A graft's capacity to deliver flow may be reduced by factors other than graft patency. One such factor is competitive flow which results when a partly stenosed native coronary continues to contribute flow to the post-anastomotic segment. Thus, the full flow potential of the bypass graft is not realized.

To test the maximum flow capacity of a graft, competitive flow from the native coronary artery must be blocked. Two measurements are necessary: one without occlusion of the native coronary and one with occlusion by finger pressure, instrument pressure, etc. Competitive flow can be instantly recognized by portions of the waveform dropping below the zero line with every beat creating a negative flow through the Flowprobe. An increase in graft flow with the native coronary artery occluded also indicates the presence of competitive flow. One can also listen with FlowSound® to the differences in the two measurements to determine the presence of competitive flow.

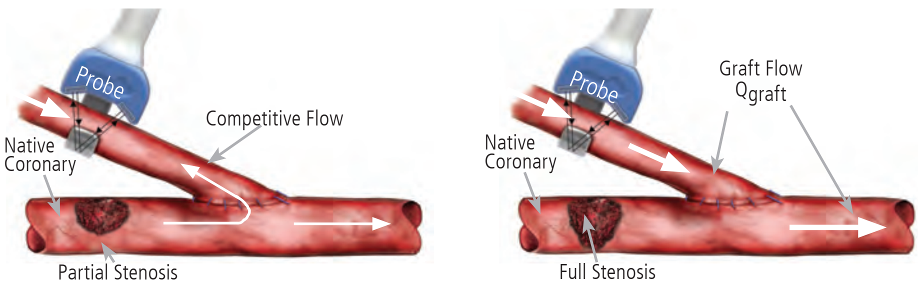


Fig. 2.8: Measuring graft flow with occlusion of the native coronary proximal to the anastomosis allows for maximal flow through the graft.

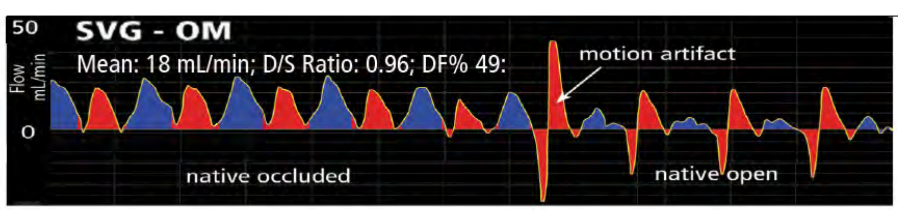


Fig. 2.9: This trace demonstrates the advisability of taking flow measurements with and without occlusion of the native coronary. With the native open, mean flow approaches zero. With the native artery occluded, flow increased to approximately 18 mL/min with a good systolic/diastolic pattern (patent graft) which indicates that native flow was competing with graft flow.

G. Competitive Flow Assessment cont.

Examples of Competitive Flow

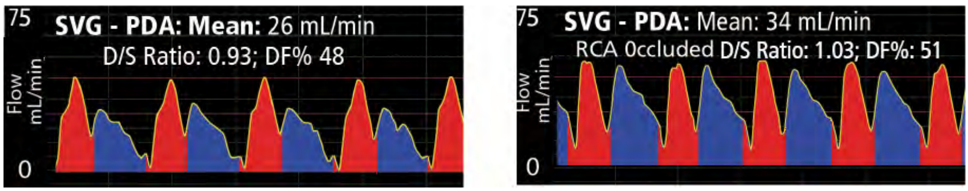


Fig. 2.10: SVG - PDA graft flow increased from 26 mL/min to 34 mL/min when the RCA was occluded.

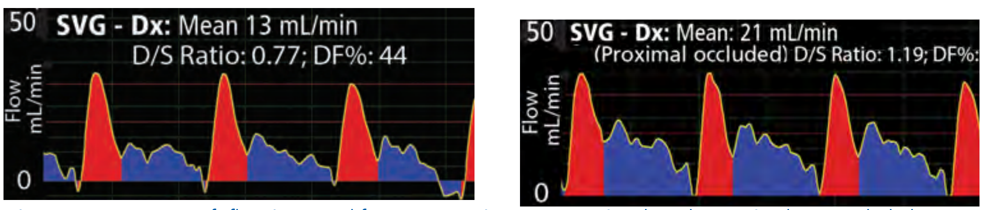


Fig. 2.11: SVG - Dx graft flow increased from 13 mL/min to 21 mL/min when the proximal was occluded.

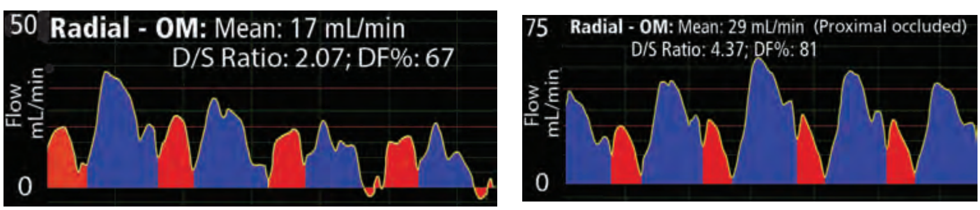


Fig. 2.12: Rad - OM graft flow increased from 17 mL/min to 29 mL/min when the proximal was occluded.

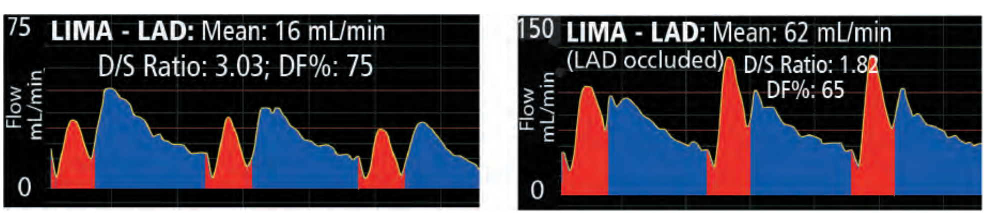


Fig. 2.13: LIMA - LAD graft flow increased from 16 mL/min to 62 mL/min when the proximal LAD was occluded.

G. Competitive Flow Assessment cont.

Patency Analysis with Competitive Flow Assessment

If competitive flow is suspected, two consecutive flow measurements are recommended: one without occlusion of the native coronary artery and a second with occlusion (snare, finger, or instrument pressure etc.). When compression fails to increase graft flow, a 100% stenosis is indicated. Subsequent graft flow measurements can then be made without further coronary occlusion. If occlusion of the native coronary produces a higher graft flow reading, competitive flow from the native coronary is present. In such instances, the graft patency analysis should be based on flow observations taken with full coronary occlusion.

- A short negative pulse in the systolic phase of the flow waveform may or may not indicate the presence of competitive flow. However, the absence of a negative pulse does not rule out the possibility of competitive flow.
- Such a negative flow pulse will occur, typically, at the start of systole, but may occur at the end of systole as well.
- Competitive flow reduces graft flow, and therefore reduces the predictive value of graft flow as a measure of graft patency.
- If flow is too low, but the anastomosis is good, consider one or more additional grafts to the affected field.

Frequently Asked Question

I see a good (≥ 30 mL/min) graft flow without proximal occlusion of the native coronary. Should I still occlude the native coronary and remeasure?

With a ≥30 mL/min mean flow reading, the graft passes the primary Flow-QC® patency test; a higher flow reading with competitive flow occluded will not alter a surgical course. One could, therefore, proceed without a measurement with the native coronary occluded.

A Technique for Evaluating Competitive Flow for Intraoperative Decision Making in Coronary Artery Surgery[1]

Bolotin G, Chitwood WR *et al.*, Ann Thorac Surg 2003; 76: 2118-20.

INTRODUCTION

"...the simple intraoperative technique is effective for measuring and evaluating native and competitive graft flow, and it is an important tool for intraoperative decision making."

STUDY TECHNIQUE

To estimate competitive flow after CABG, graft flow measurement was performed both with the native coronary open and after the proximal coronary artery was closed for several seconds. Flow was again measured when the native proximal vessel was reopened.

TWO CASE EXAMPLES

In the first, flow in the LIMA increased from 22 mL/min to 48 mL/min when the native coronary was occluded. Upon release of the snare, LIMA flow returned to 23 mL/min. The surgeons concluded that the anastomosis was optimal and the relative low flow was due to native coronary competitive flow. The second case study demonstrated how graft flow measurement influenced intraoperative decision making. LIMA flow increased to only 15 mL/min when the coronary was occluded. The surgeons concluded that the poor graft flow was due to a combination of a poor target vessel and competitive flow. They added a short SVG segment to the distal LAD to increase the LAD blood supply and as a preventative for possible LIMA closure due to low flow. After revision flow increased to 20 mL/min.

Case #1 Bypass Graft	Native Coronary Open	Native Coronary Occluded	Native Coronary Reopened	Analysis
LIMA-LAD	22 mL/min	48 mL/min	23 mL/min	competitive flow present bypass optimal

Case #2 Bypass Graft	Native Coronary Open	Native Coronary Occluded	Analysis	Graft was Revised; Flow After Revision
LIMA-LAD	minimal flow	15 mL/min	Competitive flow; Poor graft	20 mL/min

OBSERVATION

These two cases underscore the importance of occluding the native coronary artery to determine native coronary competitive flow during intraoperative assessment of graft patency.

H. Flow Profile Assessment

Waveform analysis is necessary when mean flow falls in the "questionable range." In the left ventricle, blood flow occurs primarily during diastole. The off-CPB graft flow profile is characterized by a systolic peak followed by a stronger, longer diastolic peak. The systolic and diastolic phases can be identified by the following rule of thumb: the systolic phase lasts one-third of a heart beat and diastolic phase lasts two-thirds.

Diastolic-Dominant Pattern

For left ventricle grafts, the peak that is smaller in height and duration is usually systolic, and the higher, broader peak is diastolic (Fig. 2.14). An exception occurs in the presence of severe tachycardia when the duration of diastole is shortened. An acceptable left ventricular graft waveform is diastolic dominant. The delivered diastolic blood volume (i.e., blue area under diastolic curve) exceeds the delivered systolic blood volume.

Fig. 2.14: LIMA-LAD: mean = 147 mL/min; diastolic dominant; PI =2.

Balanced Systolic/Diastolic Pattern

In grafts to the right ventricle, flow is more equally distributed between the systolic and diastolic phases. This produces a flow waveform where the systolic peak may dominate but is followed by a proportionally strong diastolic flow producing a systolic/diastolic balanced waveform (Fig. 2.15).

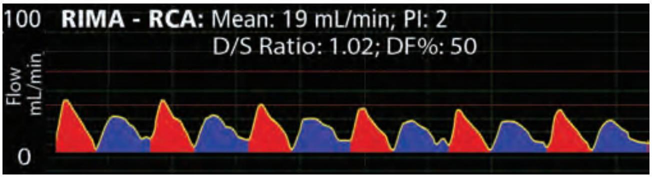


Fig. 2.15 RIMA - RCA: mean is 19 mL/min. systolic/diastolic balanced; PI=2

Questionable Flows

For questionable mean graft flows (5 - 30 mL/min), the graft is evaluated through systolic/diastolic waveform properties using FlowSound®, a printout, or snapshot to examine the graft. A rule of thumb is that systole lasts one-third of a heartbeat and diastole lasts two-thirds.

H. Flow Profile Assessment cont.

Stenotic Pattern

In case of an occlusion distal to the graft (e.g. technical error in anastomosis, or stenosis in the native coronary), antegrade flow is observed during systole, creating a systolic peak. During diastole, the flow reverses, resulting in an (almost) equally strong retrograde peak,and low to zero mean flow rate. Such a flow profile indicates that the graft should be inspected. Alternatively, if stenosis distal to the graft is suspected, another graft should be considered.

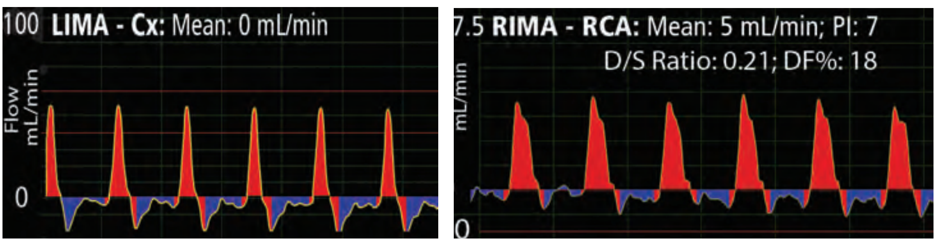


Fig. 2.16a Above, left and top right: Examples of grafts with stenotic flow profiles. In both the LIMA - Cx graft and the RIMA - RCA graft, the flow waveforms indicate (almost) purely capacitive flow (i.e. graft "inflating" and "deflating").

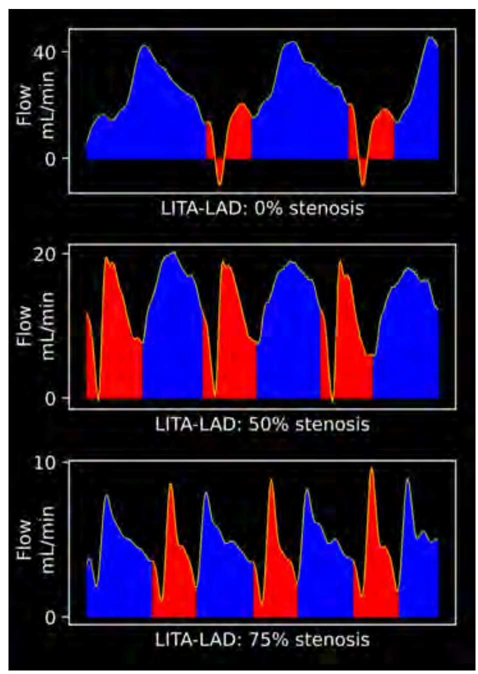


Fig. 2.16b: Representative LIMA-LAD flow waveforms for 0%, 50%, and 75% graft stenoses. Note change in scales of the three examples (data courtesy of Takahashi et al., Nippon Medical School, Tokyo, Japan).

I. FlowTrace® ECG, Diastolic/Systolic Ratio (D/S), Diastolic Filling Percentage (DF%), Diastolic Resistance Index (DRI)

FlowTrace software uses ECG signals to analyze and display D/S Ratio and DF%, two expressions used to represent the amount of blood flow through a bypass graft that occurs during diastole. A D/S Ratio compares diastolic flow to systolic flow, and a DF% compares diastolic flow to flow occurring during both systole and diastole.

Expressed mathematically:

$$\text{D/S Ratio} = \frac{\text{total diastolic flow}}{\text{total systolic flow}}$$

Transonic's D/S Ratio is an extension of Transonic's FlowSound analysis. Surgeons are encouraged to listen to FlowSound while simultaneously examining the corresponding flow waveform. FlowSound and waveform analyses correlate with Transonic's coronary artery graft assessment where:

- D/S Ratio >2 indicates an acceptable diastolic-dominant flow profile;
- D/S Ratio between 1 and 2 indicates a diastolic-systolic balanced flow profile which is acceptable for a right heart bypass;
- D/S Ratio <1 indicates a systolic dominant flow profile which signals the need for further examination of the graft if mean flow is also low.

Diastolic Filling is expressed as a percentage:

$$\text{DF\%} = \frac{\text{average diastolic flow}}{\text{total (diastolic + systolic) flow}} \times 100$$

- DF% >67% indicates a diastolic-dominant flow profile.
- DF% between 50% and 67% indicates a diastolic-systolic balanced flow profile.
- DF% <50% indicates a systolic dominant flow profile.

Comparison Between DS Ratio and DF% for Graft Patency Assessment			
	Systolic Dominant	Diastolic-Systolic Balanced	Diastolic Dominant
DS Ratio	>1	1 - 2	>2
DF%	<50%	50% - 67%	>67%

II. Flow-based Graft Patency Assessment cont.

I. FlowTrace® ECG, Diastolic/Systolic Ratio (D/S), Diastolic Filling Percentage (DF%), Diastolic Resistance Index (DRI) cont.

Optional New Parameter

Transonic founder Cor Drost conceived conceptually and undertook validation of Diastolic Resistance Index (DRI- the ratio of arterial graft pressure to arterial graft flow) to quantify invisible arterial stenoses into a surgically meaningful metric. If the Flowmeter is connected to the patient's radial artery pressure signal, you may implement Pressure/Flow-based diastolic-systolic graft patency assessment using DRI, a novel parameter that is indicative of the resistance of the anastomosis between the graft and the coronary vessel.

The Nippon Medical School (NMS) and Dr. K Takahashi recently performed a study on the effectiveness of the DRI parameter in predicting CABG patency. The results are now published online by *JTCVS Techniques*, so are now accessible for anyone with a working internet connection. (See Publication Brief on next page.) The NMS paper suggests a 3-tiered system for classifying stenosis: "patent," "sub-critically stenosed," and "critically stenosed." DRI was found to be an excellent indicator in the most critical cases—and of significant note—a statistically better predictor than Pulsatility Index.

Additionally, the parameters derived from the flow waveform—Diastolic/Systolic Ratio and Diastolic Filling help the surgeon assess the "sub critical" stenosis. In concert with DRI, a broad range of stenotic assessment with high accuracy is possible.

AHA Angiography Grading, Percent Stenosis, Takahashi Grading					
AHA Angiography Grading	0	50	75	90	99
Percent Stenosis	(0 - 25)	(26 - 50)	(51 - 75)	(76 - 90)	(>90)
Takahashi Grading of Stenoses	Patent (0 - 49)		Subcritical (50 - 74)	Critical (≥75)	

Table 1: Comparison of AHA Angiography grading, percent stenosis, and Takahashi grading of stenoses.

A novel transit-time flow metric, diastolic resistance index, detects subcritical anastomotic stenosis in coronary artery bypass grafting

Takahashi K *et al,* Nippon Medical School, Tokyo, Japan, JTCVS Techniques 2023.

BACKGROUND

There is general consensus, based on present literature, that transit time flow measurement (TTFM) can detect critical anastomotic stenoses during coronary artery bypass grafting (CABG). However, subcritical stenoses (50%-74%) are challenging to detect using TTFM.

OBJECTIVE

To test the hypothesis that diastolic resistance index (DRI), a novel TTFM metric used to measure changes in the diastolic versus systolic resistance of distal anastomosis, is more effective in evaluating subcritical stenosis than other currently available TTFM metrics.

METHODS

- During coronary artery bypass grafting (CABG), mean graft flow (Q_{mean}), pulsatility index (PI), and diastolic filling (D/S, DF%) were measured or calculated on 35 CABG patients. During off-pump CABG, TTFM was obtained just after each bypass was created. During on-pump CABG, TTFM was performed after weaning from cardiopulmonary (CP) bypass.
- A total of 123 anastomoses involving 55 (45%) anastomoses for LAD or diagonal branches, 39 (32%) anastomoses for left circumflex arteries (LCx), and 29 (23%) anastomoses for right coronary arteries (RCA) were analyzed.
- Additional data (DRI) was calculated using the Transonic AureFlo Flowmeter connected to the vital sign monitor to record real-time arterial pressure measured via an arterial line placed in the radial or femoral artery.
- To assess the effect of competitive flow on TTFM parameters, flow profiles were measured with and without the proximal coronary snare applied for each anastomosis.
- Postoperatively, stenosis of anastomoses was categorized into successful (<50%), subcritical (50%-74%), and critical (≥75%) via multidetector computed tomography scan.

RESULTS

- In total, 93 (76%) anastomoses were graded as successful, 13 (10%) subcritical, and 17 (14%) critical.
- DRI and DF% could distinguish subcritical from successful anastomoses ($P < .01$ and $< .01$, respectively). Q_{mean} and PI could not ($P = .12$ and .39, respectively).
- Receiver operating characteristic curves were used to evaluate the diagnostic ability for detecting ≥ 50% stenosis.

CONCLUSIONS

Among existing patency metrics, D/S-ratio and DF% had the best diagnostic value for detecting critical and subcritical stenoses. The performance of DRI was comparable.

I. FlowTrace® ECG, Diastolic/Systolic Ratio (D/S), Diastolic Filling Percentage (DF%), Diastolic Resistance Index (DRI) cont.

Diastolic/Systolic Calculation Prerequisites

In order to clearly delineate systolic and diastolic phases of a flow waveform, FlowTrace relies on a signal analysis of the ECG trace. FlowTrace only performs the calculation of the D/S Ratio with associated flow waveform coloring when it:

- Is connected to a compatible Transonic Flowmeter
- Has a stable ECG signal that can be analyzed by FlowTrace software to identify systolic and diastolic phase demarcations.

ECG Signal Specification Prerequisites

The ECG signal input capability, derived from any slaved device such as the anesthesia monitor, the TEE machine, or the defibrillator is connected to a compatible HT300-Series Flowmeter via a cable provided with the system.

Differences from a Chart Recorder's Visual Identification of Systole and Diastole

FlowTrace identifies the systolic and diastolic phases of the heart's electrical activity on the ECG. HT300-Series Flowmeters utilize mean flow, FlowSound, and a strip-chart recorder to analyze and record the effects of the heart's contraction and relaxation. Because electrical evidence of contraction and relaxation precede the mechanical effect, there is a slight time delay between the colorization points on the ECG and the corresponding points on a flow waveform. During isovolumetric contraction, there is no initial systolic effect on coronary flow. Comparably, during isovolumetric relaxation, coronary flow continues to perfuse the myocardium. These time lags result in coronary flow overlapping into the next mechanical phase of the heart's cycle, and the delays are reflected on the flow waveform.

Note: For complete explanation of DS Ratio and DF%, see DS Ratio & DF% Technical Note (CV-54-tn).

J. Pulsatility Index Assessment

Pulsatility Index (PI) is a combined measure of average flow and flow waveform. It is defined as the difference between the maximum flow and the minimum flow divided by the mean flow:

$$PI = \frac{(\text{Maximum Flow Value}) - (\text{Minimum Flow Value})}{(\text{Mean Flow Value})}$$

- A PI less than 5 supports an acceptable graft.
- A PI of more than 5 is often considered indicative of technical error[1] as illustrated in Fig. 2.17.

However, the danger of relying solely on Pulsatility Index to assess graft patency is that a graft can be bad, but still have an acceptable Pulsatility Index (see case report on the next page). Similarly, a PI >5 may result from competitive flow in a flawless graft (false negative).

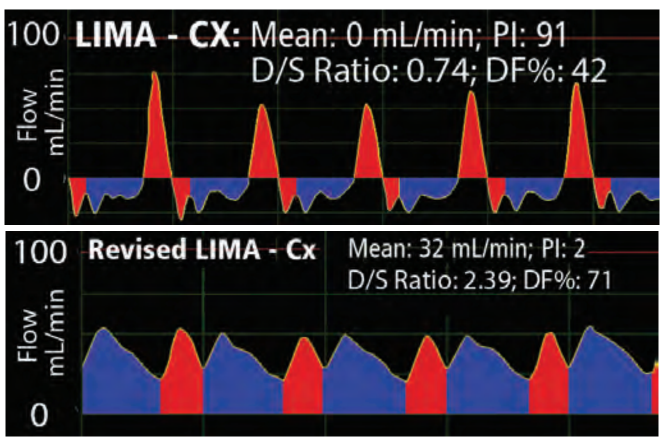


Fig. 2.17: Example: Trouble in a LIMA to circumflex graft with zero flow prior to revision is also indicated by a high PI (91). After revision, flow improved to 32 mL/min and PI became an acceptable 2.

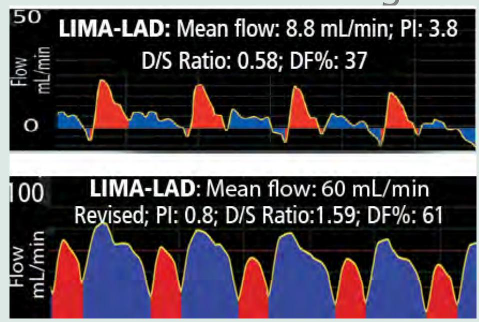
Conclusion: PI may be used as a secondary indication of graft patency, but a proper assessment must consider mean flow and waveform pulsatility separately. See CABG Protocol on pages 15-17.

J. Pulsatility Index (PI) cont.

Case Report: LIMA - LAD Graft 3.8 PI Is False Negative

A 65-year-old male patient underwent coronary artery bypass grafting (CABG) surgery to bypass a lesion in the left anterior descending (LAD) artery utilizing a left internal mammary artery (LIMA) graft. Initial LIMA-LAD mean flow measured 8.8 mL/min (PI: 3.8) (upper waveform).

The graft was revised. Following revision, LIMA-LAD mean flow improved to 60 mL/min (PI: 0.8; D/S Ratio: 1.59; DF%: 61) and was accompanied by a classic, diastolic dominant waveform profile (bottom waveform).



Flow in the top LIMA-LAD graft measured 8.8 mL/min with a PI of 3.8. Following revision flow increased to 60 mL/min and was accompanied by a diastolic dominant waveform profile (bottom waveform).

Summary: Off-CPB CABG; LIMA - LAD graft; 65-year-old male, multi-vessel coronary artery disease						
Flow Measurement	Mean Flow (mL/min)	PI	D/S Ratio	DF%	Waveform	Analysis
Post-bypass	8.8	3.8	1.59	61	Systolic dominant	Revision called for
After revision	60	0.8			Diastolic dominant	Revision successful
Example demonstrates that a PI < 5 doesn't always mean that the graft is good.						

