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CABG or PCI for 3-Vessel Disease Patients: SYNTAX Trial

Posted by Susan Eymann, MS on Feb 19, 2016

Coronary artery bypass grafting (CABG) has been considered the standard of care for patients with three-vessel disease (3VD), but long-term comparative results from randomized trials of **CABG vs. percutaneous coronary intervention (PCI)** using drug-eluting stents (DES) are limited. The five-year SYNTAX Trial sought to resolve this problem. Patients with de novo 3VD or left main disease were randomly assigned to PCI with the paclitaxel-eluting first-generation stent or to CABG surgery.

Five-year results of patients with 3VD treated with CABG or PCI (using the first-generation paclitaxel-eluting stent) show that, across the board, PCI patients had higher major adverse cardiac and cerebrovascular events, higher rates of death, myocardial infarction and repeat revascularizations than CABG patients. Stroke rates were similar between the two groups. Results were dependent on the complexity of the lesion.

These results suggest that CABG should remain the standard of care. For patients with low SYNTAX scores (0-22), PCI is an acceptable revascularization strategy, although with significantly higher rates of repeat revascularization.

SYNTAX Score: An angiographic grading tool used to determine the complexity of coronary artery disease. It is the sum of the points assigned to each individual lesion identified in the coronary tree with >50% diameter narrowing in vessels >1.5mm diameter.

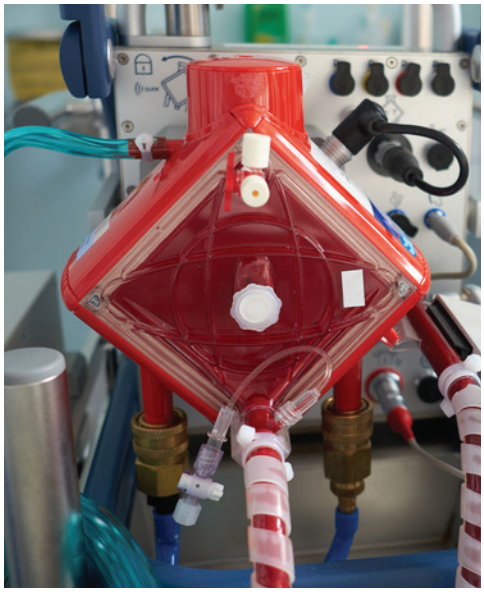
References: Head SJ, et al., "Coronary artery bypass grafting vs. percutaneous coronary intervention for patients with three-vessel disease: final five-year follow-up of the SYNTAX trial," Eur Heart Jw 2014; 35(40): 2821-30. (Transonic Reference # 10607AHR)

ELSA Monitor Used to Optimize ECMO Flow in 10-Year-Old Child

Posted by Susan Eymann, MS on Aug 23, 2019

Dr. Martin Ruß and his critical care team at the Intensive Care Clinic of Charité - Medical University and Institutes of Health in Berlin, Germany, report a case in which they used the **Transonic ELSA Monitor** to optimize oxygen flow in a 10-year-old ECMO patient.

The child suffered from extra-pulmonary acute distress syndrome (ARDS) caused by postoperative sepsis and massive transfusion. Veno-venous (V-V) ECMO was initiated in the pediatric intensive care unit (ICU) of the Charité hospital. Cannulas were inserted into GettyImages-1158812803the femoral and jugular veins to deliver oxygenated blood to the child's lungs from the ECMO circuit. However, after ECMO was initiated, oxygen in the pulmonary artery only increased from 44 mmHg to 66 mmHg. Consequently, the child was transferred to Dr. Ruß's intensive care clinic.



There, recirculation was measured with the Transonic Extracorporeal Life Support Assurance (ELSA) Monitor using the saline ultrasound dilution technique. Recirculation was high: the first measurement registered 78% and the second 65%. Effective flow was low: 680 mL/min with the first measurement which increased to 1280 mL/min with the second measurement.

The position of the two cannulas in the thorax was also visualized with CT scans. The clinicians postulated from the high recirculation, low effective ECMO flow, and the CT scans that the return cannula was inserted in so far that it caused direct jetting of blood towards the inferior vena cava which, in turn, caused the recirculation.