Frequently Asked Question

I've heard that you only need to check for Pulsatility Index > 5 to know graft patency. Why should I also do mean flow and waveform analysis?

PI does not apply well to every graft in each and every condition. For instance, competitive flow will reduce mean flow and increase pulsatility. A blind reliance on PI can produce false positives and unnecessary corrective procedures. A proximal stenosis or a partial distal stenosis may greatly reduce pulsatility and mean flow, and sole reliance on PI would yield a false negative and possibly obscure a correctable technical error. To reduce such errors, the Flow-QC® protocol considers mean flow first, and then other metrics (D/S Ratio or DF%, PI) along with flow waveform analysis. This analysis reveals both the conditions where mean flow is constricted and pulsatility high (i.e., PI >5), and those where mean flow is constricted without increase in pulsatility (i.e., PI <5).

K. Flow-Limiting Conditions[1,2]

Mean flow and flow waveforms vary over a wide range, and the surgeon must differentiate between acceptable variations due to physiologic factors and technical difficulties requiring graft revision.

Physiologic Factors

Vasospasm of Arterial Grafts

Occasionally, handling of arterial grafts may lead to vasospasm. If this is suspected, inject papaverine (Fig. 2.18) or simply wait 3-5 minutes and flow will improve (Fig. 2.19).

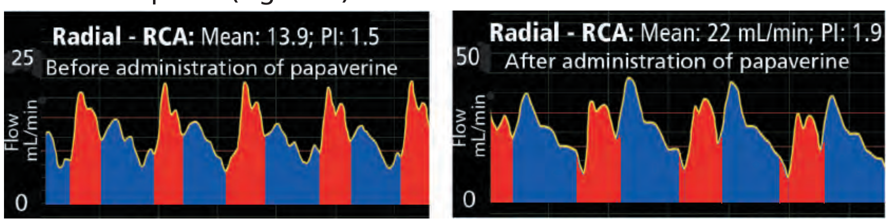


Fig. 2.18: Following administration of papaverine, flow improved from 13.9 mL/min to 22 mL/min. A strong improvement in diastolic flow pattern is observed, and the graft was considered patent. PI, D/S Ratio, and DF% before papaverine administration were 1.5, 0.97, and 49 respectively; after papaverine adminstration, PI was 1.9, D/S Ratio was 2.62, and DF% was 72, respectively.

Improvement with Time

Graft flows may sometimes improve considerably over the course of minutes as illustrated by the LIMA-LAD graft shown below.

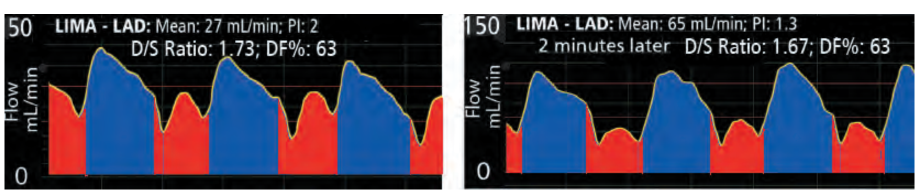


Fig. 2.19: Within two minutes, flow in this LIMA - LAD graft increased from 27 mL/min to 65 mL/min.

1 Private communication (2002) with Dr. B.P. Mindich, Valley Hospital, Ridgewood, NJ.

2 Mindich BP *et al.*, "Reduction of Technical Graft Problems Utilizing Ultrasonic Flow Measurements," NY Thoracic Society, 2001.

K. Flow-Limiting Conditions cont.

Physiologic Factors cont.

Run-off Quality of the Myocardium

An anastomosis can be technically perfect, but if there is high down-stream resistance due to myocardial infarction and/or vessel disease as seen in diabetics, flow will be relatively low. A diseased myocardium with higher resistance will alter the systolic/diastolic flow profile of the graft (Figs. 2.20, 2.21).

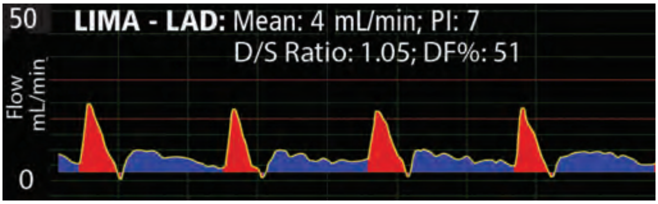


Fig. 2.20: The low flow, trailing, diastolic profile as exhibited by this LIMA-LAD graft indicates poor runoff.

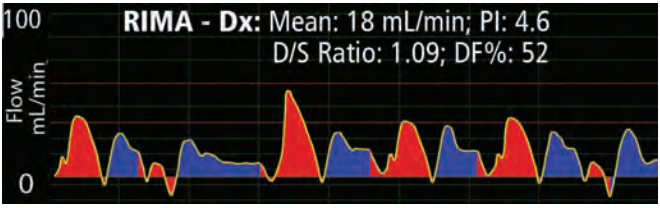


Fig. 2.21: The low flow, trailing, diastolic profile as exhibited by this RIMA-Dx graft indicates poor runoff.

Other physiologic factors to be considered include:

Size of Target Coronary Vessel
Size and Health of Patient
Size and Quality of the Graft

A small coronary artery supplies a relatively small area of the heart, with less run-off. To a large degree, flow velocity is the same throughout the arterial tree, regardless of vessel size. A transit-time Flowprobe senses volume flow, i.e., average flow velocity times cross sectional area. Therefore, expected flow in the vessel is proportional to vessel cross-sectional area: lesser flows would be expected through a 2 mm diameter vessel than through a larger 3-4 mm conduit.

K. Flow-Limiting Conditions cont.

Physiologic Factors cont.

Mean Arterial Pressure

The effect of pressure changes varies, depending on whether a patient is undergoing on- or off-pump CABG.

- ON-PUMP: There is a direct correlation with flow since the pump controls the amount of flow. Higher pump pressures result in greater graft flows. On-pump flows can be misleading since the heart/lung machine is applying a variable and undefinable amount of force to the circulation. Reliable measurements can only be made after CPB is concluded.
- OFF-PUMP: Other physiologic variables may overshadow pressure induced changes.

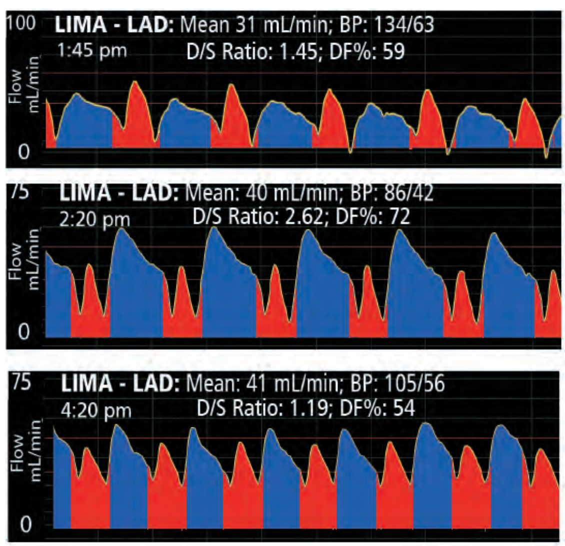


Fig. 2.22: During the case illustrated above, flow increased to 40 mL/min although BP dropped from 134/63 to 86/42 within the first half hour following grafting. Two hours later flow remained stable and BP had increased to 105/56.

K. Flow-Limiting Conditions cont.

Technical Problems

A compelling reason for routine intraoperative, flow-based graft patency assessment is the immediate identification of technical problems with the graft. Problems can then be corrected while the patient is still in the OR, and complications arising from premature graft failure are averted. Technical problems can include:

- Twists or kinks in the graft (Fig. 2.23)
- Thrombus in graft (Fig. 2.24)
- Misapplied stitch at the anastomosis (Figs. 2.25 - 2.34)

When near-zero flow is measured, FlowSound® can be used to give immediate feedback on the efficacy of corrective manipulations.

Twisted Graft

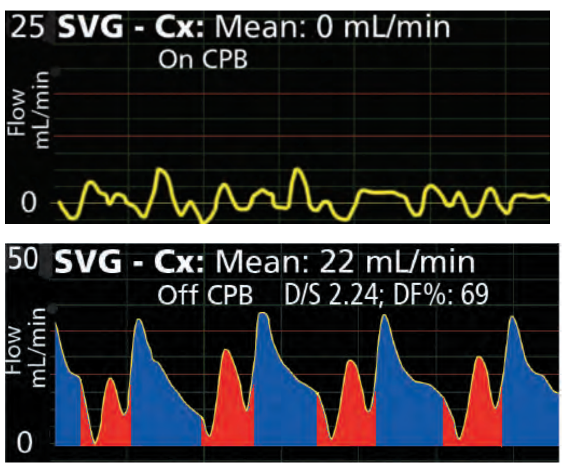


Fig. 2.23: When flow in this SVG - Cx graft registered 0 mL/min and had a poor waveform profile, the surgeon investigated and discovered a twist in the graft. Once the graft was untwisted, flow improved to 22 mL/min.

> Not a day goes by when this flowmeter doesn't solve a problem for me.
>
> BP Mindich, MD, Valley Hospital, Ridgewood, NJ

K. Flow-Limiting Conditions cont.

Technical Problems cont.

Testing the Quality of an Anastomosis

Hold the probe next to an anastomosis and "pump" (compress and release) the vessel further away from the anastomosis. If this produces free pulses of flow through the probe, the anastomosis is open. The Flowprobe and vessel must be held still with respect to each other during this procedure; there must be no motion artifacts.

Differentiating between a Misapplied Stitch and a Thrombus

One can manipulate an anastomosis (bend the vessel sideways, or compress it to alter its cross section) while listening to FlowSound®. If there is a partial stenosis from a stitch that picks up the back wall, one may identify a strong increase of flow in certain positions. If the obstruction comes from a thrombus, such manipulations will not alter the zero-flow through the graft. If the probe is positioned over a thrombus, "pumping" will not elicit a FlowSound change.

Clotted Graft

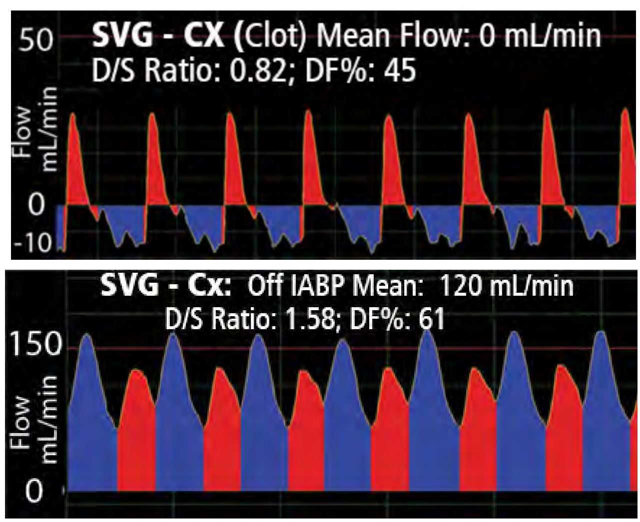


Fig. 2.24: The first flow measurement of this SVG-Cx graft registered zero flow indicating a problem with the graft. Investigation revealed a clot. As the graft was declotted, intra-aortic balloon pumping (IABP) was initiated. When the IABP was removed, graft flow measured 120 mL/min.

K. Flow-Limiting Conditions cont.

Examples of Technical Problems, and Revisions

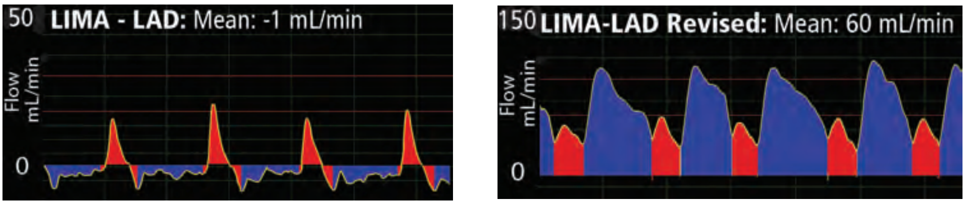


Fig. 2.25: Following graft revision LIMA - LAD mean flow increased from -1 mL/min to 60 mL/min.

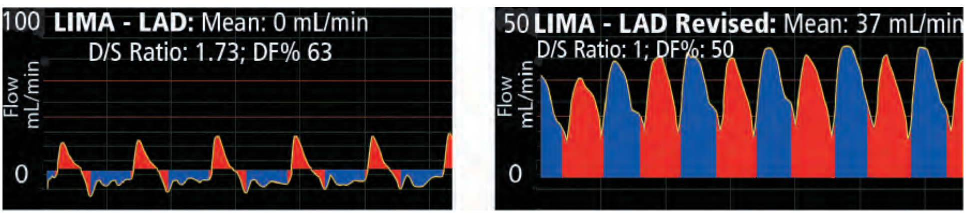


Fig. 2.26: Following graft revision LIMA - LAD mean flow increased from 0 mL/min to 37 mL/min.

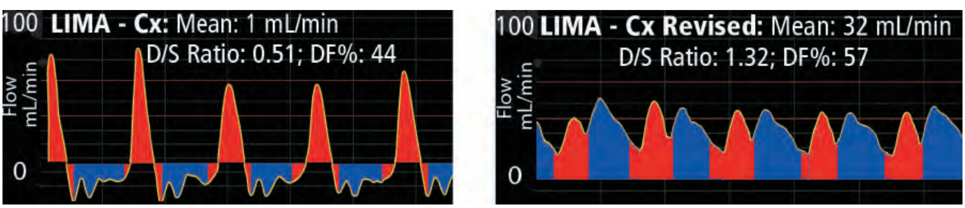


Fig. 2.27: Following graft revision LIMA - Cx mean flow increased from 1 mL/min to 32 mL/min.

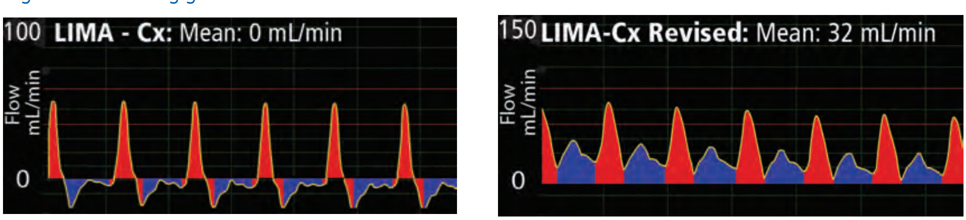


Fig. 2.28: Following graft revision LIMA - Cx mean flow increased from 0 mL/min to 32 mL/min.

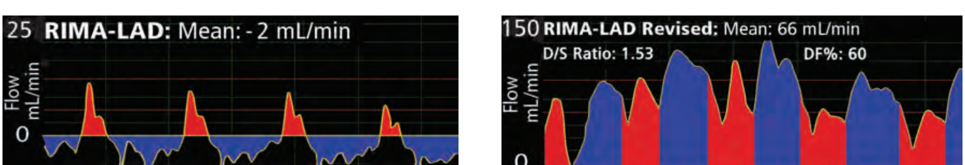


Fig. 2.29: Following graft revision RIMA - LAD mean flow increased from -2 mL/min to 66 mL/min.

K.. Flow-Limiting Conditions cont.

Examples of Technical Problems, and Revisions cont.

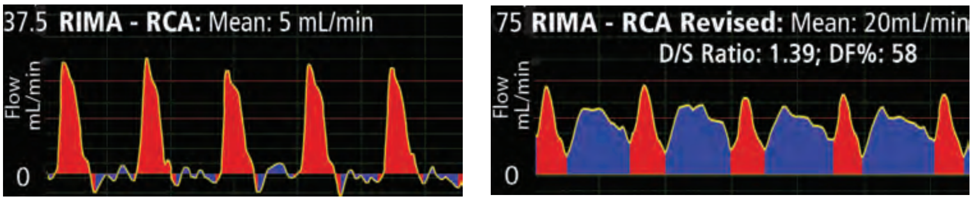


Fig. 2.30: Following graft revision RIMA - RCA mean flow increased from 5 mL/min to 20 mL/min.

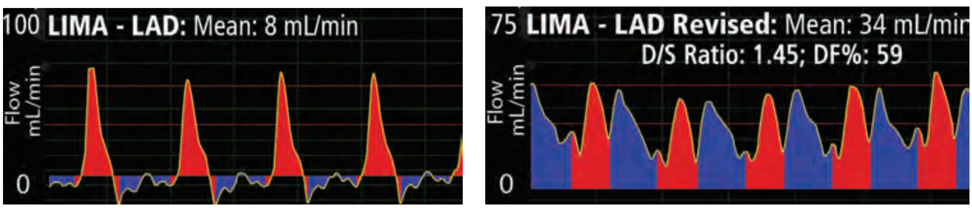


Fig. 2.31: Following graft revision LIMA - LAD mean flow increased from 8 mL/min to 34 mL/min.

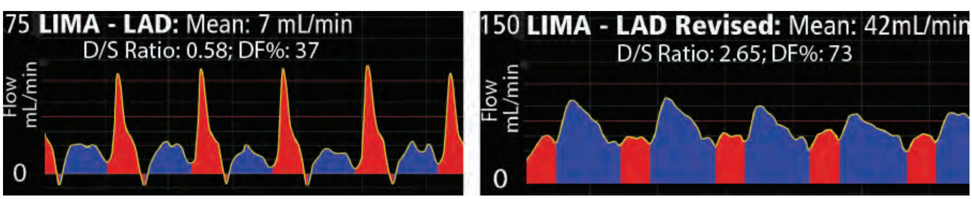


Fig. 2.33: Following graft revision LIMA - LAD mean flow increased from 7 mL/min to 42 mL/min.

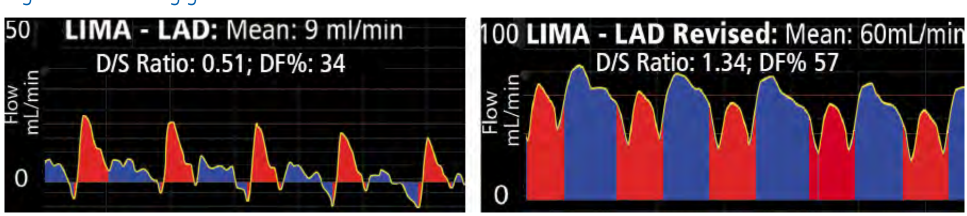


Fig. 2.33: Following graft revision LIMA - LAD mean flow increased from 9 mL/min to 60 mL/min.

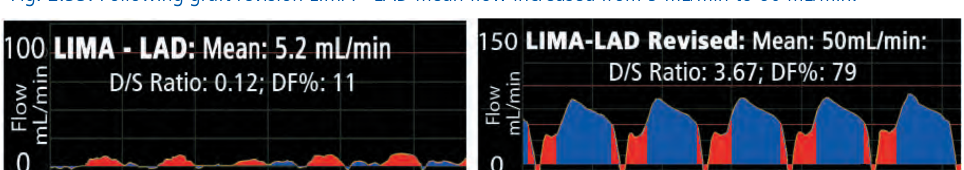


Fig. 2.34: Following graft revision LIMA - LAD mean flow increased from 5 mL/min to 50 mL/min.

K. Flow-Limiting Conditions cont.

Technical Problems cont.

Kinking of Graft during Chest Closure

Chest closure changes the geometry and positioning of grafts, and may well produce occlusions in grafts that were patent. Quick corrective action is needed, and flow measurements can rapidly direct the surgeon's attention to the problem graft.

Changes on a patient monitor (blood pressure, EKG) upon chest closure may indicate graft kinking. To correct the problem, the chest is reopened to give access to the proximal anastomoses of vein grafts. The Flowprobe is applied to these proximal sites to assess graft flow: a partial stenosis is shown by a significant decrease in flow from the first flow check, and a full occlusion is shown by zero mean flow. If no problem is found in the SVGs, flow can then be measured in the arterial grafts. If a kinked graft is found, flow can be monitored while the graft is being re-positioned; FlowSound® will provide immediate audio feedback when flow is re-established. Stay sutures may be employed to keep the graft permanently in this position.

In some circumstances, a patent graft will not completely perfuse an ischemic region of the heart. This may be due to poor runoff, a stunned myocardium, spasm, or an unrecognized sub-acute lesion distal to the anastomosis. After verifying that there is no technical error with the initial anastomosis, and flow is adequate, an additional graft should be considered.

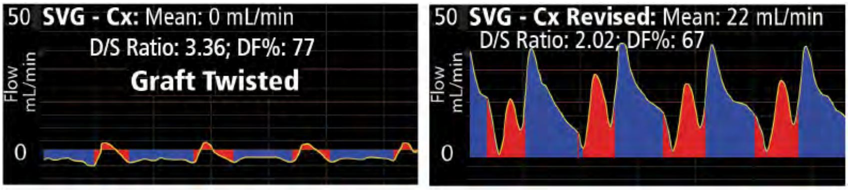
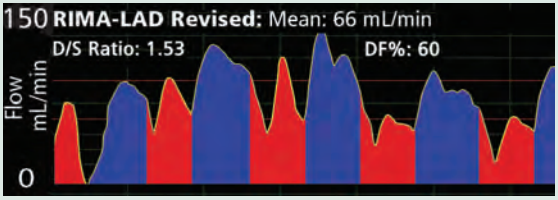


Fig. 2.35: Following chest closure, changes in the patient's hemodynamic parameters can give cause for alarm. Upon re-opening the chest, graft flow can be rechecked. A near-zero flow, as with this vein graft, indicates possible twisting of the graft. When a twist was discovered and corrected in this case, mean flow improved from 0 to 22 mL/min and was accompanied by an acceptable diastolic-dominant waveform.

Example: Technical Problem with RIMA - LAD Graft

A 71-year-old male underwent Re-do CABG to bypass a blocked left anterior descending coronary artery (LAD). His right internal mammary artery (RIMA) was anastomosed to the LAD distal to the blockage. Flow in an old SVG graft to the LAD measured 17 mL/min.

Following the anastomosis, RIMA - LAD flow measured only -2 mL/min (PI: 29). The negative mean flow, high PI, and poor waveform profile alerted the surgeons to the immediate need for graft revision. Following revision, mean graft flow increased to 66 mL/min, PI improved to 2.4 and the waveform exhibited a strong diastolic component.



The negative mean flow of the first flow measurement demonstrated a graft that required immediate attention. The RIMA to LAD anastomosis was revised and mean flow improved to 66 mL/min and the waveform exhibited a strong diastole.

Case Summary: CABG: 71-year-old male; RIMA - LAD Graft						
Flow Measurement	Mean Flow (mL/min)	PI	D/S Ratio	D/F %	Waveform Analysis	Analysis
1) Post bypass	-2	29	-	-	Poor waveform	Requires attention
2) After revision	66	2.4	1.53	60	Classic systolic/diastolic waveform profile	Revision successful
Case illustrates that quantitative graft flow assessment can lead to successful graft revision with resulting improvement in mean flow, PI, and waveform profile.						

Reduction of Technical Graft Problems Utilizing Ultrasonic Flow Measurements

Mindich, BP, NY Thorac Soc 2001.

BACKGROUND

To detect unacceptable grafts in the OR where correction can be accomplished, transit-time ultrasound intraoperative flow measurements were introduced.

METHOD

Volume flow was measured in over 1000 grafts. If flow was inadequate, an algorithm was established to determine the cause of the problem. The effects of poor run-off, competitive flow, and possible spasm were differentiated from technical errors which were then corrected.

In patients on CPB, graft flows were first measured while on CPB. The flow characteristics with the heart beating, in fibrillation or asystolic, predict the quality of flow once CPB is discontinued. Corrective measures could be instituted at that time. All patients had oximetric Swan-Ganz catheters, TEE probes, and ECG event analysis in place during the entire procedure. Curves representing poor flow were correlated with these parameters.

RESULTS

Five hundred of over 1000 cases where flow was measured were analyzed. There were 3.2 grafts/patients. Ninety-five (95%) percent of the isolated CABGs were performed as off-pump CABG. Of the 1,600 grafts evaluated, 248 demonstrated questionable curves with 82 technical problems, 93 with competitive flow, 73 with poor run-off. Revision of the 82 technical problems resulted in improvement in all grafts. One patient died of an MI directly related to a Cx graft that was corrected but not in a timely fashion. Seventeen of the competitive flow grafts and 25 poor run-off grafts were revised during the early portion of the series with no significant change in flow. The curve patterns of the last 300 cases have become more identifiable and revision was avoided. The majority of technical problems occurred in arterial grafts - 67/82. Proximal anastomotic problems occurred in 4 cases - 3 of which were "V" grafts. The LAD system was involved in 45, the circumflex 19 and RCA 18. There have been no immediate post-op studies or interventions in this group.

CONCLUSION

The intraoperative use of flow measurements provide invaluable information in a timely, accurate, cost-effective manner allowing for the surgical correction of a surgical problem. This has significantly reduced the complications related to early technically induced graft failure. In an era of rapidly changing surgical techniques this provides documentation of the sine-qua-non of the operation: patency.

K. Flow-Limiting Conditions cont.

Other Considerations

Effect of Flowprobe Positioning

A Flowprobe should be slipped around a graft so that the graft lies perpendicular to the Probe's handle (Fig. 2.36). Although transit time ultrasound flowmetry is less sensitive to misalignment than other technologies (see Appendix A.), gross misalignment can result in an inaccurate reading, particularly with smaller vessels. With repositioning a probe on the same vessel site, one may well see a ±10% variation due to ultrasound couplant and positioning variations. Importantly, all positioning and couplant imperfections lower flow readings and increase noise in the flow profiles: they will never make a bad graft test good. The highest reading is the most accurate.

Fig. 2.36: For optimal measurements, the Flowprobe should be positioned on the graft so that the graft fills between 75 - 100 % of the Probe's ultrasonic window and the graft lies parallel to the Probe's reflector.

Moving a Flowprobe from the proximal to the distal end of the graft will alter the recorded waveform, as the charge flow component will increase at the expense of the diastolic component.

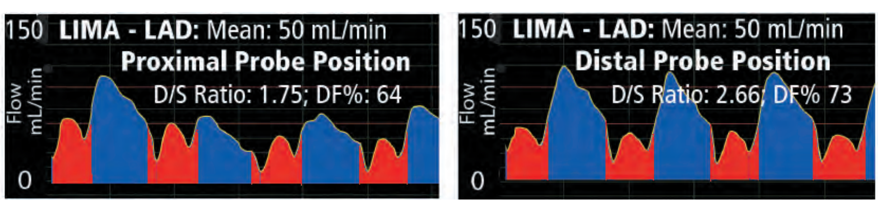


Fig. 2.37: These two LIMA - LAD waveforms demonstrate the effect of changing the site of a Flowprobe on a bypass graft. As shown in the right waveform, the flow profile is more diastolic-dominant when the Flowprobe is placed near the distal anastomosis. Note that the repetitive quality and the general shape of the waveforms do not change with a change in site. Mean flow remained the same (50 mL/min) regardless of position..

> "Placement of the probe on a bad graft will never produce a good waveform or false negative reading." BP Mindich, MD

K. Flow-Limiting Conditions cont.

Other Considerations cont.

Effect of Intra-Aortic Balloon Pumping on Flow

Intra-Aortic Balloon Pumping (IABP) is used for left ventricular support to improve mean flow after CABG. However, its efficacy depends on proper timing; if timing is off, the effect can be negligible, or even adverse.

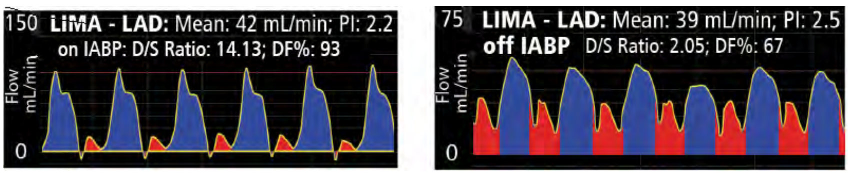


Fig. 2.38: LIMA-LAD mean graft flow dropped marginally from 42 mL/min to 39 mL/min.

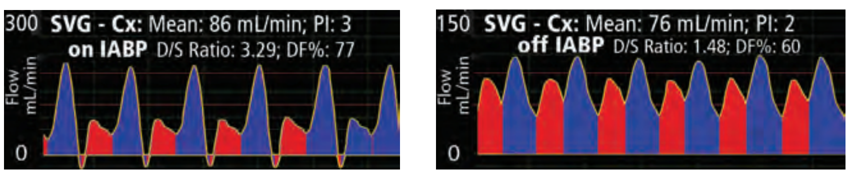


Fig. 2.39: Off IABP, SVG-Cx mean flow decreased from 86.4 mL/min to 76.2 mL/min.

In the examples shown in Figs. 2.38 & 2.39, IABP affected both flow profiles, but didn't significantly alter mean graft flow.

Two studies report other results. A 2011 retrospective study by Onorati[2] of 401 patients with 880 grafts on IABP and a 2008 study of 84 patients with 172 grafts on IABP by Takami[3] both report that the use of IABP significantly affects mean graft flow and diastolic filling.

[1] Tedoriya T et al., "The Effects on Blood Flow of Coronary Artery Bypass Grafts during Intra-aortic Balloon Pumping," J Cardiovasc Surg (Torino) 1994; 35:99-102.

[2] Onorati F et al., "Effects of intra-aortic balloon pumping on coronary artery bypass grafts blood flow: differences by graft type and coronary target," Artif Organs. 2011 Sep;35(9):849-56.

[3] Takami Y, Masumoto H, "Effects of intra-aortic balloon pumping on graft flow in coronary surgery: an intraoperative transit-time flowmetric study. Ann Thorac Surg. 2008 Sep;86(3):823-7.

Frequently Asked Questions

What if mean graft flows are lower because of small target vessel or poor runoff?

When flow is lower than expected, it is time to examine the waveform, after eliminating competitive flow as a factor. A patent graft exhibits a good flow waveform.

Reference: CABG (CV-311-mn) Rev E 2019;

How do you explain a strong flow waveform but mean zero flow?

A highly pulsatile waveform but near-zero mean flow indicates an occlusion near the distal anastomosis. When this happens, flow pulsates forward through the Flowprobe during systole and backward during diastole as the graft segment between the Flowprobe and the distal anastomosis expands and contracts during the cardiac cycle. Transonic FlowSound® has the same pitch for forward and reverse flow, but between strong flow peaks one can hear flow going down to zero. Mean flow is the primary determinant for graft patency in the Transonic Flow-QC® protocol. Zero mean flow indicates a technical error. In this case, the high pulsatility of flow indicates an obstruction downstream from the Flowprobe rather than upstream.

References: CABG (CV-311-mn) Rev E 2019; FlowSound Technical Note (CV-23-tn).

When I move the Flowprobe from one location on the graft to another, my readings vary. How is this possible?

Indeed, if flow through one portion of a conduit is 50 mL/min, it is 50 mL/min at other places of the same flow conduit until a branch or leak is encountered. The observed variability in flow measurements comes from the measurement accuracy of the Flowprobes. A potential 22% variability (e.g., 45 mL/min on one site, 55 mL/min on another in the above example) while using correct techniques is not unusual, but possible. Such variations will not alter the systolic/diastolic profile. Factors that may influence the measurement error are: improper probe size, misalignment of the vessel, air bubbles, clips, sutures, or adipose tissue within the ultrasound window. Application of a Flowprobe that is too small for the vessel being measured produces errors in the flow waveform, and consequently the mean flow.

References: CABG (CV-311-mn) Rev E 2019; Measuring PeriFlowprobe(CV-180-mn)RevA2018USltr

Frequently Asked Questions

Why is CABG flow to a "good" graft diastolic-dominant?

Coronary artery flow patterns are distinct from all other flow patterns in the body due to systolic contraction of the heart muscle which impedes arterial inflow into the arterioles and capillaries embedded in the myocardial wall. This intramyocardial pump principle, introduced by Spaan *et al.* in 1981, models this contraction as a separate flow supply "pump" – a pressure source that counteracts central pressure during systole in its delivery of blood flow to the coronary microcirculation. A publication by Mantero *et al*[3] is one of the many publications that detail this concept. The systolic compression of the heart muscle changes the resistance and compliance of the microcirculation, and greatly blocks any systolic blood flow into the arterioles as it reduces the pressure drop across the myocardium, a well-studied phenomenon (McDonald's "Blood Flow in Arteries," Chapter #17).[4]

This reduced pressure drop and increased resistance during systole from the counteracting intramyocardial pressure source explains why coronary flow in general, and thus CABG flow through a patent anastomosis, is diastolic-dominant: a reduced pressure drop across the coronary circulation during systole generates less systolic flow, while the full central pressure across the coronary tree during diastole facilitated full diastolic flow.

Why do flow patterns from a constricted graft generally show reduced diastolic dominance?

This phenomenon is why the D/S Ratio of a CABG flow waveform can identify a 50% stenosis. A progressively more severe stenosis will drive coronary perfusion into ischemia territory, starting at the deep sub-endocardium. When these strongly diastolic-dominant perfusion layers are removed from the summed coronary perfusion flow measured by a CABG flowsensor, its flow pattern will gradually transition towards the less diastolic-dominant endocardial flow pattern (see Chapter III).

This shift in the D/S Ratio is a sliding-scale transition, not a black and white one. The surgeon will need to combine Mean Flow and D/S Ratio assessment with other observations to investigate whether a low flow or suspicious flow waveform is from a technical error or other correctable source, and whether it is across the coronary tree during diastole given the other constraints of the case at hand.

Ultimately, the call of whether a graft should be taken down and repaired when mean flow is in the medium territory (between 5mL/min - 25mL/min for an average patient) and D/S is inconclusive remains a surgical judgment call until such time that a more definitive surgical tool is available.

Ultrasonic Assessment of Internal Thoracic Artery Flow in the Revascularized Heart

Canver CC, Dame N, Ann Thorac Surg 1994; 58:135-8.

OBJECTIVE

To investigate the clinical applicability of measuring ITA (internal thoracic artery) flow during on-pump coronary artery revascularization and to validate the reliability of ultrasonic transit-time measurements.

METHOD

- Arterial and venous (saphenous vein) graft flows were measured intraoperatively in 63 patients with 3 and 4 mm Perivascular Flowprobes and a dual-channel Flowmeter.
- Native ITA free flow was measured in all patients by collecting flow from the distal end of the ITA in an open beaker for 30 seconds at normal pressure after the ITA was cut.
- Simultaneously, ITA blood flow was measured by transit-time ultrasound Flowprobes on the skeletonized proximal end of the ITA.
- SVG and ITA flows were measured during cardio-pulmonary bypass and immediately before closure of the sternum.

RESULTS

- Flow measurements added ≤ 15 minutes to the total operation time.

PARAMETER	N	FLOW (mL/min)
Native Left ITA	55	7 ± 0.8
Native Right ITA	8	6 ± 1.5
Mean ITA Free Flow	63	60 ± 8

CONCLUSION

Transit-time ultrasound can accurately quantify physiologic blood flow through an ITA graft immediately after CABG and provides the surgeon with valuable information.

TRANSONIC OBSERVATIONS

- This landmark validation paper was the first to validate intraoperative blood flow on the internal thoracic artery during coronary artery bypass grafting (CABG) surgery. Earlier electromagnetic flowmeters could not measure ITA flows accurately.
- Flow was validated with simultaneous measurements of proximal ITA flow and collection of distal blood flow from the cut ITA in a beaker with a stopwatch.

L. Summary

Presented in this chapter were the following:

Mean Flow Assessment (pages 18-22)

Mean flow is the primary determinant of graft quality and alerts the surgeon to one of three graft conditions:

1. Mean flow falls within the normal range (20 mL/min) or above: the graft provides adequate flow and may be considered patent.
2. Mean flow below 5 mL/min: flow is unacceptably low; the graft is compromised and requires further examination.
3. Mean flow between 5 mL/min and normal range: further analysis should be performed to assess whether this graft performs acceptably.

FlowSound® Volume Flow Analysis (pages 23-24)

Competitive Flow Assessment (pages 25-28)

Flow Profile Assessment (pages 29-30)

FlowTrace® ECG, Diastolic/Systolic Ratio (D/S), Diastolic Filling Percentage (DF%) (pages 31-34)

Pulsatility Index Assessment (pages 35-36)

Flow Limiting Conditions (pages 37-51)

III: CABG Flow Physics and Physiology

A. Introduction

The purpose of CABG surgery is to restore flow to the myocardium when native coronary flow is impaired, by stenosis for example. Flow-based intraoperative graft patency assessment quantifies a coronary bypass graft's efficacy to supplement coronary flow. Poor graft mean flows and abnormal waveforms can indicate impairment to a graft's functionality.

However, flow-based patency evaluation is complicated by the many factors influencing the appearance of the flow waveform in coronary arteries and grafts, such as target coronary, graft type (e.g. arterial or venous, single or sequential), competitive flow (resulting from incomplete occlusion of native coronary), autoregulation, quality of coronary microvasculature, but also heart rate, cardiac index, blood pressure, and BMI[1] . This is why no universally applicable threshold values exist for flow-based patency metrics, and consequently, why sub-optimal metric values should not automatically lead to graft revision.

On the other hand, a basic understanding of how these factors affect the flow waveform will facilitate the interpretation of flow measurements taken in a graft, be it in a qualitative rather than a quantitative manner. By presenting a review of the mechanical, fluid dynamical, and physiological principles that govern coronary flow, this chapter seeks to assist the reader in developing a feel for "normal", "questionable", and "problematic" flow waveforms and metric values.

Topics addressed in this chapter are:
Section B. Flow waveform in patent coronary arteries and grafts
Section C. Effects of stenosis
Section D. Interpretation of flow-based patency metrics

1 Lee S-W, Jo J-Y, Kim W-J, Choi D-K, and Choi I-C. Patient and haemodynamic factors affecting intraoperative graft flow during coronary artery bypass grafting: an observational pilot study. Scientific Reports, 10, 2020.

A. Why Understanding CABG Flow Basics Helpful cont.

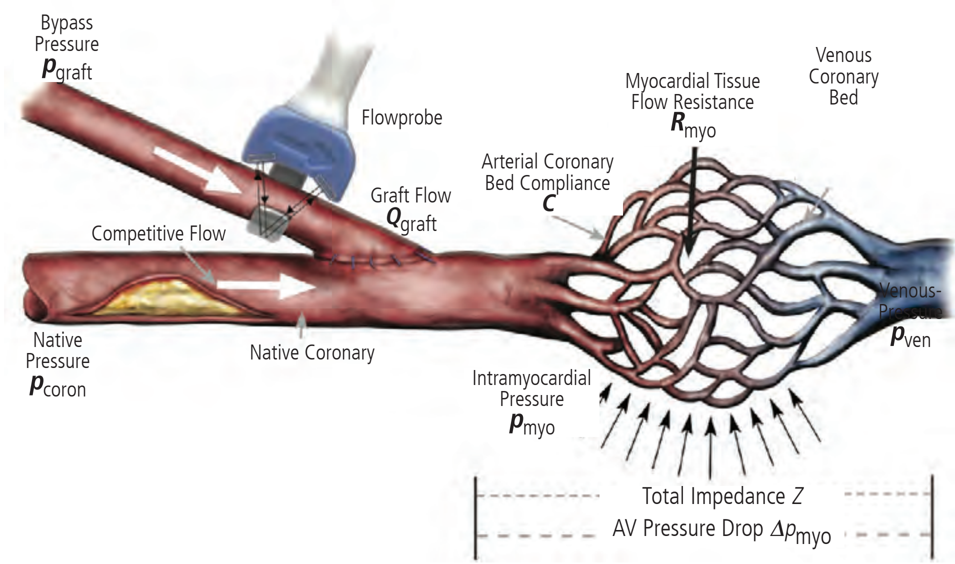


Fig. 3.1: Simplified representation of coronary artery with stenosis and bypass graft, where:

Q_{graft} = Graft flow passing through the Flowprobe
Δp_{myo} = Arterio-venous pressure difference distal to the coronary anastomosis
Z = Total impedance over the Δp length of vessels and tissue (myocardial flow resistance and flow-dynamic effects such as vessel compliance, inertia of blood). It is dominated by two components:
R_{myo} = Flow resistance of the myocardial tissue
C = Vascular compliance downstream of the Flowprobe: graft segment + small coronary arteries

Coronary artery flow waveforms, and hence those of CABG grafts (Fig. 3.1), differ from those in other arteries, in that their flow rate is low during systole, and high during diastole. In other words, a coronary arterial flow waveform is diastolic-dominant. This is due to the alternating contraction and expansion of the beating heart: contraction of the myocardial wall impedes arterial inflow into the arterioles and capillaries running through it. In fluid dynamics terms, flow rate Q is proportional to the pressure gradient Δp and inversely proportional to resistance R: higher Δp means higher Q, higher R means lower Q as explained in Fig. 3.2.

B. Flow Waveforms in Patent Coronary Arteries & Grafts

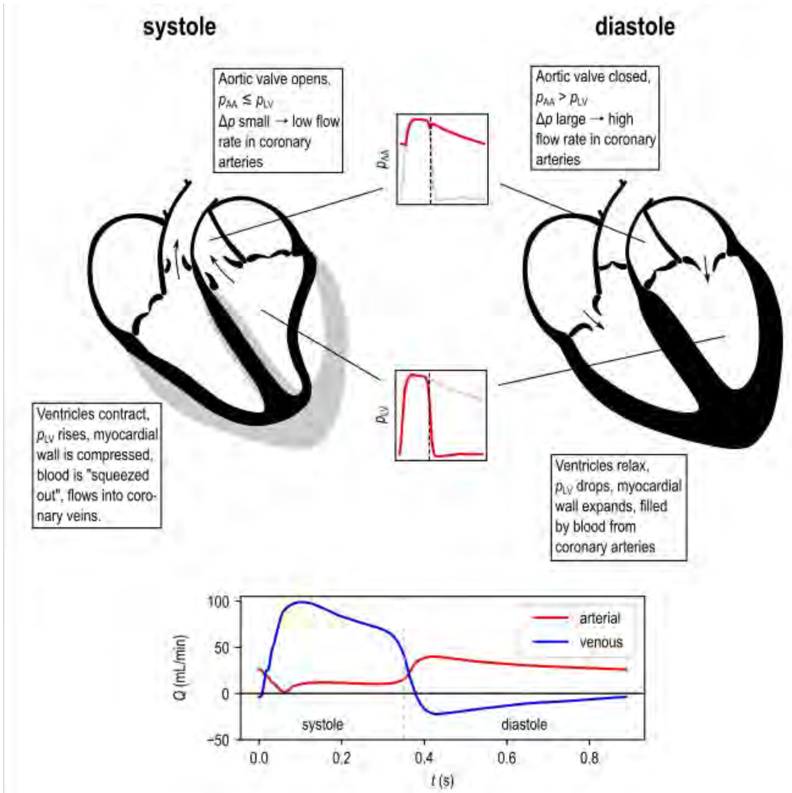


Fig. 3.2: Diastolic Dominance: Flow in coronary arteries is driven by the pressure p_{AA} in the ascending aorta. During systole, the ventricles contract, ventricular pressure p_{LV} rises, and the aortic and pulmonary valves open, so that also p_{AA} rises, and $p_{AA} \leq p_{LV}$. At the same time, the high ventricular pressure causes the myocardial wall to be compressed, and blood is squeezed out of the intramyocardial vessels. This blood flows into the coronary veins, where pressure is low, so that coronary venous flow rate is high during systole (bottom plot, blue curve). Compression of the myocardial wall, and the resulting high intramyocardial pressure impede coronary arterial flow: the pressure gradient Δp between the coronary ostia and the intramyocardial vessels is small, while resistance to flow in the compressed vessels is high, so that a low systolic flow rate results in the coronary arteries (bottom plot, red curve). During diastole, the ventricles relax, p_{LV} drops, and the aortic and pulmonary valves are closed. As a result, $p_{AA} > p_{LV}$, leading to a large pressure gradient Δp. The myocardial wall and the vessels in it expand, so that the resistance to flow decreases, and additionally, a slight suction effect is generated. In combination with the large Δp, this results in a high coronary arterial flow rate, which is used to replenish the blood volume in the intramyocardial vessels.

B. Flow Waveforms in Patent Coronary Arteries & Grafts cont.

The exact shape of a coronary arterial flow waveform depends on several factors, one of which is the position of the artery. For example, the flow waveform in a LAD differs from that in the LCx, and, more importantly, flow waveforms in left coronaries differ from those in right coronaries. Because the right ventricle supplies the relatively small pressure pulmonary circulation, it doesn't contract as strongly as the left ventricle, which supplies the entire systemic circulation. As a result, flow in right coronary arteries is not impeded as much during systole, and diastolic dominance is not as noticeable as in left coronary arteries (Fig. 3.3).

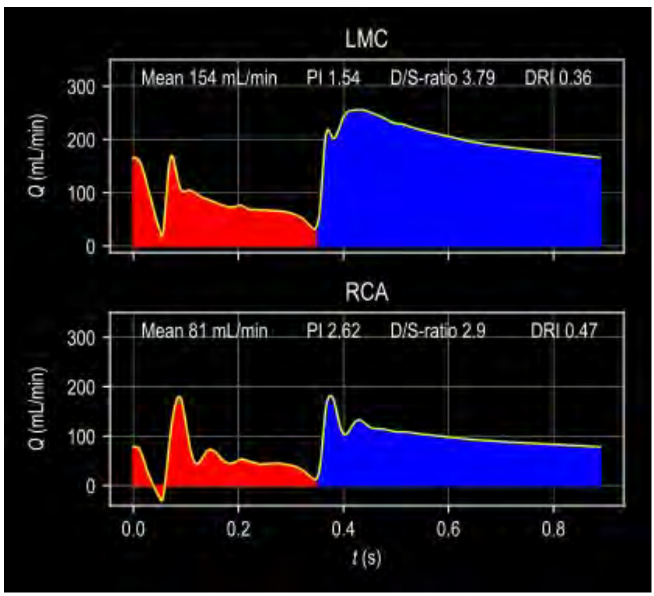


Fig. 3.3: Because contraction of the right ventricle is weaker than left ventricular contraction, diastolic dominance in right coronary arteries (bottom plot, right coronary artery RCA) is not as strong as in left coronary arteries (top plot, left main coronary LMC).

Because grafts are anastomosed onto a coronary artery, they experience a similar systolic flow impediment as do coronary arteries. Moreover, the driving pressure waveform in a graft is similar to that in coronary arteries. This is especially true for saphenous vein grafts, which have their proximal anastomosis close to the coronary ostia. The driving pressure waveform

B. Flow Waveforms in Patent Coronary Arteries & Grafts cont.

in *in-situ* arterial grafts, such as the LITA graft, is slightly delayed and distorted with respect to the pressure waveform in the ascending aorta, but still very similar in shape. Therefore, the flow waveform in a patent graft closely resembles the flow waveform in the coronary artery onto which it is anastomosed.

Patent Graft Flow Waveform

- Diastolic dominant: flow rate is highest during diastole
- Target coronary: graft flow waveform depends on position of target coronary
- Arterial or venous graft: flow waveform depends on type of graft

C. Effects of Stenosis

If a blood vessel becomes constricted, several things happen to the flow (Fig. 3.4). At the site of the constriction, the reduction in diameter causes an increase in flow resistance. This results in an increased pressure drop across the constriction and, in severe cases, turbulence on the distal side (which, in combination with the acceleration and deceleration through the constriction, increases the pressure drop even further). Additionally, the pressure drop over a constriction depends on flow rate, so that the effect of a stenosis is stronger in diastole (high flow rate) than in systole (low flow rate). This leads to a reduction in diastolic dominance of the flow waveform.

In the coronary circulation, the reduced perfusion pressure Δp_{myo} distal to a constriction, in combination with unaltered intramyocardial pressure p_{im}, decreases the **transmural pressure**[2] p_{tm} in the intramyocardial bed. Because the wall of a blood vessel is flexible, this reduction of p_{tm} causes the diameter of the vessels in the intramyocardial vascular bed to decrease. This diameter decrease, in turn, results in decreased myocardial volume and increased intramyocardial resistance[3].

Continued on next page.

2. Transmural pressure: difference between pressure inside and outside vessel, $p_{tm} = p_{internal} - p_{external}$
3. Spaan JAE, Piek JJ, Siebes M. Coronary circulation and hemodynamics. In: Sperelakis N, Kurachi Y, Terzic A, Cohen MV, editors. Heart physiology and pathophysiology. Fourth edition, 2001.

C. Effects of Stenosis cont.,

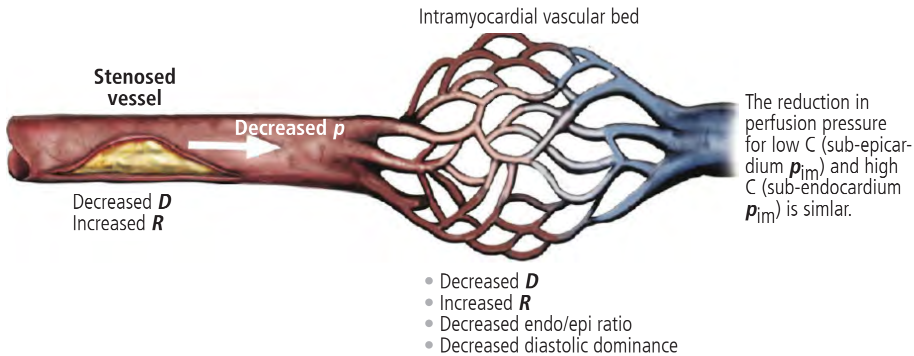


Fig. 3.4: Causes of reduced Q_{mean} and reduced diastolic dominance of CABG flow waveform in the presence of stenosis:
1. Local: decreased diameter results in increased resistance and lower pressure distal to stenosis.
2. Distal: decreased pressure causes decreased vessel diameter and hence higher resistance in the intramyocardial vascular bed, resulting in decreased endo/epi flow ratio. As subepicardial flow suffers less from systolic flow impediment than subendocardial flow, decreased endo/epi ratio results in decreased diastolic dominance.
3. Dynamic: Pressure drop over stenosis depends on flow rate, so decrease in flow rate is stronger during diastole (high flow rate) than during systole (low flow rate), and diastolic dominance is reduced.

Expressed mathematically, intramyocardial resistance R_{myo} is inversely proportional to intramyocardial volume V_{myo} squared:

$$R_{myo} \propto \frac{1}{V_{myo}^2}$$

The change in vessel volume is proportional to the flexibility, or compliance of the vessel wall, and to the rate of change in transmural pressure $\partial p_{tm}/\partial t$:

$$\frac{\partial V}{\partial t} = C\frac{\partial p_{tm}}{\partial t}$$

C. Effects of Stenosis cont.

That is, the higher its compliance, the more the volume of a vessel increases or decreases with an increase or decrease in transmural pressure, respectively. Because compliance is higher in the subendocardium than in the subepicardium, and the reduction in p_{tm} is the same, the diameter decrease and resistance increase are larger in the former. Therefore, the blood flow through the subendocardium is reduced more than that through the subepicardium, resulting in a reduced endo/epi flow ratio.[4] This is generally seen as the explanation why the subendocardium is more vulnerable to ischemia.

Considering that the influence of ventricular pressure is stronger in the subendocardium than in the subepicardium (i.e. $p_{im,endo} > p_{im,epi}$), subepicardial flow suffers less from systolic flow impediment than subendocardial flow. Therefore, a reduction of endo/epi flow ratio leads to a further decrease in diastolic dominance. It should be noted, however, that the increase in intramyocardial resistance may (in part) be compensated by autoregulation.

The above effects may be observed in both coronary arteries and grafts. Additionally, in a severely stenosed graft, a compliance-related Windkessel phenomenon occurs. The increased resistance caused by the stenosis prevents the flow from passing freely. This leads to an increase in so-called **charge flow**, or **capacitive flow**: during systole, the increasing driving pressure "inflates" the portion of the graft proximal to the stenosis, while during diastole, the decreasing driving pressure has the opposite effect (Fig. 3.5). In the extreme case of a completely stenosed graft, the volume of blood flowing into the graft during systole equals the volume flowing back out of the graft during diastole, resulting in a zero mean flow.

4. Algranati D, Kassab GS, Lanir Y. Why is the subendocardium more vulnerable to ischemia? A new paradigm. Am J Physiol Heart Circ Physiol 300: H1090-H1100, 2011.

C. Effects of Stenosis cont.

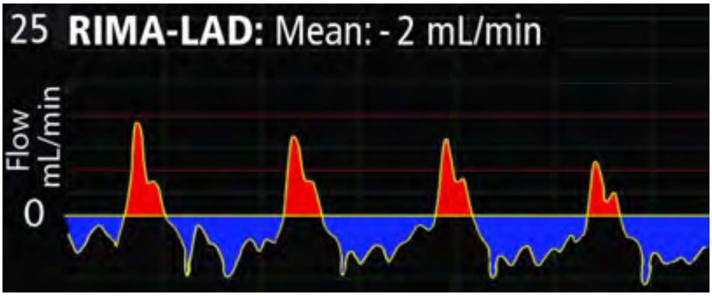


Fig. 3.5: Example of purely capacitive graft flow: during systole, blood flows into the portion of the graft proximal to the stenosis, resulting in a positive signal from the flow probe. Because the graft is completely blocked, the decreasing pressure during diastole causes the blood to flow back out of the graft, resulting in a negative signal from the flow probe, and overall, zero mean flow (the mean of -2 mL/min in this plot may be caused by the averaging algorithm, or by a small measurement inaccuracy).

Stenosed Graft Flow Waveform

- Reduced mean flow
- Reduced diastolic dominance
- Increased charge flow: leads to increased systolic flow, reduced diastolic flow, and hence, further reduction of diastolic dominance

D. Interpretation of Flow-based Patency Metrics

Flow-based patency metrics quantify one or more of the aspects discussed in Section C. At present, TTFM flow monitors used for intraoperative CABG patency evaluation display a selection of metrics (Box 1; Q_{mean} is averaged over the displayed period, $|V_{dia}|$, $|V_{sys}|$, and $|V_{tot}|$ designate absolute flow volume passed through the flow probe in diastole, systole, and the full cardiac cycle, respectively).

Continued on next page.

D. Interpretation of Flow-based Patency Metrics cont.

Box 1: Existing CABG patency assessment metrics

Mean flow rate: $$Q_{\text{mean}} = \frac{1}{T}\int_0^T Q(t)\,\mathrm{d}t,$$

Pulsatility index: $$\text{PI} = \frac{Q_{\text{max}} - Q_{\text{min}}}{Q_{\text{mean}}},$$

Diastolic filling percentage: $$\text{DF\%} = 100 \times \frac{|V_{\text{dia}}|}{|V_{\text{tot}}|},$$

Diastolic/systolic ratio: $$\text{D/S-ratio} = \frac{|V_{\text{dia}}|}{|V_{\text{sys}}|}.$$

If one or more metrics exceed a critical value, the surgeon is prompted to check the newly created graft for technical imperfections, such as twists, kinks, or misapplied stitches. It should be noted that sub-optimal metric values should not automatically lead to graft revision; TTFM is intended as a supportive tool, subordinate to the surgeon's expert judgment.

The rationale of deploying Q_{mean} as a patency metric is simply that in a narrowed anastomosis the resistance to flow is greater (Fig. 3.4), leading to a reduction of Q_{mean} (see pages 18-22). However, Q_{mean} is also influenced by other factors like graft diameter, autoregulation, driving pressure gradient, competitive flow, and quality of distal run-off, which makes it an unreliable metric if used solely on its own.

PI quantifies flow pulsatility relative to mean flow rate, which tends to increase with increasing occlusion (see pages 35-36). This is an effect of decreasing Q_{mean} and increasing capacitive flow (i.e. Windkessel effect of the graft itself), and thus depends on graft compliance and flowprobe position.[5] Also, a negative systolic spike caused by competitive flow leads to elevated PI, irrespective of graft quality.

5 Jelenc M et al., Understanding coronary artery bypass transit time flow curves: role of bypass graft compliance. Interact Cardiovasc Thorac Surg. 2014 Feb;18(2):164-8.

D. Interpretation of Flow-based Patency Metrics cont..

Why Is Flowprobe Position Important?

Even though the small intramyocardial arterioles, capillaries, and venules are the most important source of compliance in the coronary circulation, also charge flow in the graft itself, due to its own compliance, also influences the measured flow waveform. Assuming competitive flow is blocked, the graft flow waveform measured by a Flowprobe is made up of the sum of resistive flow and charge flow:

$$Q_{graft} = Q_{res} + Q_{charge}$$

where Q_{charge} is the flow associated with the volume change of the segment of the graft between the flowprobe and the coronary anastomosis. In the extreme case of complete graft occlusion, mean flow rate is zero and only charge flow remains, with positive flow during systole (increasing pressure, expanding graft) and negative flow during diastole (decreasing pressure, contracting graft).

The influence of the graft's compliance can be seen by comparing the flow waveforms measured on the proximal and distal ends of the graft: even though the mean flow rate is the same at both positions, the flow amplitude on the proximal side is larger than that on the distal side.[1]

An important consequence of charge flow in the graft is that the values of PI, D/S-ratio, DF%, and DRI depend on the position of the Flowprobe on the graft. This is why Transonic recommends always placing the probe in the same position, around 1 cm from the distal anastomosis.

1 Jelenc M *et al,* Understanding coronary artery bypass transit time flow curves: role of bypass graft compliance. Interact Cardiovasc Thorac Surg. 2014 Feb;18(2):164-8.

DF% and D/S-ratio quantify diastolic dominance of the graft flow waveform by comparing volume delivered during diastole with per-beat volume or systolic volume, respectively (see page 31). As explained at the beginning of this section, the diastolic dominance of the flow wave-form decreases with increasing graft occlusion (see also representative LITA-LAD flow waveforms in Fig. 3.6). Critical values of DF% and D/S-ratio depend on graft target site and flow probe position.

D. Interpretation of Flow-based Patency Metrics cont.

From the definitions in Box 1, it can be seen that DF% and D/S-ratio are directly related:

$$DF\% = 100\times \frac{D/S\text{-ratio}}{1 + D/S\text{-ratio}}.$$

Still, the different definitions make a difference in practice: D/S-ratio provides a direct comparison between diastolic and systolic delivered flow volumes. DF% compares diastolic delivered flow volume to total delivered flow volume. As a result, the decrease of D/S-ratio with increasing stenosis is relatively greater than that of DF%. This is illustrated in Table 1, using the values of DF% and D/S-ratio corresponding with the flow waveforms in Fig. 3.6. The percentage changes are noticeably larger for D/S-ratio than for DF%. This potentially makes it easier to distinguish between patency classes based on D/S-ratio.

Table 1: Values of D/S-ratio and DF% corresponding to flow waveforms in Figure 3.6; percentual changes (in outer margins) are noticeably larger for D/S-ratio than for DF%.

	D/S-ratio	Stenosis (%)	DF%	
	4.88	0	83	
-65%	1.70	50	63	-24%
-12%	1.50	75	60	-4.8%

Finally, the amount of retrograde graft flow is sometimes displayed on flow monitors. Called insufficiency ratio, or backflow percentage, it is quantified by the ratio (negative flow volume)/(total flow volume). While retrograde flow may cause string sign in an arterial graft and eventual failure, it is in itself not necessarily a direct indicator of technical error in the graft or anastomosis. Much depends on when in the cardiac cycle it occurs: Retrograde flow during diastole, accompanied by (almost) equally strong antegrade flow during systole, is a sign of (almost) purely capacitive flow, and thus, of severe graft constriction. On the other hand, retrograde flow during systole generally has other causes, unrelated to graft quality.

D. Interpretation of Flow-based Patency Metrics cont.

Retrograde Flow

Retrograde flow in itself is not necessarily a direct indicator of technical error in the graft. Even in healthy coronary arteries, a modest amount of transient retrograde flow may occur in early and/or late systole. Factors of influence are:

- Perfusion pressure: lower perfusion pressure ↔ more retrograde flow
- Myocardial contractility: higher contractility ↔ more retrograde flow in early systole
- Vasodilation: lower resistance and higher compliance in myocardium ↔ more retrograde flow in late systole
- Aortic stenosis ↔ more retrograde flow in early systole
- Aortic regurgitation ↔ more retrograde flow in late systole
- Competitive flow, caused by incomplete occlusion of the native coronary ↔ more retrograde flow in early systole
- **Retrograde flow during diastole, accompanied by equally strong antegrade flow during systole, is a sign of purely capacitive flow, and thus, of severe graft constriction.**

Diastolic Resistance Index: As a more complete metric, with a more conceptually tangible link to graft patency, Transonic is supporting the development of a novel metric, the diastolic resistance index (DRI) (see pages 32-33):

$$\mathrm{DRI} = \frac{\bar{p}_{\mathrm{dia}}/|\bar{Q}_{\mathrm{dia}}|}{\bar{p}_{\mathrm{sys}}/|\bar{Q}_{\mathrm{sys}}|}.$$

In this equation, the bars over p and Q indicate averages. Like DF% and D/S-ratio, DRI compares (absolute) diastolic and systolic flow rates and will therefore quantify the decrease of diastolic dominance with increasing occlusion. Because DRI uses mean flow rates rather than volumes, it is expected to be less sensitive to diastolic time fraction. The influence of perfusion pressure is taken into account by including the ratio of mean diastolic to mean systolic pressure. Central pressure is estimated from peripheral measurements using a transfer function.[6] With increasing anastomotic occlusion, resistance increases, and so does DRI, rendering it more intuitive than DF% or D/S-ratio.

6 Chapter 28 in: Nichols WW, O'Rourke MF, Vlachopoulos C. McDonald's Blood Flow in Arteries - Theoretical, Experimental and Clinical Principles. 6th ed. Hodder Arnold; 2011

D. Interpretation of Flow-based Patency Metrics cont.

Generally, it is recommended to use a combination of metrics to evaluate graft quality. For example, one might first look at the value of Q_{mean}, and only if this is not decisive, also include D/S-ratio or DF% in the evaluation (see measurement protocol and flow diagram, pages 11-12, 17).

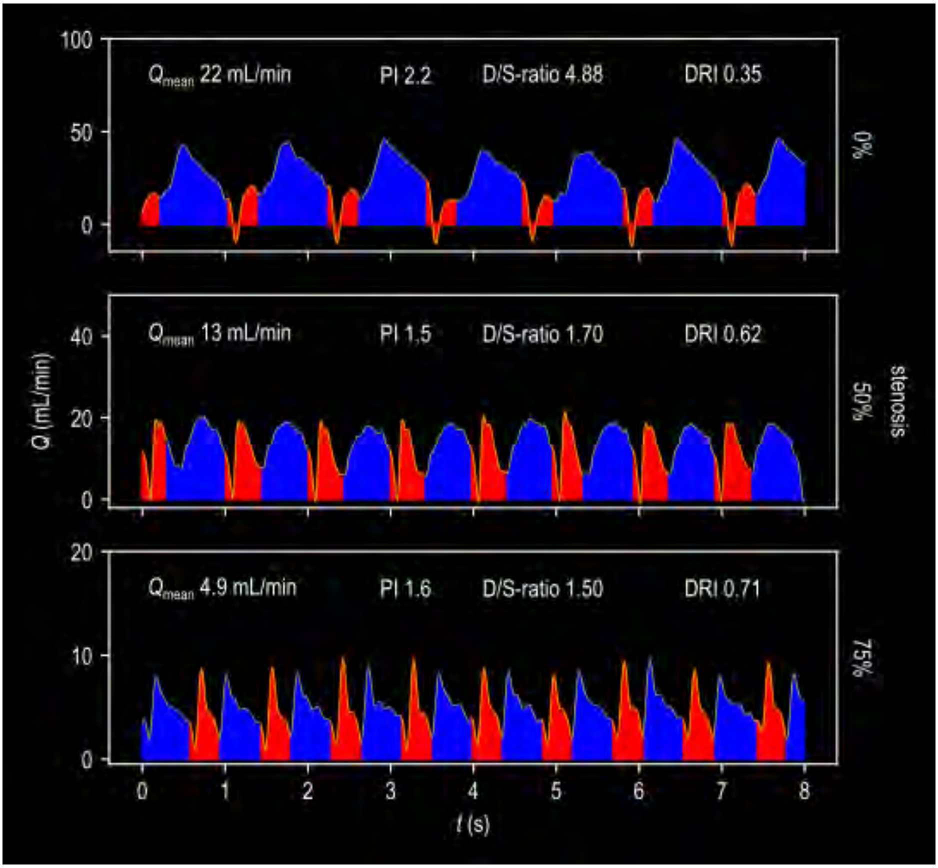


Fig. 3.6: Diastolic dominance of coronary flow waveform decreases with increasing occlusion (representative flow waveforms courtesy of Takahashi et al., Nippon Medical School, Tokyo, Japan)

D. Interpretation of Flow-based Patency Metrics cont.

Box 2: Intraoperative TTFM CABG patency assessment protocol

Flow probe: Match graft diameter, avoid graft constriction or compression.

Timing: Off-pump: after each distal anastomosis completion. On-pump: once after each distal anastomosis completion (arrested heart), and once after weaning from CPB.

Position: About 1 cm from distal anastomosis (too far from anastomosis: compliance artifacts, too close: disturbed flow).

Competitive flow: If competitive flow is suspected (e.g. low Q_{mean}, presence of retrograde flow), repeat measurement with temporarily occluded native coronary, use measurement with highest Q_{mean}.

Negative of near-zero flow: Absolute flow rate is used for DF%, D/S-ratio, to avoid negative or near-infinite values.

IV. Representative Graft Flow Profiles

This chapter presents representative examples and analyses of characteristic CABG flow waveforms from a cache of waveforms culled by Dr. Mindich from more than 500 CABG cases.

Presented first are native flow profiles of the left internal mammary artery (LIMA), left (LAD) and right (RCA) coronary arteries (Figs. 4.1-4.3). These are followed by examples of graft waveforms to the left ventricle (Figs. 4.1-4.19), and then graft waveforms to the right ventricle (Figs. 4.20-4.25).

A. Native Arterial Flow Profiles

Volume flow and flow profiles through arteries and grafts are highly dependent upon the properties of the organ they perfuse. A graphic example of this is flow through a native internal mammary artery (IMA, Fig. 4.1). Also known as the internal thoracic artery (ITA), its flow profile changes dramatically when it is used as a coronary graft (LIMA-LAD, Fig. 4.4). A coronary graft will transport flow in a pattern similar to native coronary arteries (Figs. 4.2 - 4.3) if the pattern is not compromised by factors such as competitive flow, diseased myocardium, technical error, etc.

The classic flow pattern for coronary arteries is the M pattern. The systolic peak of the "M" is lower than the diastolic peak in the left heart (Fig. 4.2) and higher in the right heart (Fig. 4.3) because of the different strengths of their respective systolic contraction, the depth of the coronaries in the myocardium, and different myocardial thicknesses.

In Situ (native) LIMA Flow

Fig. 4.1: Note that this LIMA flow is entirely in systole. LIMA flows are generally low in the native state because the artery is supplying the chest wall, a high resistance bed. Free flow from an open LIMA graft typically exceeds 90 mL/min, since there is then no resistance.

A. Native Arterial Flow Profiles cont.

In Situ LAD (Coronary Flow to the Left Heart)

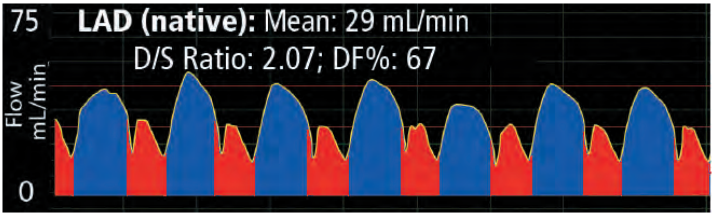


Fig. 4.2: The native left anterior descending coronary artery (LAD) exhibits a bi-phasic systolic/diastolic "M"-shaped flow pattern in contrast to the *in situ* LIMA's mono-phasic systolic profile.

In Situ RCA (Coronary Flow to the Right Heart)

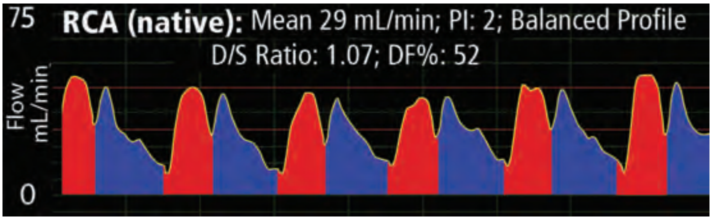


Fig. 4.3: The classic flow pattern of right ventricle coronary arteries is also a bi-phasic "M," but in these instances, the systolic peak often is higher than the diastolic peak.

B. Bypass Grafts to the Left Ventricle

Left ventricle bypass graft patency is critical because the left ventricle pumps blood into the aorta and then throughout the systemic circulation. In all left ventricular grafts, patency is indicated if, with competitive flow occluded, when:

- Mean flow is in the "Normal" range or higher (table, page 19) or
- Mean flow is in the "Questionable" range but flow is "diastolic-dominant."

The graft flow profiles below demonstrate a disparity in systolic and diastolic flow to the myocardium as explained by the beat-to-beat profiles of pressure and resistance as explained in Chapter III.B (Figs. 3.1 and 3.2, page 55). Representative waveform profiles include:

Left Internal Mammary Artery (LIMA) Grafts

Before applying the Flowprobe to the graft for a measurement, skeletonize a 1.5 cm of the pedicle end of the LIMA.

LIMA - LAD Graft

LIMA - LAD Flow (classic diastolic profile)

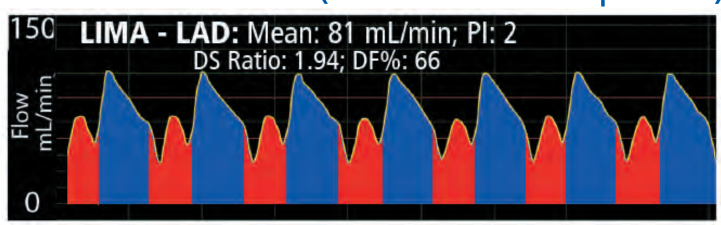


Fig. 4.4: This waveform exhibits a classic LIMA - LAD flow profile. Mean flow is 81 mL/min, the pulsatility index is 2; and the flow profile exhibits diastolic dominance.

LIMA - Dx Graft

LIMA -Dx Flow (classic diastolic profile)

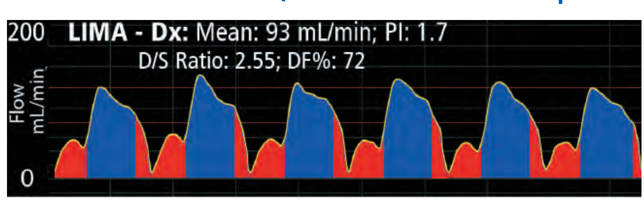


Fig. 4.5: This LIMA - Dx waveform exhibits a diastolic dominant flow profile. Mean flow is 93 mL/min, the pulsatility index is 1.7.

B. Bypass Grafts to the Left Ventricle cont.

LIMA Grafts cont.

LIMA - Cx Graft

LIMA -Circumflex (Cx) Flow

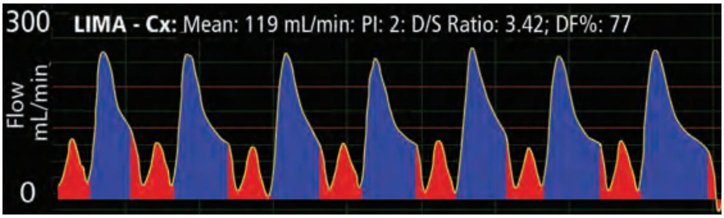


Fig. 4.6: This waveform exhibits a diastolic-dominant profile with excellent mean flow of 119 mL/min and a PI of 2.

LIMA - Dx Graft

LIMA -Dx Flow (classic diastolic profile)

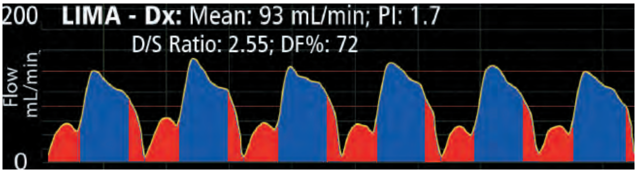


Fig. 4.7: This LIMA - Dx waveform exhibits a diastolic dominant flow profile. Mean flow is 93 mL/min, the pulsatility index is 1.7.

LIMA - OM Graft

LIMA - Obtuse Marginal (OM) Flow

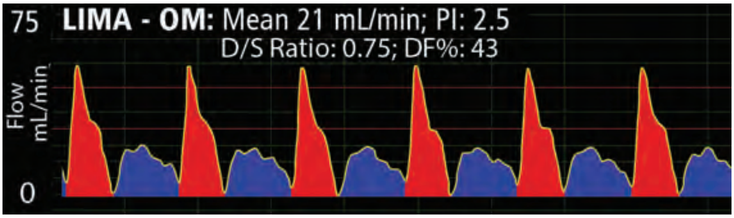


Fig. 4.8: Although waveform analysis reveals a balanced systolic/diastolic profile more representative of right heart grafts than a diastolic dominant profile seen in left heart grafts, this graft was accepted based on its good diastolic component and mean flow. An acceptable PI supported this decision.

B. Bypass Grafts to the Left Ventricle cont.

Right Internal Mammary Artery (RIMA) Grafts

Before applying the Flowprobe to the RIMA for a measurement, skeletonize approximately 1.5 cm of the graft, similar to the LIMA.

RIMA - LAD Graft

RIMA - LAD Flow

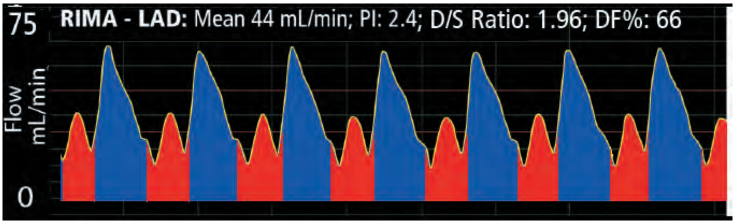


Fig. 4.9: The good RIMA - LAD mean flow indicates patency which is confirmed by the classic diastolic dominant waveform profile and 2.4 PI.

RIMA - Cx Graft

RIMA - Circumflex (Cx) Flow

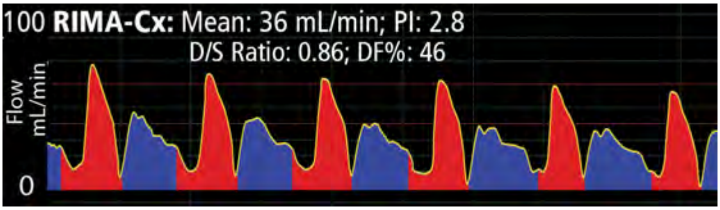


Fig. 4.10: Good mean flow (36 mL/min) indicates patency. Balanced waveform and acceptable PI confirm an acceptable graft.

RIMA - OM Graft

RIMA - Obtuse Marginal (OM) Flow

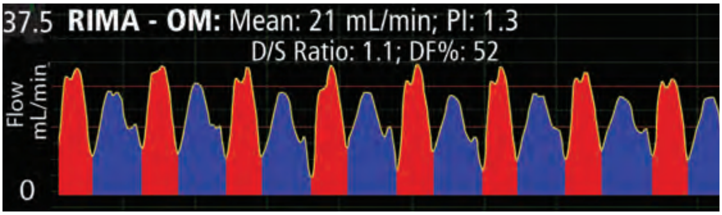


Fig. 4.11: The mean flow (21 mL/min), the diastolic waveform component and an acceptable PI of 1.3 indicate an acceptable graft.

B. Bypass Grafts to the Left Ventricle cont.

RIMA Graft Flows cont.

RIMA - Dx Graft

RIMA - Diagonal (Dx) Flow

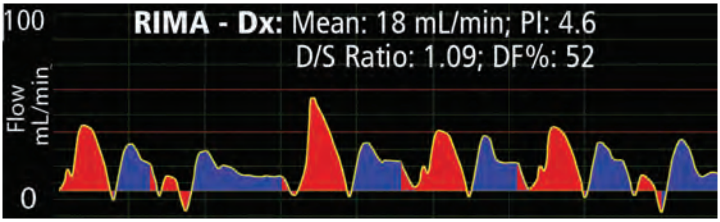


Fig. 4.12: This waveform exhibits characteristic poor runoff into the myocardium. Given the clear diastolic component of the waveform and the stage of the myocardial disease, the graft was considered patent.

Radial (Rad) Graft Flows

Rad - LAD Graft

Rad - LAD Flow

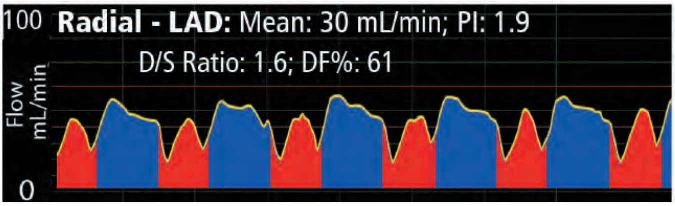


Fig. 4.13: This graft profile indicates a patent graft with an acceptable (30 mL/min) mean flow.

RAD - Cx Graft

Rad - Circumflex (Cx) Flow

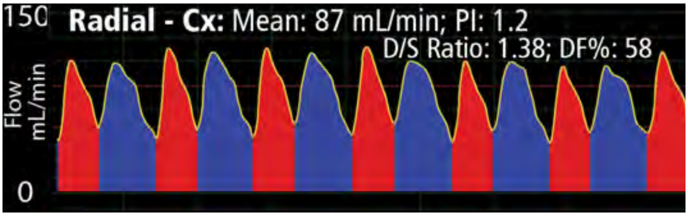
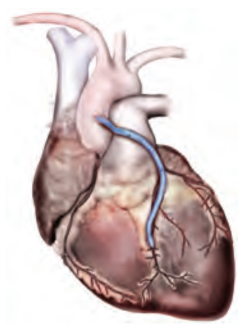


Fig. 4.14: High mean flow indicates an acceptable graft.

B. Bypass Grafts to the Left Ventricle cont.

Vein (SVG) Grafts

Mean flow and waveform assessment rules for vein grafts are similar to those for arterial grafts. When a graft to the left posterior descending artery (PDA) supplies the left heart, the waveform also exhibits a diastolic dominant pattern (see Fig. 4.19 on next page).



SVG - LAD Graft

SVG - LAD Grafts

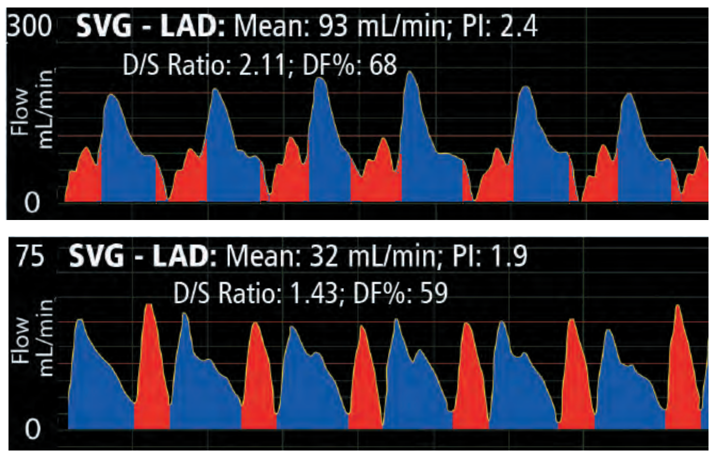


Fig. 4.15: Each of these two SVGs is anastomosed to the LAD in two respective patients. Both grafts indicate graft patency, based on their good mean flows, diastolic-dominant flow profiles, and low PIs.

SVG - Ramus Graft

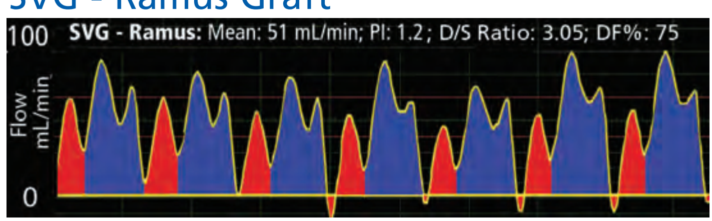


Fig. 4.16: The 51 mL/min mean flow, diastolic-dominant flow profile, and low PI of this SVG - Ramus bypass graft indicates graft patency. The ramus intermedius is present in ~20% (range 15-30%) of the population and supplies either the anterior or medial aspect of the heart. It is a coronary artery varient resulting from trifurcation of the left main coronary artery. (Waveform courtesy of R. Poston)

B. Bypass Grafts to the Left Ventricle cont.

Vein (SVG) Grafts cont.

SVG - Circumflex (Cx)

SVG - Cx Graft

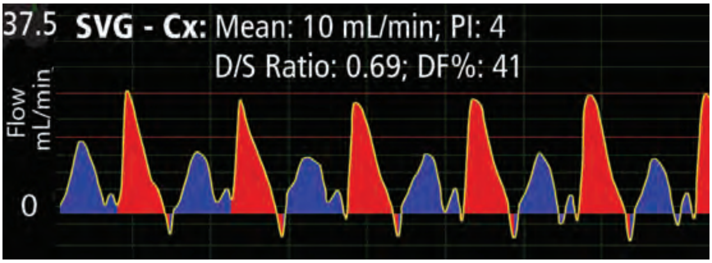


Fig. 4.17: Low mean flow (10 mL/min) accompanied by a fair waveform profile raised questions about the patency of this graft. The negative troughs at the end of systole indicate competitive flow. A repeat measurement is recommended with the native coronary occluded..

SVG - Obtuse Marginal (OM)

SVG - OM Graft

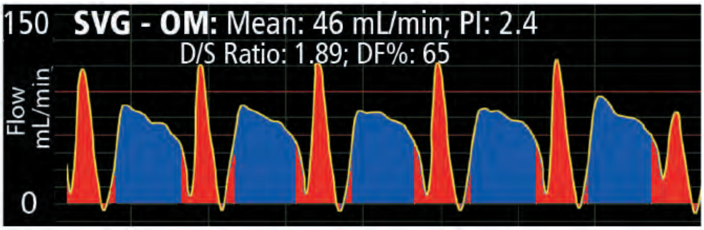


Fig. 4.18: Good mean flow (46 mL/min) with a strong diastolic profile indicates an acceptable SVG - OM graft.

SVG - Left Posterior Descending Artery

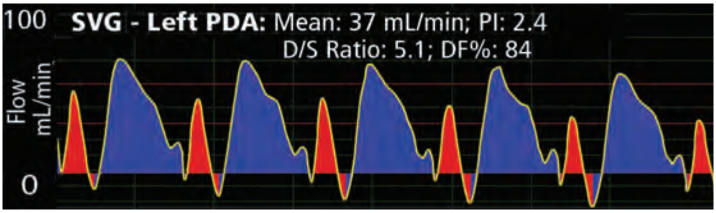


Fig. 4.19: This left heart SVG - PDA graft exhibits a diastolic-dominant profile, that contrasts to the more balanced systolic/diastolic profiles exhibited in SVG - PDA waveforms to the right heart..

C. Bypass Grafts to the Right Ventricle

Flow in right ventricle grafts is characterized by a more balanced systolic/diastolic profile. This is explained by the fact that the systolic contraction of the right ventricle is not as strong as that of the left ventricle (Chapter III.B, page 56, Fig. 3.3).

The right heart exerts less resistance during systole. Therefore, patent graft flow patterns to the right heart follow the arterial pressure waveform, but with large variations in the level of flow during systole.

In grafts to the right ventricle, patency is indicated if, with native coronary artery occluded:

- Mean flow is in the "Normal" range or higher or:
- Mean flow is in the "questionable" range but flow is "systolic/diastolic balanced."

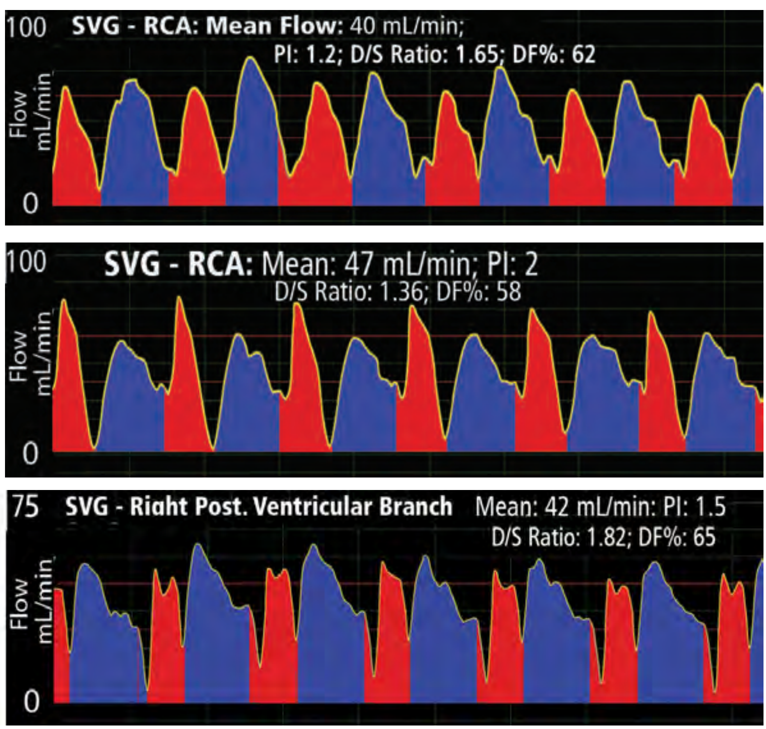


Fig. 4.20: Alternate normal flow profiles in right ventricular grafts, with altered systolic/diastolic flow peak ratio and timing.

C. Bypass Grafts to the Right Ventricle cont.

Arterial Grafts to the Right Ventricle

RIMA - RCA Graft

RIMA - RCA Graft Flows

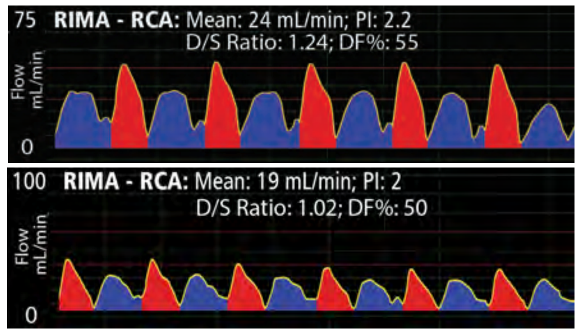


Fig. 4.21: The two waveforms above demonstrate common graft flow patterns to the right ventricle with balanced flow distributions between systole and diastole. These systolic/diastolic balanced profiles indicate acceptable grafts despite rather low mean flows.

Radial (Rad) - RCA Flow

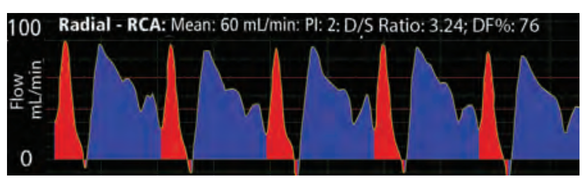


Fig. 4.22: The high mean flow (60 mL/min), good waveform, and acceptable PI indicate an acceptable graft.

C. Bypass Grafts to the Right Ventricle cont.

Vein Grafts to the Right Ventricle

SVG - RCA Graft Flows

SVG - RCA Graft

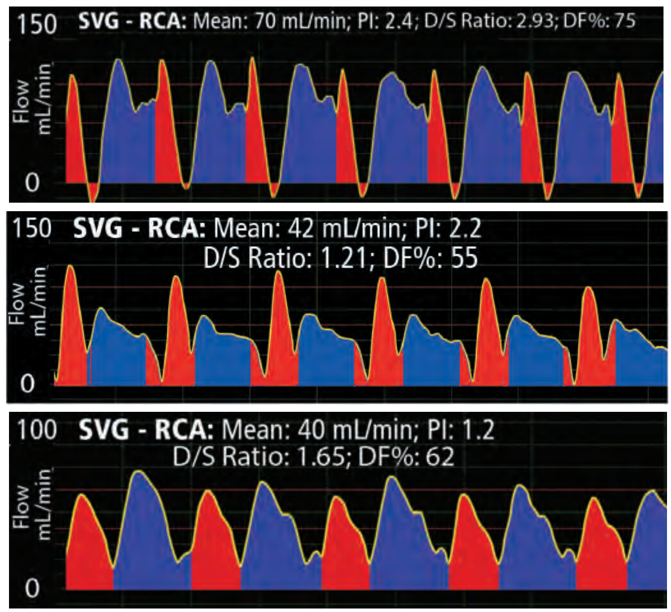


Fig. 4.23: All three of these SVG -RCA grafts have good mean flows that indicate acceptable grafts. The flow profiles illustrate some of the variations that may be encountered with acceptable grafts.

SVG - Post-Ventricular Branch Graft Flow

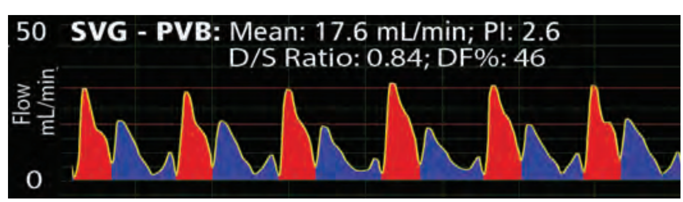


Fig. 4.24: Mean flow of this SVG to the post-ventricular branch coronary artery is questionable, but the systolic/diastolic balanced waveform profile indicates a patent graft. An acceptable PI supports this conclusion.

C. Bypass Grafts to the Right Ventricle cont.

Vein Grafts to the Right Ventricle cont.

SVG - PDA Graft Flows

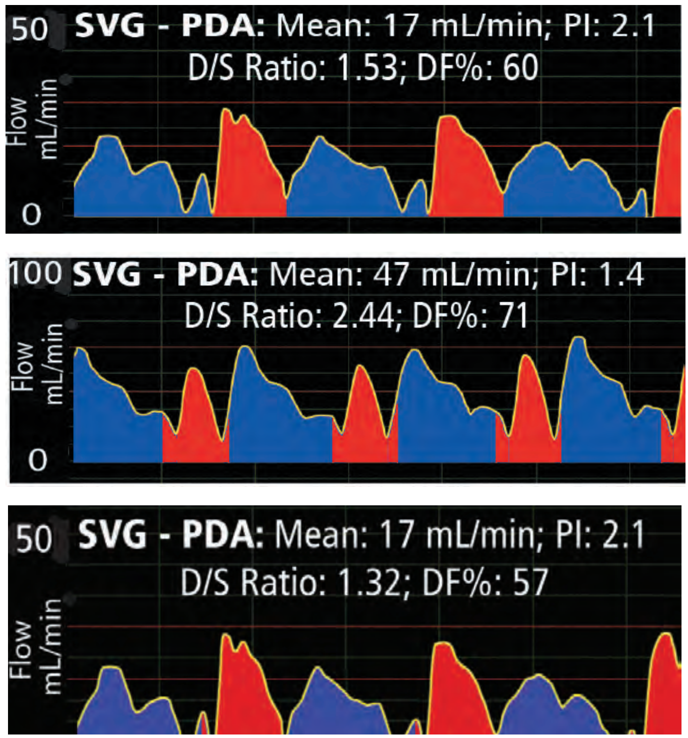


Fig. 4.25: All three of these SVG - PDA grafts have acceptable mean flows that indicate acceptable grafts. The variations in flow profiles illustrate some that may be encountered with acceptable grafts to the right heart.

D. Composite Graft Flow Profiles

In composite Y grafts, T grafts, or sequential grafts, the patency of each individual branch is evaluated by the same mean flow and flow waveform rules that apply to single left or right ventricles grafts.

Y Graft Waveforms

To measure the patency of a composite graft, the Flowprobe is applied to the main trunk of the graft before its first bifurcation. The patency of each branch is then tested consecutively by:

a) Blocking potential competitive flow from the native coronary artery, and
b) Occluding all other branches of the composite graft to direct maximal flow through the single branch being tested.

Y Graft: SVG - Dx, OM

Y Graft: SVG - Diagonal (Dx) and OM1

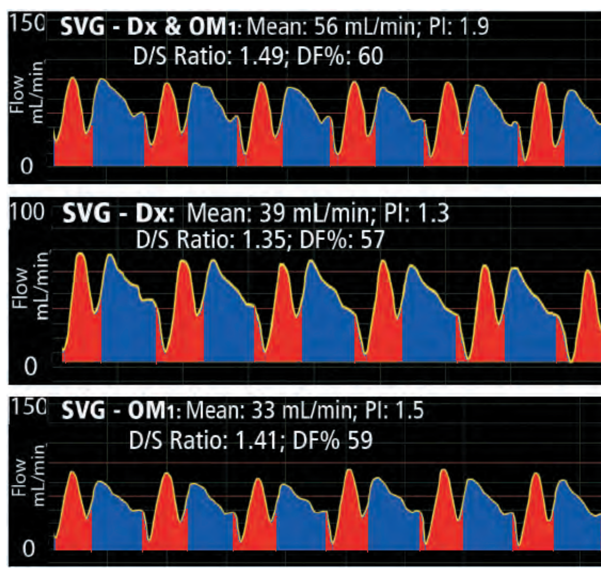
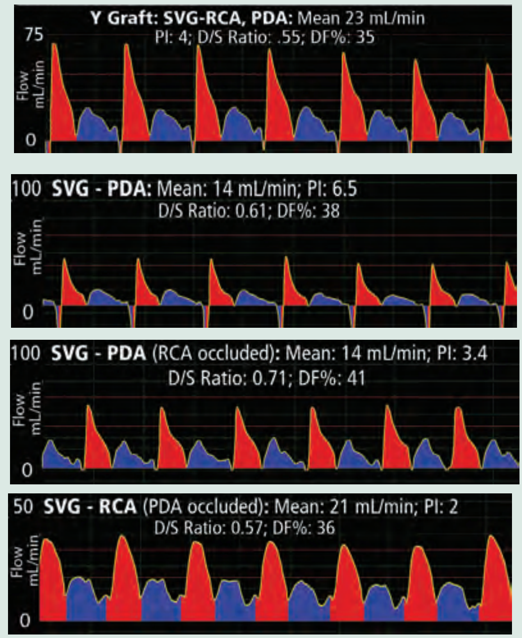


Fig. 4.26: Flow through the two branches (top trace) of the Y graft indicates graft functionality at the proximal anastomosis. Individual measurements of the diagonal (middle trace) and OM1 (bottom trace) branch reveal good mean flows, and diastolic-dominant flow profiles to indicate patency for each branch.

D. Composite Graft Flow Profiles cont.

Example: Y Graft with Competitive PDA Flow

A patient with multi-vessel coronary artery disease underwent CABG surgery. A saphenous vein Y graft was anastomosed to the Right Coronary Artery (RCA) and then to the Posterior Descending Artery (PDA). Mean flow through the graft was 23 mL/min. Mean flow to the PDA was 14 mL/min with a PI of 6.5. There was evidence of competitive flow in the systolic/diastolic waveform. When the RCA was occluded SVG - PDA flow remained at 14 mL/min but the PI improved to 3.4. When SVG - RCA flow was measured with the PDA occluded, mean flow remained at 21 mL/min, but the PI improved from 4 to 2. All four waveforms exhibited balanced systolic/diastolic profiles.



Y grafts 23 mL/min: SVG-RCA & PDA: with each branch RCA occluded. SVG - RCA flow was 21 mL/min; SVG - PDA flow remained at 14 mL/min.

Case Summary: **Off-CPB CABG; Y Graft to RCA, PDA**				
Flow Measurement	Graft Occluded	Mean Flow (mL/min)	PI	Waveform & Flow
1. Y Graft to RCA, PDA		23	4	Systolic/diastolic waveform; acceptable flow
2. Y Graft to PDA		14	6.5	Repetitive systolic/diastolic waveform; ? flow
3. Y Graft to PDA	RCA	14	3.4	Repetitive systolic/diastolic waveform; ? flow
3. Y Graft to RCA	PDA	21	2	Systolic/diastolic waveform; acceptable flow
Case illustrates waveforms with negative spikes that indicate the presence of competitive flow.				

Speziale *et al.*, "Intraoperative Flow Measurement in Composite Y Arterial Grafts," Eur J Cardiothorac Surg 2000; 17: 505-8.

D. Composite Graft Flow Profiles cont.

To measure the patency of a sequential graft, the Flowprobe is applied to the main trunk of the graft and flow is measured. Then, flow is remeasured with the distal sequential graft occluded. The resulting flow through the first coronary can then be evaluated for patency. When the occlusion is lifted, flow to the second graft can be calculated by subtracting the flow to the first coronary with occlusion from the first total sequential flow measurement.

Sequential SVG - OM1, OM2

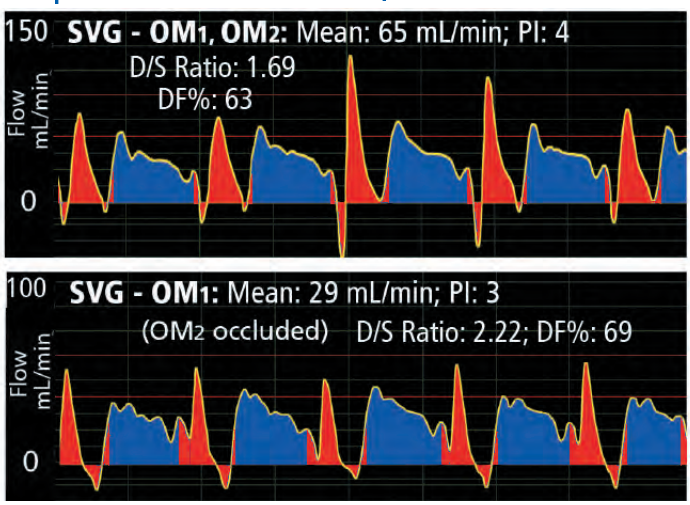


Fig. 4.27: Mean flow of the sequential SVG to OM1 and OM2 graft was 65 mL/min. When the OM2 was occluded, flow from the SVG to OM1 graft was 29 mL/min, indicating OM1 patency. OM2 patency is inferred from the drop in flow: at least 65 - 29 = 36 mL/min perfused the OM2 during the OM1 & OM2 measurement.

Gwozdziewicz M et al., "Sequential bypass grafting on the beating heart: blood flow characteristics," Ann Thorac Surg 2006; 82(2): 620-3.

Onorati F *et al.*, "Single versus sequential saphenous vein grafting of the circumflex system: a flowmetric study," Scand Cardiovasc J 2007; 41(4): 265-71.

Yu Y *et al.*, "The application of intraoperative transit time flow measurement to accurately assess anastomotic quality in sequential vein grafting," Interact Cardiovasc Thorac Surg. 2013; 17(6): 938-43.

D. Composite Graft Flow Profiles cont.

Sequential Bypass on the Beating Heart Can Be Achieved without Compromising Patient Safety or Regional Myocardial Blood Flow

Quigley RL *et al.*, Int Surg. 2010;95(3):257-60.

BACKGROUND

Some surgeons who prefer to operate off pump on the beating heart (OPCABG) use a sequential reversed saphenous vein graft (rSVG) to revascularize the lateral, inferior, and posterior myocardium with a single proximal aortic anastomosis in addition to the internal mammary artery to the left anterior descending coronary artery (LIMA-LAD).

OBJECTIVE

To summarize a series of OPCABG cases, and evaluate distal conduit blood flow.

STUDY

- 175 patients were enrolled in study between January 1, 2005 and January 1, 2007.
- OPCABG performed with 1 IMA graft and 1 sequential SVG performed by one surgeon.
- The average number of grafts per patient was 3.4 (range: 3-5).
- Flow rates were measured in each segment of the sequential graft.

RESULTS

- Mean flow through the distal segment of the sequential venous bypass was 36 mL/min. This was found not to be significantly influenced by the number of proximal coronary anastomoses nor by the size of the proximal coronary bed.
- 0% 30-day mortality and stroke rate.
- 29% incidence of postoperative atrial fibrillation in patients with normal baseline sinus rhythm (49/169).
- No myocardial failure or renal failure requiring dialysis occurred.

CONCLUSION

OPCABG using sequential reversed saphenous vein grafts (SVG) is safe, and regional coronary blood flow is not compromised by the creation of sequential anastomoses.

E. Other CABG Flow Profile Phenomena

Reverberant Waveform Phenomena

Flow profile derivations use a simple systolic/diastolic pressure wave. From the literature we know that the pressure wave may develop a diastolic peak as well. This oscillation in pressure explains the more "reverberant" flow profiles as shown in Figs. 4.28- 4.30.

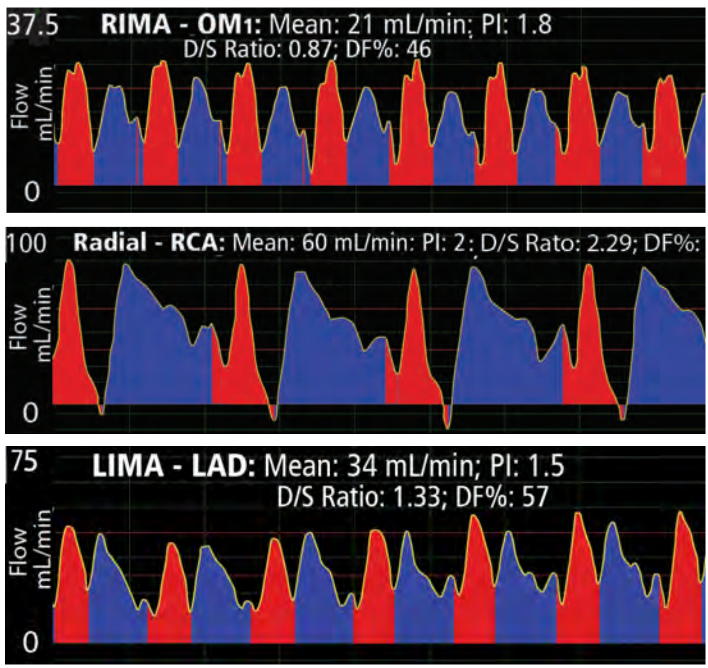


Fig. 4.28: Examples of reverberant flow patterns. Both systolic and diastolic flow phase may become double-peaked (RIMA - OM_1). The decaying slope of the diastolic flow wave often exhibits an oscillating pattern (Radial - RCA, LIMA - LAD).

E. Other CABG Flow Profile Phenomena cont

Reverberant Waveform Phenomena cont.

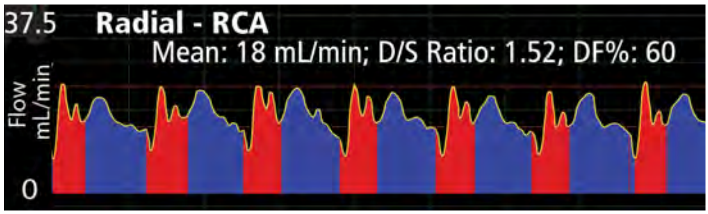


Fig. 4.29: Case example of reverberant Radial-RCA waveform.

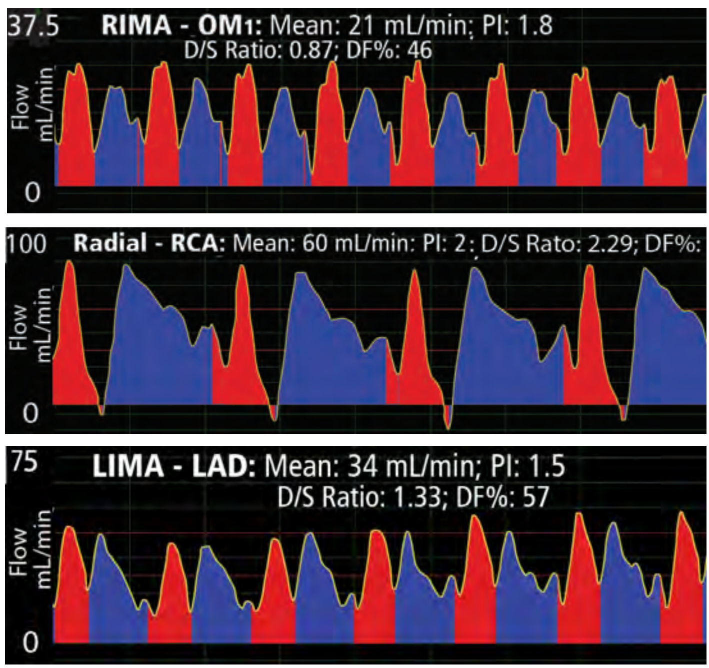


Fig. 4.30: Additional examples of reverberant flow patterns. Both systolic and diastolic flow phase may become double-peaked (RIMA - OM1). The decaying slope of the diastolic flow wave often exhibits an oscillating pattern (Radial - RCA, LIMA - LAD).

E. Other CABG Flow Profile Phenomena cont.

Many coronary arterial branches supply both the left and the right ventricle. In these cases, the high systolic flow resistance of the left ventricle is paralleled by the more moderate flow resistance of the right ventricular myocardium. Total systolic myocardial flow will not approach the near-zero condition of the left ventricular profile. These flow waveforms will follow right ventricular rules. A normal flow profile for coronaries supplying both sides of the heart is thus systolic/diastolic-balanced (see Fig. 2.15, page 29).

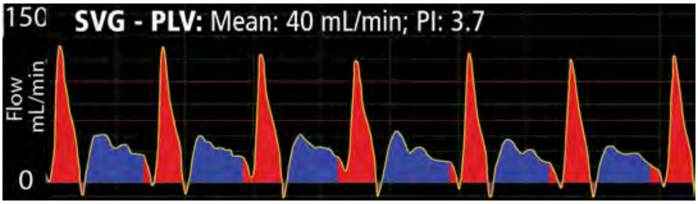


Fig. 4..31: Typical flow profile in a graft supplying both left and right ventricular tissue (systolic/diastolic balanced).

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

Jelenc M et al, Univ. Med. Ctr. Ljubljana, Ljubljana, Slovenia. Interact Cardiovasc Thorac Surg. 2014 Feb;18(2):164-8.

BACKGROUND

Mean bypass graft flow (Q) measured by transit time flow measurement (TTFM) and calculated high pulsatility index (PI) are not specific for anastomotic stenosis, but occur with competitive flow and poor coronary run-off. Changes in a flow curve occur when stenosis at the anastomosis reaches hemodynamic significance.

OBJECTIVE

To test the hypothesis that graft compliance is responsible for changes in flow as a stenosis increases 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

- TTFMs of 15 left internal thoracic artery (LITA) to left anterior descending (LAD) bypass grafts and 10 saphenous vein grafts (SVGs) to either the right coronary artery (RCA) or posterior descending artery (PDA) were analyzed.
- All bypass grafts had a single distal anastomosis and SVG grafts had the proximal anastomosis on the aorta.
- TTFM was performed on the proximal and distal ends of each graft, and proximally with distal occlusion of the graft (to test for competitive flow).
- Low mean bypass graft flow PI and diastolic filling (DF) measured distally and proximally were compared. Graft compliance was estimated.

RESULTS

- Diastolic filling was higher distally in every 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

- TTFM measured at the proximal end of the coronary bypass can be viewed as a sum of graft capacitive flow and the flow that passes through the distal anastomosis.
- Graft compliance significantly influences TTFM.
- 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.

TAKE HOME

- PI cannot be used as a measure of graft patency. It only reflects the ratio of capacitive to mean flow.
- Only mean flow should be used to judge the function of the bypass grafts.
- 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.

V. CABG Case Reports

This chapter presents case reports culled by Dr. Bruce Mindich from more than 500 CABG cases. The chapter has three sections. The first offers case examples of grafts where poor intraoperative flow measurements, for a variety of reasons (clot, twisted graft, technical problem), triggered subsequent revisions in the grafts. The second section offers case examples where on-CPB flow measurements augmented later off-CPB flows. The final section presents interesting case examples.

A. Flow Measurements Trigger Graft Revisions

Zero Flow Demands Revision of LIMA - Cx Graft

A 78-year-old female patient underwent single coronary bypass grafting to bypass a blocked circumflex (Cx) coronary artery with the LIMA. Flow first measured 0 mL/min (PI: 91) following anastomosis of the LIMA to the Cx. The flow waveform had a spiky systolic profile (top waveform). Revision was demanded.

Following revision of the graft, mean graft flow improved to 32 mL/min (PI: 2), and the waveform exhibited a balanced systolic/diastolic profile (bottom waveform). Zero mean flow was the determining factor in the decision to revise the graft.

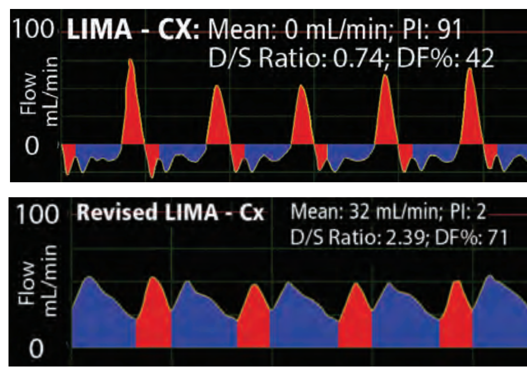


Fig. 5.1: The top waveform exhibited a spiky systolic profile, which, accompanied by zero mean flow, called for the surgeon to revise the LIMA-Cx graft without hesitation. Flow improved to 32 mL/min after revision and the waveform exhibited a balanced LIMA-Cx profile (bottom waveform).

Case Summary: 78-year-old female, single-vessel coronary artery disease Off-CPB CABG; LIMA-Cx Graft						
Flow Measurement	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform	Analysis
Post-bypass	0	0.74	42	91	Spiky systolic profile	Revision demanded
After revision	32	2.39	71	2	Balanced profile	Revision successful
Zero mean flow was the determining factor that called for revision.						

V. CABG Case Reports cont.

A. Flow Measurements Trigger Revisions cont.

Technical Problem with LIMA - LAD Graft

An 80-year-old female underwent CABG to bypass a blocked left anterior descending coronary artery (LAD). Her left internal mammary artery (LIMA) was anastomosed to the LAD distal to the blockage.

Following the anastomosis, LIMA - LAD flow measured -1 mL/min with a PI of 51. Blood pressure was 110/53 and pulmonary arterial pressure was 46/21. The patient's deteriorating BP, zero mean flow, high PI, and poor waveform profile indicated the immediate need for graft revision. Following revision, mean graft flow increased to 60 mL/min, PI improved to 1.7 and the waveform exhibited a classic LIMA-LAD profile with a strong diastolic component. Blood pressure decreased to 87/46 and pulmonary arterial pressure decreased to 24/7 demonstrating the cascade of sequelae triggered by flow.

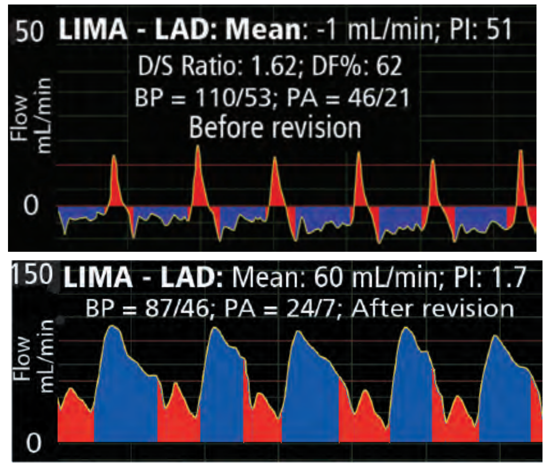


Fig. 5.2: The zero mean flow of the first flow measurement demonstrated a graft that required immediate attention. Mean flow was -1 mL/min. The LIMA to LAD anastomosis was revised and mean flow improved to 60 mL/min with an excellent diastolic flow pattern.

Case Summary: CABG: 80-year-old female; LIMA - LAD Graft						
Flow Measurement	Mean Flow (mL/min)	PI	BP	PA	Waveform Analysis	Analysis
1) Post bypass	-1	51	100/53	46/21	Poor waveform	Requires attention
2) After revision	60	1.7	87/46	24/7	Classic systolic/ diastolic wave-form profile	Revision successful
Case illustrates how a -1 mL/min mean flow in a LIMA - LAD graft spurred a successful revision of the graft.						

A. Flow Measurements Trigger Revisions cont.

Low Mean Flow Spurs Rad - OM1 Graft Revision

A 48-year old male patient with multi-vessel coronary artery disease underwent quadruple CABG. Four grafts including a LIMA-LAD, SVG-OM, SVG-Dx, and Rad-OM1 were constructed to deliver flow to the distal myocardium. Mean flows in the LIMA-LAD, SVG-OM, and SVG-Dx grafts were acceptable.

However, mean Rad-OM1 graft flow measured 3.6 mL/min (D/S Ratio; 0.18, DF%: 15, PI: 12.7) signaling the need for revision of the graft. Following Rad-OM1 graft revision, mean graft flow improved to 18.3 mL/min (D/S Ratio; 2.04, DF%: 56, PI: 1.7) and was accompanied by a diastolic dominant waveform.

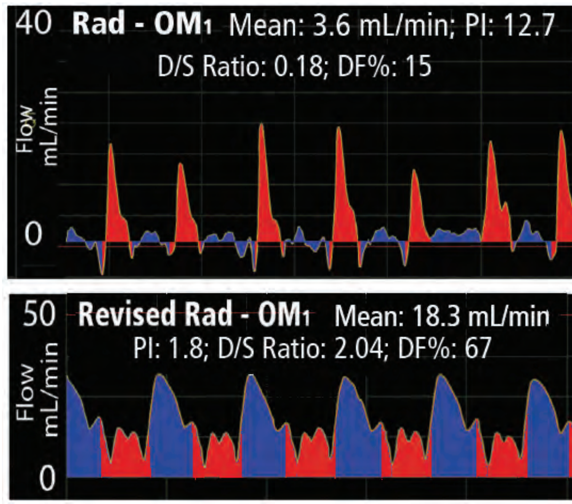


Fig. 5.3: The top waveform with a spiky systolic profile shows initial Rad-OM1 graft flow of 3.6 mL/min. Following revision of the graft, flow increased to 18.3 mL/min and was accompanied by a diastolic dominant waveform profile (lower waveform).

Summary: 48-year-old male; multi-vessel coronary artery disease Off-CPB CABG; RAD-OM$_1$ Graft						
Flow Measurement	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform	Analysis
Post RAD - OM1 bypass	3.6	0.18	15	12.7	Systolic dominant waveform.	Revision warranted
After revision	18.3	2.04	56	1.7	Repetitive systolic/diastolic profile	Revision successful
Case illustrates that revision of a graft with unacceptable mean flow can improve mean flow, other metrics (D/S Ratio, DF%, PI), and waveform profile.						

A. Flow Measurements Trigger Revision cont.

Poor Rad - LAD Graft Flow Sparks Graft Revision

A 71-year-old male with single-vessel coronary artery disease underwent CABG surgery. A segment of the radial artery (Rad) was harvested and grafted proximally to the aorta and distally to the LAD. Initial Rad-LAD mean flow measured 1.8 mL/min (D/S Ratio 0.78; DF%: 44; PI: 29) indicating that revision of the graft was warranted (upper waveform).

After revision, graft flow improved to 77.5 mL/min (D/S Ratio 1.28; DF%: 56; PI: 3). The flow was accompanied by a repetitive systolic/diastolic waveform profile (lower waveform).

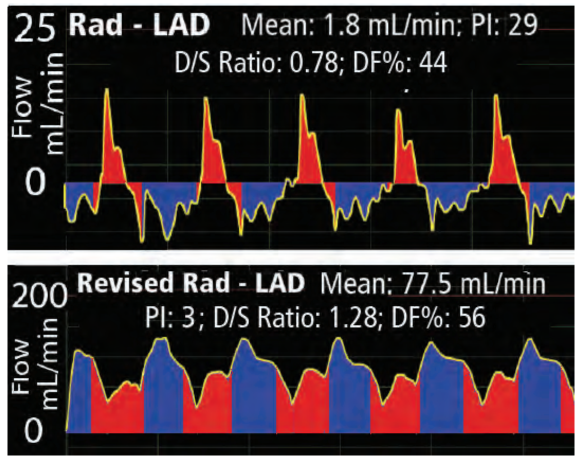


Fig. 5.4: The upper Rad-LAD waveform exhibits a spiky systolic profile and is coupled with an initial graft flow of 1.8 mL/min. Following revision of the graft, flow increased to 77.5 mL/min and was accompanied by a diastolic dominant waveform (bottom).

Case Summary: 71-year-old male; single vessel coronary artery disease Off-CPB CABG; Rad-LAD Graft						
Flow Measurement	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform	Analysis
Post Rad-LAD bypass	1.8	0.78	44	29	Atypical diastolization although pulse and pressure appeared functional	Revision warranted
After revision	77.5	1.28	56	3	Classic repetitive systolic/diastolic profile	Revision successful
Case illustrates that, by revising a graft that measures almost no mean flow, graft flow can improve dramatically.						

V. CABG Case Reports cont.

A. Flow Measurements Trigger Revisions cont.

Zero Flow Spurs LIMA - Cx Graft Revision

A 78-year old male patient underwent OPCAB. The LIMA was used as a bypass to the Cx. Initial flow measured 0 mL/min and was accompanied with a systolic (upper) waveform profile.

The graft was revised and flow increased to 32 mL/min and was accompanied by a more balanced systolic/diastolic waveform (lower waveform). The PI went from 100 to 2.

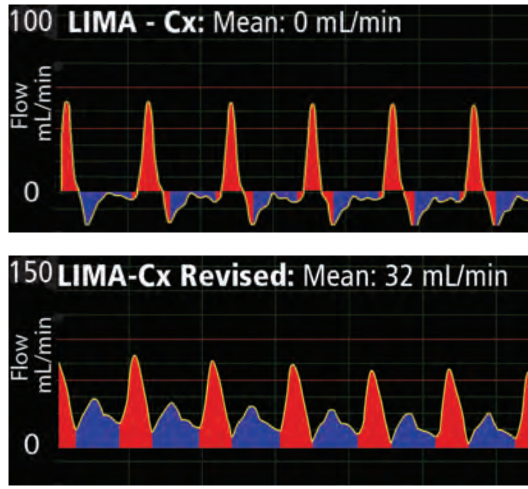


Fig. 5.5: The upper spiky systolic waveform profile shows initial 0 mL/min LIMA - Cx graft flow following anastomosis of the bypass. After the graft was revised, flow increased to 32 mL/min and was accompanied by a more balanced diastolic/systolic profile (lower waveform).

Case Summary: 78-year-old male Off-CPB CABG; LIMA - Cx Graft						
Flow Measurement	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform	Analysis
Post LIMA-Cx bypass	0			100	Systolic dominant waveform	Revision necessary
After revision	32			2	Systolic/diastolic profile	Revision successful
Case illustrates that revision of a graft that can improve mean flow, PI and waveform profile.						

V. CABG Case Reports cont.

A. Flow Measurements Trigger Revisions cont.

Clotted SVG - Cx Graft

An 80-year-old male underwent CABG to bypass a blocked circumflex coronary artery (Cx). His left internal mammary artery (LIMA) was anastomosed to the Cx distal to the blockage.

Following the anastomosis, SVG - Cx flow measured -1 mL/min (PI: 40). The negative mean flow, high PI, and poor waveform profile indicated the immediate need to investigate the anastomosis. A clot was discovered. Following declotting, flow was remeasured and improved with intra-aortic balloon pumping (IABP) to 86 mL/min. When IABP was removed, flow remained high at 76 mL/min (PI: 2).

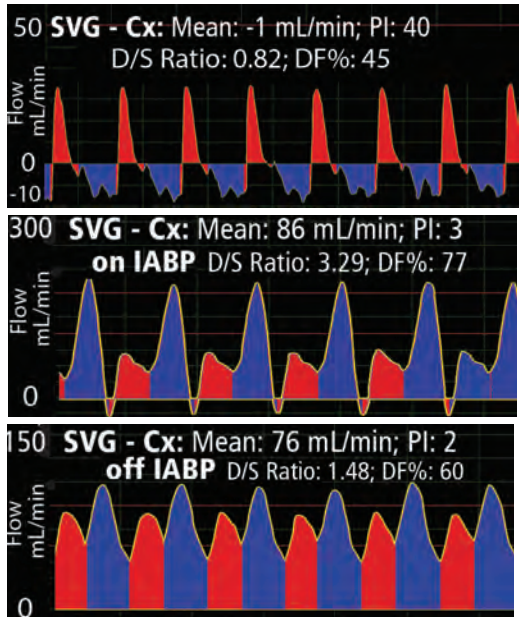


Fig. 5.6: This SVG - Cx graft first registered zero flow indicating a problem. Investigation revealed a clot. The second and third grafts show flow on and off IABP after declotting the graft.

Case Summary: 80-year-old male; CABG: SVG - Cx Graft						
Flow Measurement	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform Analysis	Analysis
1) Post bypass	-1	0.82	45	40	Poor waveform	Requires attention
A clot was discovered in the graft. Graft was declotted.						
2) Graft declotted, on IABP	86	3.29	77	3	Systolic/diastolic profile	Remove IABP
3) Graft declotted, off IABP	76	1.48	60	2	Systolic/diastolic profile	Revision successful
Case illustrates that quantitative graft flow assessment can signal a problem with a graft that can be fixed.						

B. On-CPB Flows Foreshadow Off-CPB Flows

Measuring graft flow on CPB predicts rough qualitative and quantitative indications of post-CPB flow. An acceptable on-CPB flow with an oscillating pulsatile waveform and diminution in systole foreshadows a good corresponding systolic/diastolic off-CPB flow and waveform. A 2005 study by Hagiwara concluded, "TTFM during CPB was useful to detect graft failure, and grafts were revised safely during CPB."[1]

Good On-CPB Flows Predict Excellent Off-CPB Flows

On-CPB Graft Flows | Off-CPB Graft Flows

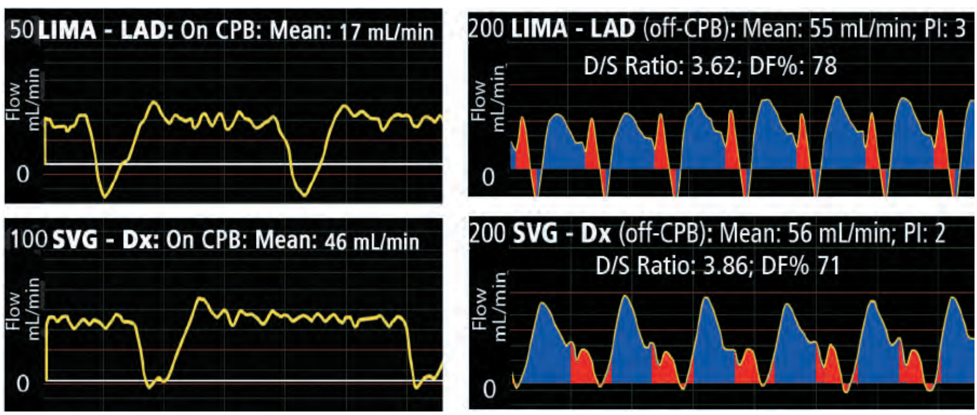


Fig. 5.7: Two good on CPB flows (LIMA - LAD: 17 mL/min, SVG - Dx: 46 mL/min) predict excellent off-CPB flows (LIMA - LAD: 55 mL/min; SVG - Dx: 56 mL/min). Also, SVG - OM flow was 53 mL/min off CPB.

Case Summary: 81-year-old male; CABG: Three Bypass Grafts

Bypass Grafts	On CPB	Off-CPB				
	Mean Flow (mL/min)	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform Analysis
LIMA - LAD	25	55	3.52	78	3	Excellent diastolic dominant profile
SVG - Dx	46	56	3.86	71	2.2	Systolic/diastolic balanced profile
SVG - OM	31	53	not shown			
Case illustrates how good on-CPB flows predict good off-CPB flows.[1]						

[1] Hagiwara H et al., "The correlation between flow pattern during cardiopulmonary bypass and patency of the coronary artery bypass grafts" Kyobu Geka. 2005 Jul;58(7):519-23; discussion 524-6.

B. On-CPB Flows Foreshadow Off-CPB Flows cont.

On-, Off-CPB Graft Flows with Heart Fibrillating

SVG - RCA Graft Flows

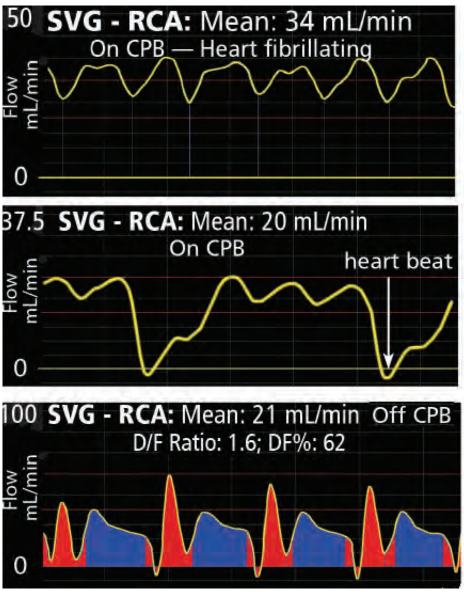


Fig. 5.8: Top row: SVG - RCA on-CPB when the heart is fibrillating; 2nd row: SVG - RCA on-CPB without fibrillation. Acceptable on-CPB SVG - RCA mean flow foreshadowed an acceptable off-bypass flow and waveform (third row).

SVG - Dx Graft Flows

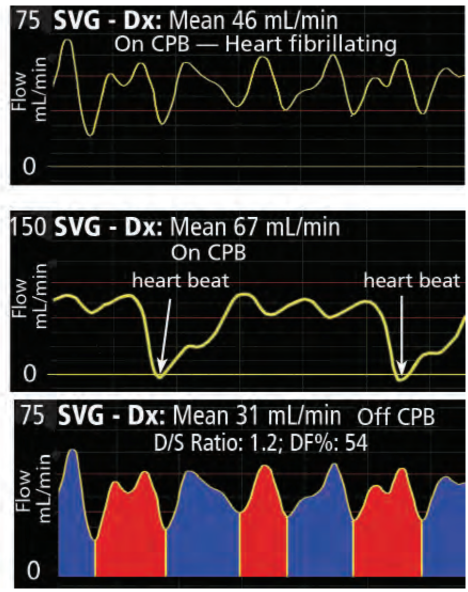


Fig. 5.9: Top row: SVG - Dx on-CPB when the heart is fibrillating; 2nd row: SVG - Dx on-CPB without fibrillation. Acceptable on-CPB SVG - Dx flow foreshadowed an acceptable off-bypass flow (third row).

Case Summary: 73-year-old male; CABG: Two Grafts: SVG - RCA; SVG - Dx

	On CPB (fibrillating)	On CPB (not fibrillating)	Off-CPB (not fibrillating)			
Bypass Grafts	Mean Flow (mL/min)	Mean Flow (mL/min)	Mean Flow (mL/min)	D/S Ratio	DF%	Waveform Analysis
SVG - RCA	34	20	21	1.6	62	Good systolic diastolic balance
SVG - Dx	46	67	31	1.2	54	Good systolic diastolic balance
Case illustrates how fibrillation affects flow.						

B. On-CPB Flows Foreshadow Off-CPB Flows cont.

Zero Mean Flows Lead to Discovery of Twisted Graft

A 73-year-old male had a SVG - Cx graft. Graft flow was measured both on- and then off-CPB (#1, 2). The zero mean flow and poor waveforms signaled a problem with the graft. A twist in the vein SVG graft was discovered. After untwisting the graft, flow was measured again, both on- and off-CPB (# 3, 4). Flow improved to 21 mL/min on-CPB, and 22 mL/min off-CPB. This case demonstrates how an on-CPB mean flow reading will forecast the subsequent off-CPB flow, unacceptable as in measurements #1 and 2 or acceptable as in measurements #3 and 4.

1.
2.

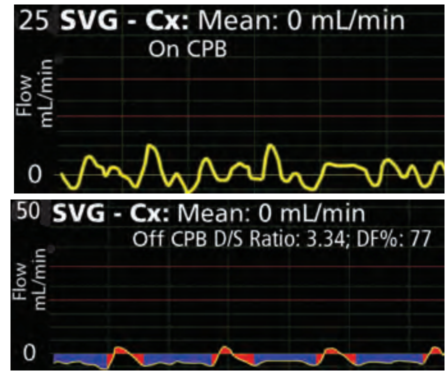


Fig. 5.10: Zero mean flows on & off CPB.

3.
4.

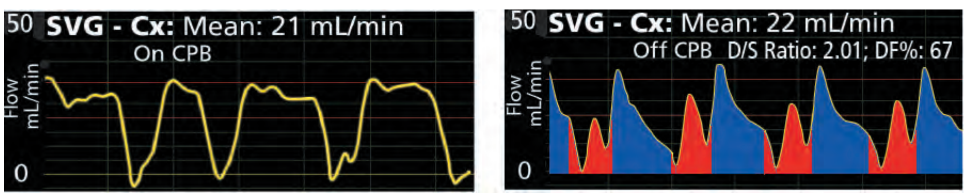


Fig. 5.11: When graft is untwisted, on-CPB flow increased to 21 mL/min; off-CPB flow was 22 mL/min.

Case Summary: 73-year-old male; CABG: SVG - Cx Graft						
Flow Measurement	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform Analysis	Action
1) On CPB	0				Poor waveform supports 0 mL/min mean flow	Remeasure off CPB
2) Off CPB	0	3.34	77		Poor waveform corroborates on-CPB measurement	Graft must be revised
SVG - Cx graft was twisted. Graft was untwisted and flow was remeasured.						
3) On CPB	21				Repetitive	Remeasure off CPB
4) Off CPB	22	2.01	67	2	Classic diastolic profile	Graft is patent
Case illustrates how poor on-CPB flows and waveforms can signal problem with graft.						

B. On-CPB Flows Foreshadow Off-CPB Flows cont.

Vein Grafts Questionable: LIMA - LAD Graft Good

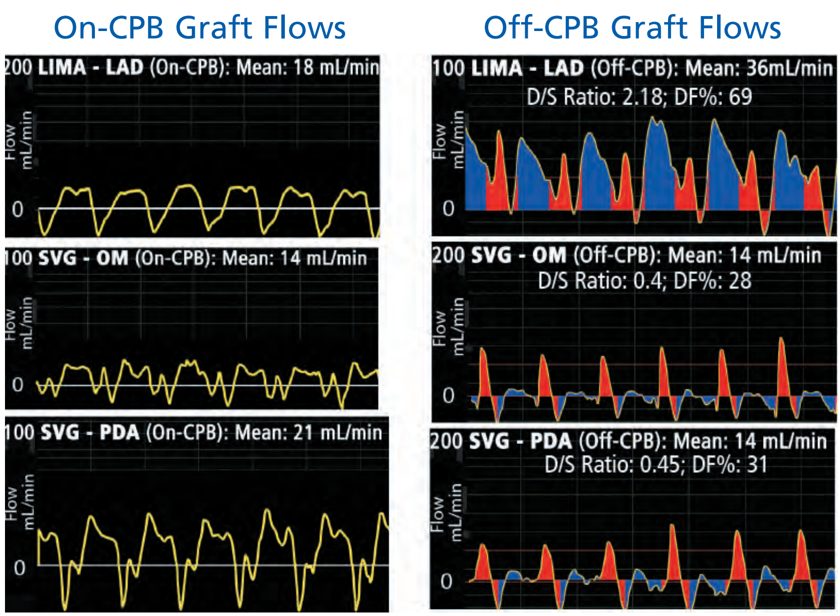


Fig. 5.12: LIMA - LAD graft flows on total CPB registered 18 mL/min. Off bypass LIMA - LAD flow measured 36 mL/min with a characteristic 2/3 diastolic, 1/3 systolic waveform profile. However, both SVG grafts, to the OM had questionable on-pump measurements of 14 mL/min. Even with systolic/diastolic balanced waveform profiles with negative dips that suggest competitive flow, the PIs were high at 15 and 14. The measurements and waveform profiles alert the surgeon to take a closer look at the grafts.

Case Summary: 73-year-old female; CABG: Three Bypass Grafts						
	On CPB	Off-CPB				
Bypass Grafts	Mean Flow (mL/min)	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform Analysis
LIMA - LAD	18	36	2.18	69	3	Classic LIMA - LAD profile
SVG - OM	14	14	0.4	28	15	Systolic dominant, competitive flow?
SVG - PDA	21	14	0.45	31	14	Systolic dominant, competitive flow?
Case illustrates how on-CPB flows can mirror off-CPB flows.						

B. On-CPB Flows Foreshadow Off-CPB Flows cont.

80-Year-Old Female with Two Good Grafts

On-CPB Graft Flows | **Off-CPB Graft Flows**

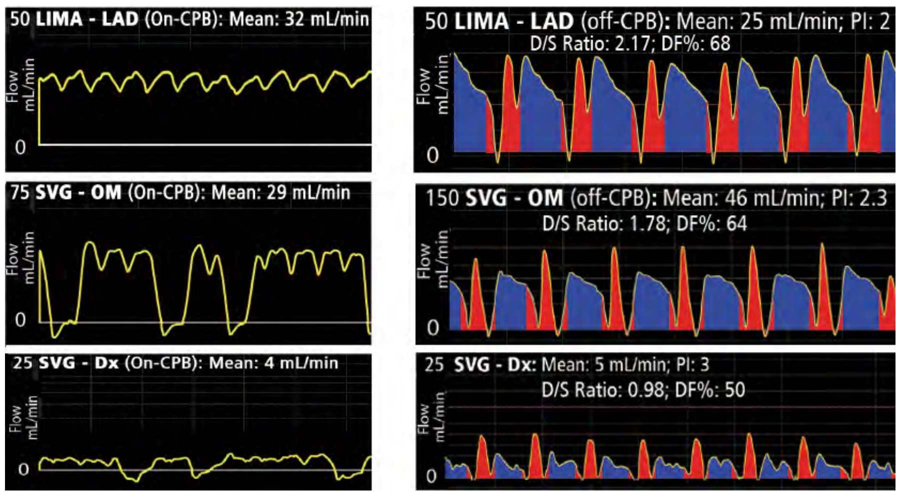


Fig. 5.13 On CPB, LIMA - LAD graft flows registered 32 mL/min. Off bypass LIMA - LAD flows measured 25 mL/min with a characteristic 2/3 diastolic, 1/3 systolic waveform profile. Similarly, the SVG - OM graft flow of 29 mL/min foreshadowed excellent off-CPB flow (46 mL/min). Moreover, poor on-CPB SVG - Dx graft flow (4 mL/min) augured poor unacceptable 5 mL/min flow off CPB, even though the PI of 3 equaled a false positive.

Case Summary: 80-year-old female; CABG: Three Bypass Grafts						
	On CPB	Off-CPB				
Bypass Grafts	Mean Flow (mL/min)	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform Analysis
LIMA - LAD	37	25	2.17	68	2	Classic LIMA - LAD profile
SVG - OM	29	46	1.7	64	2.3	Systolic/diastolic balanced
SVG - Dx	4	5	0.99	50	3 (false negative)	Systolic/diastolic balanced; runoff
Case illustrates how poor on-CPB SVG - DX flow and waveform signals a problem with graft. Also, of note is that the SVG - Dx flow off-CPB showed a false positive PI of 3.						

C. Interesting Cases

RIMA - RCA Flow Suppressed by Competitive Flow

A 60-year-old male underwent CABG to bypass a right coronary artery (RCA) blockage with a right internal mammary artery graft (RIMA). Following the RIMA-RCA anastomosis, flow measured 5 mL/min (PI: 7). Low mean flow, a high PI and a systolic dominant waveform profile indicated the need for graft revision.

After revision, flow improved to 20 mL/min (PI: 3.2), but this flow was not as high as the surgeon expected given the size of the patient. Suspecting the presence of competitive flow from the native RCA, the surgeon occluded the native RCA proximal to the anastomosis. Mean graft flow increased to 64 mL/min (PI: 2). Another graft was added distally on the RCA. Runoff improved, competitive flow decreased and graft flow was > 40 mL/min. The increase in mean graft flow affirmed the surgeon's suspicion that competitive flow was suppressing graft flow.

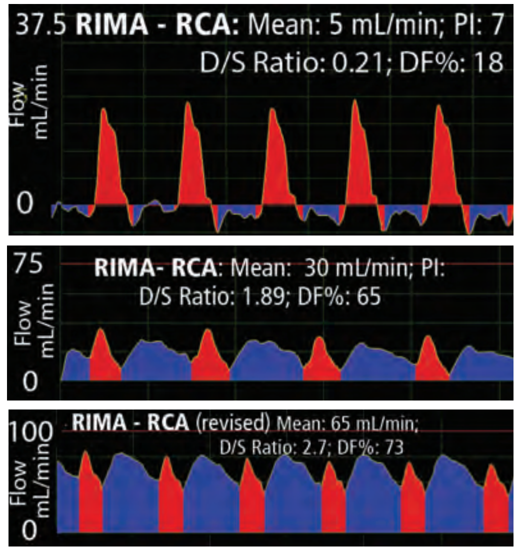


Fig. 5.14: The three waveforms show the systolic dominant profile of the RIMA-RCA graft before revision (top), the systolic/diastolic flow waveform profile following revision of the graft (middle), and the similar graft waveform with the proximal RCA occluded (bottom).

Case Summary: 60-year-old male, CABG: Off-CPB, RIMA-RCA Graft

Bypass Graft	Mean Flow (mL/min)	D/S Ratio	DF%	Pulsatility Index (PI)	Waveform	Analysis
Post RIMA - RCA bypass grafting	5	0.21	18	7	Systolic	Revision necessary
After revision	30	1.89	65	3.2		Possible competitive flow; occlude proximal RCA
Proximal RCA Occlusion	65	2.7	73	2	Diastolic dominant	
Case demonstrates the presence of significant competitive flow from the native RCA.						

C. Interesting Cases cont.

Y SVG - PLB, PDA Graft with Low Flow in One Branch

A 66-year-old male with multi-vessel coronary artery disease underwent CABG surgery. A saphenous vein Y graft was anastomosed to the Posterior Descending Artery (PDA) and to the Posterior Lateral Branch (PLB). When the PDA branch was occluded and flow was measured in the PLB, mean flow was only 5 mL/min, but the flow exhibited a good systolic/diastolic wave pattern. Negative troughs in the flow profile indicate that the mean flow of that branch of the Y was being compromised by competitive flow from the native coronary. Flow in the PDA branch was 25 mL/min, indicating that most of the flow of the Y graft was going through that branch. A vein graft was subsequently anastomosed to the obtuse marginal coronary (OM) in the patient.

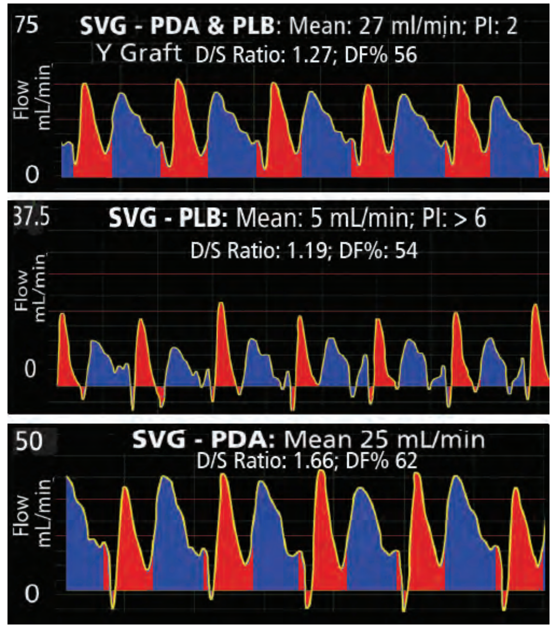


Fig. 5.15: The three waveforms show the acceptable flow waveforms of a Y graft to the PDA and PLB, even though flow to the PLB was low (5 mL/min) due to competitive flow from the native coronary artery.

Case Summary: 66-year-old male, CABG: Off-CPB; Y Graft to PLB, PDA					
Flow Measurement	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform & Flow
1. Y Graft to PDA, PLB	27	1.27	56	2	Repetitive systolic/diastolic
2. Y Graft to PLB	5	1.19	54	>6	Good waveform; poor flow
3. Y Graft to PDA	25	1.66	62	2.1	Good waveform; good flow
SVG - OM1 (not shown)	14			2	Good waveform; acceptable flow
Case demonstrates that flow might be flowing predominantly through one branch of a Y graft.					

C. Interesting Cases cont.

Three Arterial Grafts with Good Flows/Waveforms

A 70-year-old male underwent CABG surgery. The surgeon chose to use only arterial grafts during the surgery. The left internal mammary artery (LIMA) was anastomosed to the left anterior descending coronary artery (LAD); the right internal mammary artery was connected to the right coronary artery (RCA) and the radial (Rad) artery was harvested from the forearm and anastomosed to the posterior descending coronary a (PDA). All three grafts exhibited good flows and excellent waveforms. "Exclusive use of arterial conduits to achieve coronary revascularization is a goal that many surgeons see as a potential solution for premature failures of saphenous vein grafts."[1]

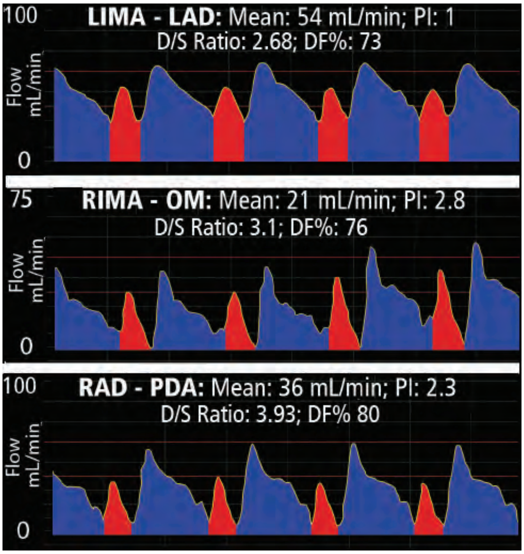


Fig. 5.16: These three arterial graft all exhibit good flows, acceptable PIs and excellent waveform profiles.

Case Summary: 70-year-old male, CABG: Off-CPB; Three Arterial Grafts					
Bypass Graft Flow	Mean Flow (mL/min)	D/S Ratio	DF%	Pulsatility Index (PI)	Waveform
LIMA - LAD	54.5	2.68	73	1	Excellent
RIMA - OM	21	3.1	76	2.8	Good
Radial - PDA	35.4	3.93	80	2.3	Excellent
Case illustrates total arterial coronary revascularization using the LIMA, RIMA, and Radial artery as the grafts of choice. Total arterial revascularization is a strategy favored by some cardiac surgeons.[1]					

[1]Royse et al., "Blood Flow in Composite Arterial Grafts and Effect of Native Coronary Flow," Ann Thorac Surg 1999; 68(5): 1619-1622.

C. Interesting Cases cont.

Left & Right Heart Waveform Comparisons

Case #1 Right Heart Waveforms Case #2

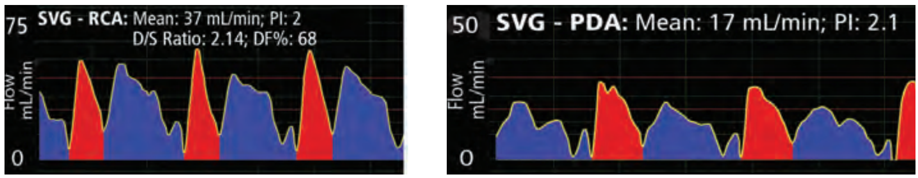


Fig. 5.17: Right heart grafts (SVG - RCA in Case #1, and SVG - PDA in Case #2) both demonstrate the balanced systolic/diastolic waveform profiles typical of bypass flows to the right heart.

Case #1 Left Heart Waveforms Case #2

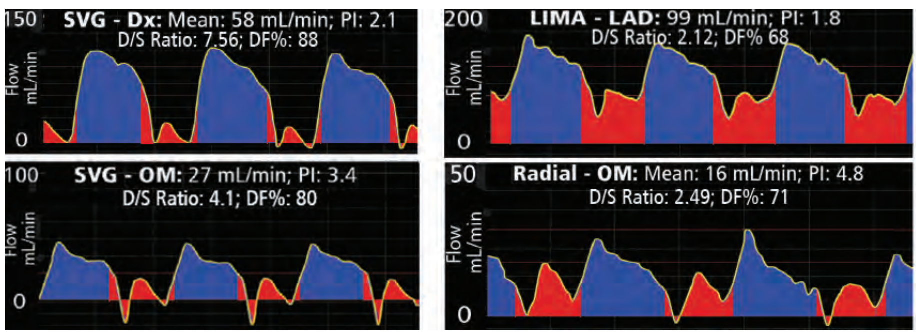


Fig. 5.18: Left heart grafts (SVG - Dx & SVG - OM in Case #1, and LIMA - LAD & Rad - OM in Case #2) all demonstrate strong diastolic dominant profiles typical of left heart bypass flows.

Case #1: Bypass to the right heart						Case #2: Bypass to the left heart					
Graft	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform	Graft	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform
Right Heart											
SVG-RCA	37	2.14	68	2	Balanced	SVG - PDA	17			2.1	Balanced
Left Heart											
SVG - Dx	58	7.56	88	2.1	Diastolic Dominant	LIMA - LAD	99	2.12	68	1.8	Diastolic Dominant
SVG - OM	27	4.1	80	3.4	Diastolic Dominant	Rad - OM	16	2.49	71	4.8	Diastolic Dominant

C. Interesting Cases cont.

Four Patent Grafts with Unusual Waveforms

A 66-year-old male with multi-vessel coronary artery disease underwent CABG surgery. Four bypass grafts (LIMA - LAD, SVG - Dx, SVG - OM1, SVG - OM2) were constructed. Mean flows in the four grafts were acceptable (LIMA - LAD 28 mL/min; SVG - Dx, 20 mL/min; SVG - OM1, 35 mL/min and SVG - OM2, 21 mL/min). The accompanying waveforms had unusual profiles with strong diastolic components in all the waveforms with almost no systole in the left heart LIMA - LAD and SVG - Dx grafts and small systole in the right heart OM1, OM2 grafts.

This is most often due to sub-myocardial coronaries, and has no negative implications on anastomostic quality.

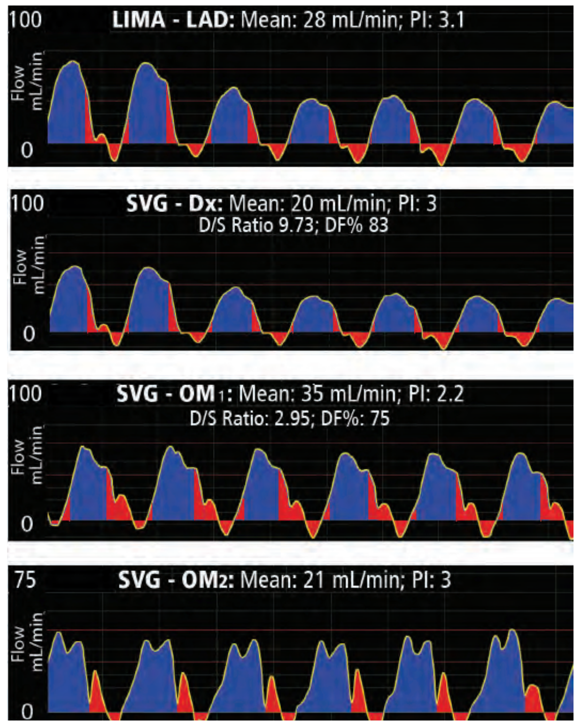


Fig. 5.19: Four grafts with acceptable mean flows and PIs but unusual waveforms with large diastolic components.

Case Summary: 66-year-old male; Quadruple CABG: Off-CPB Bypass Grafts: LIMA - LAD, SVG - Dx, SVG - OM1, SVG - OM2					
Flow Measurement	Mean Flow (mL/min)	D/S Ratio	DF%	PI	Waveform
LIMA - LAD	28			3.1	Unusual but acceptable
SVG - Dx	20	9.73	83	3	Unusual but acceptable
SVG - OM1	35	2,95	75	2.2	Unusual but acceptable
SVG - OM2	21			3	Unusual but acceptable
Case is example of most unusual waveforms for each of the grafts.					

C. Interesting Cases cont.

Phenomenal 17-Year-old SVG - OM1, OM2 Y Graft

A 90-year-old woman with cardiac symptoms underwent off-CPB CABG. She had had CABG surgery 17 years before when she was 73 years old. The surgeon measured flow in an old SVG - OM1, OM2 Y graft and was astounded to find that the old graft was still delivering 120 mL/min to the myocardium.

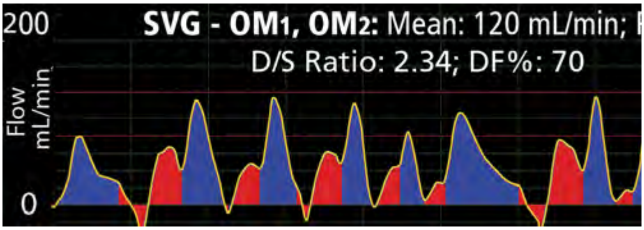


Fig. 5.20: This 17-year-old Y graft to the OM1, OM2 exhibited phenomenal flow of 120 mL/min in a 90-year-old woman. The D/S Ratio was 2.334; DF%: 70.

Excellent LIMA - LAD Flow and Waveform Profile

A 58-year-old male underwent off-CPB CABG. When the surgeon measured flow in the recently constructed LIMA - LAD graft, flow measured 125 mL/min and was accompanied by a classic diastolic dominant left heart waveform.

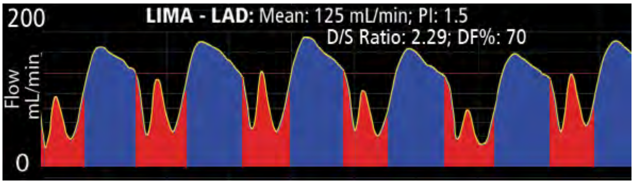


Fig. 5.21: Excellent LIMA - LAD graft flow and diastolic dominant waveform in a 58-year old patient. Mean flow: 125 mL/min; D/S Ratio: 2.29; DF%: 70; PI: 1.5.

LIMA - LAD Flow with Excellent Waveform Profile

A 66-year-old male underwent off-CPB CABG. Although LIMA - LAD graft flow was only one-fourth of the flow in the above case (29 mL/min), it was accompanied by an excellent diastolic dominant left heart waveform profile similar to the one above.

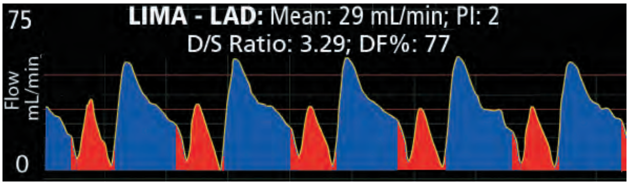


Fig. 5.22: LIMA - LAD graft flow in a 66-year old patient was accompanied by a classic diastolic dominant left heart waveform. Mean flow: 29 mL/min; D/S Ratio: 3.29; DF%: 77; PI: 2.

C. Interesting Cases cont.

Four Patent Grafts in 83-Year-Old Patient

An 83-year-old female underwent quadruple CABG surgery. The left internal mammary Artery (LIMA) was anastomosed to the left anterior descending coronary artery (LAD). Saphenous vein grafts were connected from the aorta to the right coronary artery (RCA), the diagonal coronary (Dx) and to the obtuse marginal OM1.

All four grafts exhibited excellent flows (LAD, 40 mL/min; RCA, 40 mL/min; Dx, 63 mL/min, OM, 36 mL/min) and diastolic dominant waveforms (see waveform profiles on right).

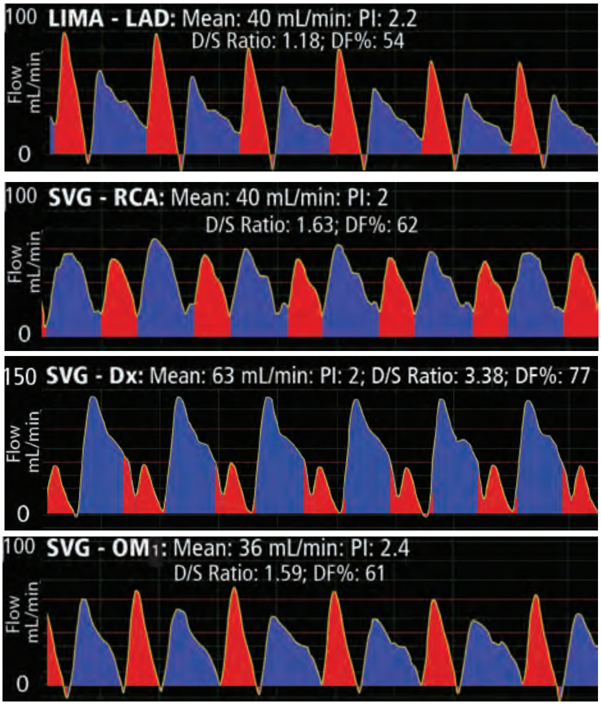


Fig. 5.23: All four grafts in this CABG patient exhibits good flow, acceptable PIs and excellent waveforms.

Case Summary: 83-year-old female; CABG for multi-vessel disease						
Flow Measurement	Post Bypass Mean Flow (mL/min)	D/S	DF%	PI	Waveform Analysis	Analysis
LIMA - LAD	40	1.18	54	2.2	Systolic/diastolic profile	Good graft
SVG - RCA	40	1.63	62	2	Systolic/diastolic profile	Good graft
SVG - Dx	63	3.25	77	2	Systolic/diastolic profile	Good graft
SVG - OM1	36	1.59	61	2.4	Systolic/diastolic profile	Good graft

Intraoperative Graft Flow Measurements during Coronary Artery Bypass Surgery Predict In-hospital Outcomes

Herman C *et al.*, Interact CardioVasc Thorac Surg 2008;7:582-585.

OBJECTIVE

To assess the predictive value of measured graft flows on early and medium-term outcomes.

STUDY

- 985 patients at a single institution over the course of 3 years.
- Abnormal flow values were defined as having a PI >5.
- Patients were followed up to 1.8 years after discharge.

RESULTS

- 19% of patients were found to have abnormal flow values in ≥1 graft.
- 90% of all graft problems were surgically correctable after identification.
- 45% of all graft problems were identified as being anastomotic issues.
- Overall in-hospital mortality was 4.7% and not significant between the group with abnormal flow values and the group with normal flow values.
- Patients with abnormal flow values, after adjusting for covariates, were almost twice as likely to have an in-hospital adverse cardiac event than those with normal flow values (31% vs. 17%).
- Abnormal flow was not an independent predictor of the medium-term mortality and readmission to hospital for cardiac reasons.

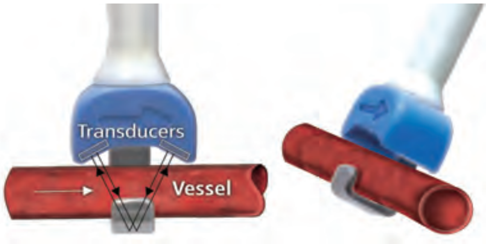
CONCLUSION

- Our findings suggest that abnormal flows measured intraoperatively are independently associated with short-term in-hospital adverse outcome.

Appendix A: Transit-time Ultrasound Technology

A Transonic Perivascular Flowprobe consists of a probe body housing ultrasonic transducers and a fixed acoustic reflector. The transducers are positioned on one side of the conduit under study and the reflector is at a fixed position between the two transducers on the opposite side. Opposing crystals emit ultrasound waves upstream and downstream. The circuitry identifies the difference.

Just as the speed of a swimmer depends, in part, on water currents, the transit time of ultrasound passing through a vessel/conduit is affected by the motion of liquid flowing through that vessel. During the upstream cycle, the sound wave travels against flow and total transit time is increased by a flow-dependent amount. During the downstream cycle, the sound wave travels with the flow and the total transit time is decreased by the same flow-dependent amount. The Flowmeter subtracts the downstream transit time from the upstream transit time using wide-beam ultrasonic illumination. This difference of integrated transit times multiplied by the cross-sectional area yields a measure of volume flow.



Side and front schematic views of a Transonic Perivascular Flowprobe. Using wide beam illumination, two transducers pass ultrasonic signals back and forth, alternately intersecting the flowing liquid in upstream and downstream directions. The Flowmeter derives an accurate measure of the "transit time" it takes for the wave of ultrasound to travel from one transducer to the other. The difference between the upstream and downstream integrated transit times is a measure of volume flow.

UPSTREAM TRANSIT-TIME CYCLE

An electrical excitation causes the downstream transducer to emit a plane wave of ultrasound. This ultrasonic wave intersects the vessel under study in the upstream direction,then bounces off the fixed acoustic reflector to again intersect the vessel. The ultrasonic signal is received by the upstream transducer where it is converted into an electrical signal. From these signals, the Flowmeter derives an accurate measure of the transit time it takes for the wave of ultrasound to travel from one transducer to the other.

DOWNSTREAM TRANSIT-TIME CYCLE

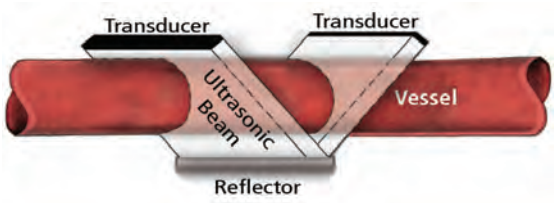
The same sequence is repeated, but with the transducers transmitting

Drost CJ, "Vessel Diameter Independent Volume Flow Measurements Using Ultrasound," Proceedings San Diego Biomedical Symposium 1978; 17: 299-302. US Patent 4,227,407, 1980.

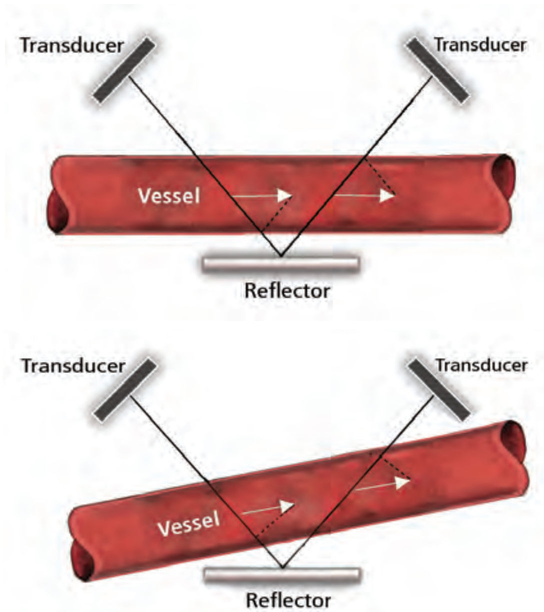
and receiving functions reversed so that the flow is bisected by an ultrasonic wave in the downstream direction. The Flowmeter derives and records from this transmit-receive sequence an accurate measure of the transit time it takes for the wave of ultrasound to travel from one transducer to the other.

WIDE BEAM ILLUMINATION

One ray of the ultrasonic beam undergoes a phase shift in transit time proportional to the average velocity of the liquid times the path length over which this velocity travels. With wide-beam ultrasonic illumination, the receiving transducer integrates these velocity-chord products over the vessel's full area and yields volume flow: average velocity times the vessel's cross sectional area. Since the transit time is sampled at all points across the vessel diameter, volume flow measurement is independent of the flow velocity profile. Ultrasonic beams which cross the acoustic window without intersecting the vessel do not contribute to the volume flow integral. Volume flow is therefore sensed by Perivascular Flowprobes even when the vessel is smaller than the acoustic window.



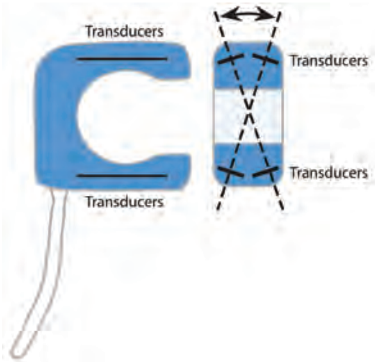
The vessel is positioned within a beam that fully and evenly illuminates the entire blood vessel. The transit time of the wide beam then becomes a function of the volume flow intersecting the beam, independent of vessel dimensions.



The ultrasonic beam intersects the vessel twice on its reflective path. With each intersection, the transit time through the vessel is modified by a vector component of flow. The full transit time of the ultrasonic beam senses the sum of these two vector components. With misalignment (bottom), one vector component of flow increases as the other decreases, with little consequence to their sum.

X-BEAM ILLUMINATION

AU-Series COnfidence Flowprobes® and XL Tubing Flowsensors use four transducers in X-beam illumination to accomplish the same volume flow measurements as the standard two-crystal Perivascular Flowprobes. Ultrasound waves are transmitted in both the upstream and downstream directions by each pair of transducers. This provides two upstream and two downstream transit times which the Flowmeter combines into a single true volume flow measurement. The X-beam pattern of ultrasonic illumination provides the same advantages as wide beam illumination: measurement independence from velocity profile and vessel orientation.



Front and side schematic of COnfidence Flowprobes and XL- Tubing Flowsensors with four-crystal transducers and X-beam illumination.

The extra two crystals create an increased level of accuracy, particularly useful for larger, curved lumens where turbulence and inertia are dominant factors.

Appendix B: Annotated References

Neumann FJ *et al*, **"2018 ESC/EACTS Guidelines on myocardial revascularization,"** Eur Heart J. 2019 Jan 7;40(2):87-165. *"5.1.7 INTRAOPERATIVE QUALITY CONTROL: Besides continuous ECG monitoring and transoesophageal echocardiography immediately after revascularization, intraoperative quality control may also include graft flow measurement to™ confirm or exclude a technical graft problem.513 Transit-time flow measurement is the most frequently used technique for graft assessment and has been able to detect 2-4% of grafts that require revision.513,514 In observational studies, the use of intraoperative graft assessment has been shown to reduce the rate of adverse events and graft failure, although interpretation can be challenging in sequential and T-graft configurations."*

Nakamura, M, Yaku, H, Ako, J, Arai, H, Asai, T, Chikamori, T et al. JCS/JSCVS **2018 Guideline on Revascularization of Stable Coronary Artery Disease**. Circ J 2022; 86:477-588. "...TTFM is easy and reproducible, and thus most commonly used for intraoperative graft assessment. With TTFM, mean graft flow, pulsatility index (PI), and diastolic filling index (DFI) are the common measures. These 3 measures are used in intraoperative graft evaluation (to detect anastomotic errors and whether revision is necessary.)"

Takahashi K, Morota T, Ishii Y, **"A novel transit-time flow metric, diastolic resistance index, detects subcritical anastomotic stenosis in coronary artery bypass grafting,"** JTCVS Tech. 2022 Dec 13;17:94-103. *DRI and diastolic filling had a reliable diagnostic ability for detecting ≥50% stenosis during coronary artery bypass grafting. In left anterior descending artery grafting, DRI had a more satisfactory detection capability than other TTFM metrics.*

Thuijs DJFM, Bekker MWA, Taggart DP, Puskas JD, Head SJ*et al*, "**Improving coronary artery bypass grafting: a systematic review and meta-analysis on the impact of adopting transit-time flow measurement,"** Eur J Cardiothorac Surg. 2019 Oct 1;56(4):654-663. *A comprehensive literature review and meta-analysis of 66 publications, 8,943 patients, and 15,673 grafts, showed that a mean graft flow of 20mL/min was a commonly used threshold for flow. The PI threshold used was more variable. Some studies use a threshold PI value < 5 to indicate an acceptable graft while other studies suggest that a PI threshold of < 3 may be a more appropriate threshold. Overall reported sensitivity of TTFM for predicting a failing graft was as low as 20-30%, the specificity of TTFM was more often in the 90% range.*

Caliskan E, de Souza DR, Böning A, Liakopoulos OJ, Choi YH, Pepper J, Gibson CM, Perrault LP, Wolf RK, Kim KB, Emmert MY, **"Saphenous vein grafts in contemporary coronary artery bypass graft surgery,"** Nat Rev Cardiol. 2020 Mar;17(3):155-169. (Transonic Reference # 118902AHR) *To improve long-term SVG patency rates, a systematic, step-by-step, best practice approach should include intraoperative graft assessment to help identify grafts that might fail early and lead to revision of the low-flow graft, thereby improving graft patency.*

Kim KB, Choi JW, Oh SJ *et al*, **"Twenty-Year Experience with Off-Pump Coronary Artery Bypass Grafting and Early Postoperative Angiography,"** Ann Thorac Surg. 2020;109(4):1112-1119. (Transonic Reference # 115882AHM) *Twenty-year single center study reported a TTFM-based intraoperative revision rate of 5.6%. TTFM adoption was associated with a higher LIMA patency rate (99.4%) compared pre-TTFM (97.1%,p=0.009). They compared outcomes before and after TTFM introduction and found that the postoperative reintervention rate decreased from 7.2% (16/221) prior to TTFM adoption to 2.3% (60/2599) after TTFM adoption; p<0.001. Of the 76 patients who underwent re-intervention, most (73/76) underwe*nt reoperation; three patients were treated using PCI.

Quin JA, Noubani M, Rove JY, Krstacic JE, Hattler B, Collins JF, Grover FL, Almassi GH, Shroyer AL, **"Veterans Affairs Randomized On/Off Bypass Follow-up Study (ROOBY-FS) Group. Coronary Artery Bypass Grafting Transit-Time Flow Measurement: Graft Patency and Clinical Outcomes,"** Ann Thorac Surg. 2020 Dec 22:S0003-4975(20)32150-0. (Transonic Reference # 11879AH) *The investigation suggests that intraoperative TTFM assessment, however used, may be associated with higher 1-year angiographic graft patency.*

Di Giammarco G, Rabozzi R, **"Can transit-time flow measurement improve graft patency and clinical outcome in patients undergoing coronary artery bypass grafting?"** Interact Cardiovasc Thorac Surg. 2010 Nov;11(5):635-40. (Transonic Reference # 1705V) *"We conclude that TTFM is a reliable method to verify intraoperative graft patency. There is some evidence that checking graft patency intraoperatively may improve mid-term outcomes."*

Bauer SF *et al*, "**Intraoperative Bypass Flow Measurement Reduces the Incidence of Postoperative Ventricular Fibrillation and Myocardial Markers after Coronary Revascularization,"** Thorac Cardio Surg 2005; 53: 217-22. (Transonic Reference # 6997AH) *"Routine use of intraoperative transit-time flow measurements reduces the incidence of postoperative anastomosis failure and related technical complications of bypass surgery and leads to a significant reduction of postoperative mortality in CABG."*

Mindich BP *et al,* **"Reduction of Technical Graft Problems Utilizing Ultrasonic Flow Measurements,"**NY Thoracic Society, 2001. *"The intraoperative use of flow measurements provide invaluable information in a timely, accurate, cost-effective manner allowing for the surgical correction of a surgical problem. This has significantly reduced the complications related to early technically induced graft failure. In an era of rapidly changing surgical techniques this provides documentation of the sine-qua-non of the operation: patency."*

Leong DK, *et al,***"Transit-time flow measurement is essential in coronary artery bypass grafting,"** Ann Thorac Surg. 2005 Mar;79(3):854-7; discussion 857-8. (Transonic Reference # 6917AHM) *"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."*

Tokuda Y *et al,* **"Predicting midterm coronary artery bypass graft failure by intraoperative transit time flow measurement,"** Ann Thorac Surg 2008 Aug;86(2):532-6. (Transonic Reference # 7673AHM) *"Transit time flow measurement provides a good prognostic index, not only for the immediate term but also for the midterm follow-up. A graft with intraoperative lower mean flow, and especially with a higher percentage of backward flow, should be carefully monitored, even if it was initially anatomically patent."*

Becit N *et al,* **"The impact of intraoperative transit time flow measurement on the results of on-CPB coronary surgery,"** Eur J Cardiothorac Surg 2007 Aug;32(2):313-8. (Transonic Reference # 10753AHM) *"We believe that TTFM seems to be a crucial tool for deciding if a graft is well-functioning or not, and it allows for improvement of graft failure during operation. Our results suggest that detection of graft dysfunction intraoperatively by TTFM improves the surgical outcome."*

*Herman C *et al,* **"Intraoperative Graft Flow Measurements during Coronary Artery Bypass Surgery Predict In-hospital Outcomes,"** Interact CardioVasc Thorac Surg 2008;7:582-585. (Transonic Reference # 7626AHM) *"Our findings suggest that abnormal flows measured intraoperatively are independently associated with short-term in-hospital adverse outcome."*

Jokinen JJ, Werkkala K, Vainikka T, Peräkylä T, Simpanen J, Ihlberg L,**"Clinical value of intra-operative transit-time flow measurement for coronary artery bypass grafting: a prospective angiography-controlled study,"** Eur J Cardiothorac Surg. 2011 Jun;39(6):918-23. (Transonic Reference # 8113AHM) *"TTFM predicts graft failure within the 6 months after CABG."*

Validations

Beldi G *et al,* **"Transit Time Flow Measurement: Experimental Validation and Comparison of Three Different Systems,"** Ann Thorac Surg 2000; 70(1): 212-217. (Transonic Reference # 1705V) *"Transit time flow measurements are exact and reproducible."*

Canver CC, Dame, N, **"Ultrasonic Assessment of Internal Thoracic Artery Graft Flow in the Revascularized Heart,"** Ann Thorac Surg 1994; 58:135-8. J. Cardiovasc Surg (Torino)1997;38:211-5. (Transonic Reference # 51V) *"Transit-time ultrasound can accurately quantify physiologic blood flow through an ITA graft immediately after CABG and provides the surgeon with valuable information."*

Nordgaard HB, Vitale N, Astudillo R, Renzulli A, Romundstad P, Haaverstad R, **"Pulsatility index variations using two different transit-time flowmeters in coronary artery bypass surgery,"** Eur J Cardiothorac Surg. 2010;37(5):1063-7. (Transonic Reference # 7902AH) *The Transonic flowmeter displayed a lower PI than the MediStim, due to a lower filter setting. In the Transonic, flow signals are filtered at a lower level, rendering a 'smoother' pattern of flow curves. Because different filter settings determine different PIs, caution must be taken when flow values and flowmeters are compared. The type of flowmeter should be indicated whenever graft flow measurements and derived indexes are provided [corrected].*

Appendix C: Bibliography of Waveform Profiles

Native Vessels

LIMA: Fig. 4.1, p. 67.

LAD: Fig. 4.2, p. 68.

LCA: Fig. 3.3, p. 56.

RCA: Fig. 4.3, p. 68.

Bypasss Grafts

Grafts to the LAD

LIMA - LAD: Fig. 2.3b, p. 13; Fig. 2.5, p. 20; Fig. 2.13, p. 26; Fig. 2.14, p. 29; Fig. 2.16a, p. 30; Fig. 16b, p.30; Case Example, p. 36; Fig. 2.19, p. 37; Fig. 2.20, p. 38; Fig. 2.22, p. 39; Figs. 25-26, p. 42; Figs. 2.31-34, p. 43; Fig. 2.37, p. 47; Fig. 2.38, p. 48; Fig. 3.6, p. 65; Fig. 4.28, p. 83; Fig. 4.30, p. 83; Fig. 5.2, p. 88; Fig. 5.7, p. 93; Fig. 5.12, p. 96; Fig. 5.13, p. 97; Fig. 5.16, p. 100; Fig. 5.18, p. 101; Fig. 5.19, p. 102; Fig. 5.20, p. 103; Fig. 5.23, p. 104.

RIMA - LAD: Fig. 2.29. p. 42; Case example p. 45, Fig. 3.5, p. 60. Fig. 4.9, p. 71.

RAD - LAD: Fig. 4.12 p. 73; Fig. 5.4 p. 90.

SVG - LAD: Fig. 4.15, p. 73.

Grafts to the Cx

LIMA - Cx Case example, p. 4; Fig. 2.6, p. 20; Fig. 2.17, p. 35; Figs. 2.27, 2.28, p. 42; Fig. 4.6, p. 70; Fig. 5.1, p. 87; Fig. 5.5, p. 91.

RIMA - Cx: Fig. 4.10, p. 71.

RAD - Cx: Fig. 4.13 p. 73.

SVG - Cx: Fig. 2.23, p. 40; Fig. 2.24, p. 41; Fig. 2.39, p. 48; Fig. 4.17, p. 74; Fig. 5.5, p. 92; Fig. 5.10, 5.11, p. 95.

Grafts to the Dx

LIMA - Dx: Fig. 4.7, p. 70.

RIMA - Dx: Fig. 2.21, p. 38; Fig. 4.12, p. 73.

SVG - Dx: Fig. 2.11, p. 26; Fig. 4.8, p. 70; Fig. 5.7, p. 93; Fig. 5.9, p. 94; Fig. 5.13, p. 97; Fig. 5.18, p. 101; Fig. 5.19, p. 102; Fig. 5.23, p. 104.

Grafts to the OM

LIMA - OM Fig. 4.8, p. 70.

RIMA - OM: Fig. 4.11, p. 71; Fig. 4.28, p. 83. Fig. 4.30, p. 84; Fig. 5.16, p. 100.

RAD - OM: Fig. 2.12, p. 26. Fig. 5.3, p. 89, Fig. 5.18, p. 101.

SVG - OM: Fig. 2.3a, p. 13; Fig. 2.9, p. 25; Fig. 4.18, p. 74; Fig. 5.12, p. 96; Fig. 5.13, p. 97; Fig. 5.18, p. 101; Fig. 5.19, p. 102; Fig. 5.23, p. 104.

Graft to the Ramus Fig. 4.16, p. 73.

Grafts to the RCA

RIMA - RCA: Fig. 2.15, p. 29; Fig. 2.16a, p. 30; Fig. 2.30, p. 43; Fig. 4.21, p. 76; Fig. 4.23, p. 77; Fig. 5.14, p. 98.

RAD - RCA: Fig. 2.18, p. 37; Fig. 4.22, p. 76; Fig. 4.28, p. 83;; Fig. 4.29, p. 83; Fig. 4.30, p. 83.

SVG - RCA: Fig. 2.2, p. 13; Fig. 4.20, p. 75; Fig. 4.27, p. 81; Fig. 4.30, p. 84; Fig. 5.8, p. 94 Fig. 5.17, p. 101; Fig. 5.23, p. 104.

Grafts to the PDA

RAD - PDA: Fig. 5.16, p. 100.

SVG - PDA: Fig. 2.4, p. 14; Fig. 2.10, p. 26; Fig. 4.19, p. 74; Fig. 4.2, p. 78; Fig. 5.12, p. 86. Fig. 5.17, p. 101.

Grafts to the PVB

SVG - PVB: Fig. 4.20, p. 75; Fig. 4.26, p. 77.

Graft to the PLV

SVG - PLV: Fig. 4.31, p. 85.

Y Grafts

SVG - Dx, OM: Fig. 4.26, p. 79.

SVG - PDA & PLB: Fig. 5.15, p. 99.

SVG - RCA & PDA: Case example p. 80.

SVG - OM1, OM2: Fig. 5.20, p. 103.

Sequential Grafts

SVG - OM1, OM2: Fig. 4.27, p. 81.

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CV-50-hb, Rev D 2024