In an attempt to reduce recirculation, the cannula was pulled back approximately 2 cm. Measurements were repeated with the ELSA Monitor. The results showed that recirculation had dropped to 25%, effective ECMO blood flow increased to 1800 mL/min and pulmonary artery oxygen levels increased to 187 mmHg.

From this experience, the critical care team concluded that, when initiation of high flow V-V ECMO did not sufficiently support systemic oxygenation in their 10-year old patient, measurements of recirculation with the ELSA Monitor, imaging techniques and applied ECMO physiology did guide them to change the cannula position and thus optimize oxygenation and provide protective ventilation of the lungs of the child.

Surgical Checklists Updates: 4 New Risk Areas from the ACS

Posted by Susan Eymann, MS on Aug 23, 2019

It's been 10 years since the World Health Organization (WHO) released its surgical care **checklist tools** to help improve outcomes and decrease postoperative mortality rate. Now, the checklists are receiving a few updates.

The WHO first introduced the checklist approach in 2009 after a study published in surgical checklistthe **New England Journal of Medicine** reported a 29-item checklist cut postoperative complications by an average of 36% and decreased mortality by an average of 47%.

Now, the American College of Surgeons (ACS) Strong for Surgery program (S4S) is adding four new surgical safety checklists that target common risk areas.

New Surgical Checklists: 4 Risk Areas

To help surgical teams spot signs of surgical complications and intervene more quickly, the ACS added the following four pre-op and **post-op risk** areas to its checklists:

Delirium: Delirium is often associated with functional decline, extended hospitalization, higher costs and an increased risk of mortality. Alcohol abuse, age and reduced cognitive or physical functioning can put patients at a higher risk of postoperative delirium.

Prehabilitation: Without proper rehabilitation, patients are at an increased risk of surgery-related morbidity, longer hospital stays and readmissions. Focusing on cognitive function, gait, balance and nutrition before surgery can help improve postoperative function.

Pain Management: Ineffective pain management can lead to poor postoperative function, increased hospitalization, increased readmission rates and more outpatient visits. Conducting pre-surgery counseling and setting realistic expectations about the postsurgical experience can help reduce the risk of pain management issues.

Patient Directives: A lack of thorough patient education can lead to presurgery anxiety and a poor post-surgery experience. Discussing topics such as post-procedure pain, risks and financial burdens can help patients feel more supported before and after surgery.

How to Use Checklists Effectively

Since its release, the screening checklist approach has been met with occasional skepticism. Dr. Atul Gawande's address at the annual clinical congress of the American College of Surgeons, identified such resistance as more of a cultural issue:

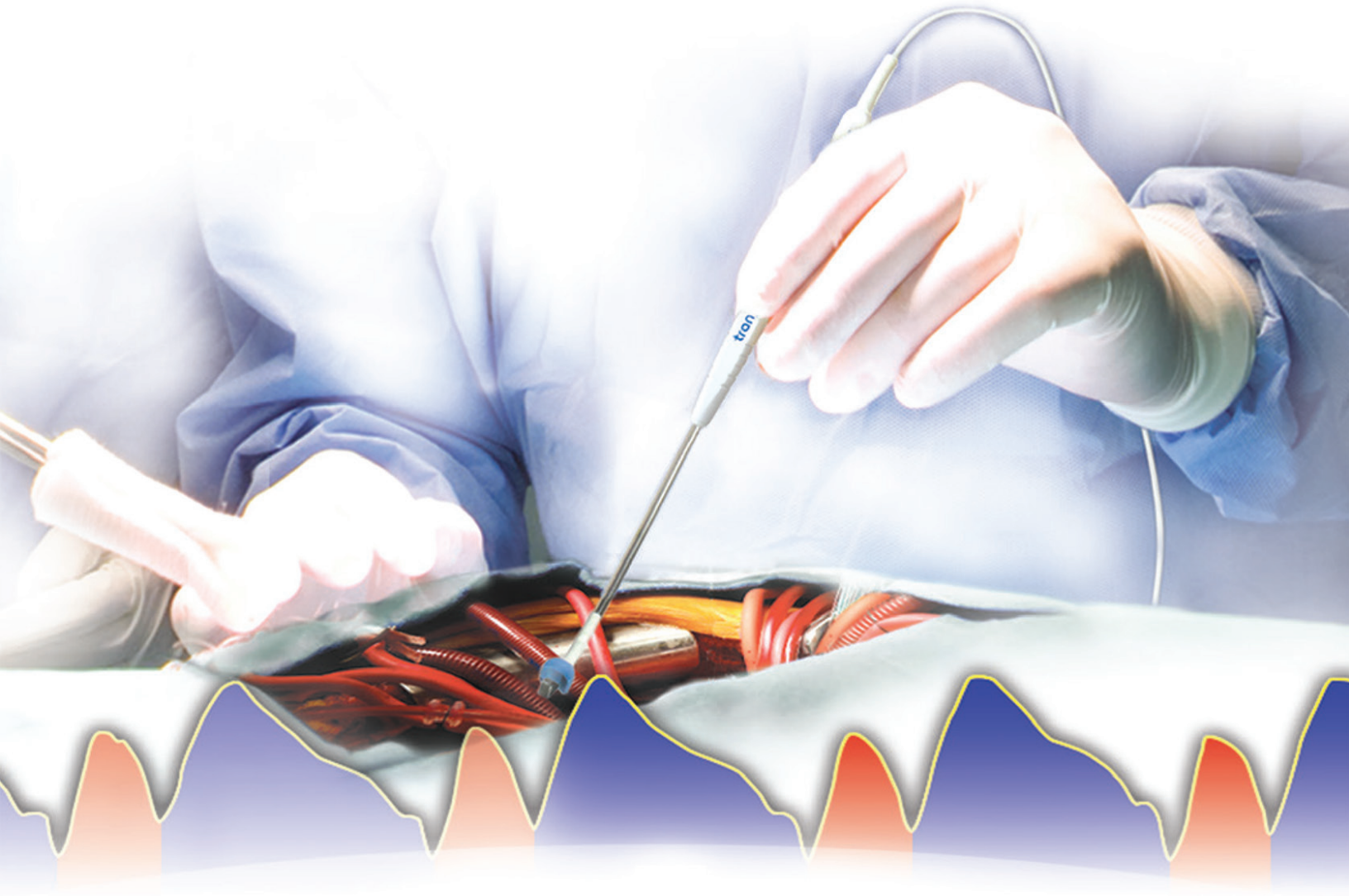
"It's a challenge in a fundamental way, to our values," said Dr. Gawande, as reported by the **ACS Surgery News**. "What we have valued in our life as surgeons is our autonomy as clinicians, and here was an approach which required you to work with different values: humility, discipline, teamwork."

Many surgical teams are open-minded and the adoption of these checklists are proving beneficial; however implementing a checklist alone is not enough.

To substantially improve outcomes, healthcare organizations must also embrace teamwork, cooperation and, most importantly, **effective communication**. When a care team is aligned, a checklist can provide life-saving value.

By focusing on improving your healthcare organization's culture and making sure you and your team are properly communicating during critical preoperative and postoperative moments, you will likely see much higher success with your checklist approach.

THE CABG HANDBOOK



This second edition of the Flow-based Intraoperative Coronary Artery Bypass Patency Assurance handbook presents flow-based intraoperative graft patency assessment with transit-time ultrasound flowmetry.

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We gratefully acknowledge the invaluable collaboration of Dr. Bruce Mindich, former chief of cardiac surgery at The Valley Hospital, Ridgewood, NJ. His expertise with routine intraoperative flow measurement and data interpretation, as well as his gracious sharing of cases have made both editions of this handbook possible.

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I. Why Measure Bypass Graft Flow

A. Introduction

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

That 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 measurement of bypass grafts as a quantitative quality assurance 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 arenas, intraoperative graft patency measurement has become more accepted, especially in Europe, where graft patency assessment was included in the 2010 European Guidelines for Myocardial Revascularization[1]. The Guidelines state: "Graft flow measurement, related to graft type, vessel size, degree of stenosis, quality of anastomosis, and outflow area, is useful at the end of surgery. Flow < 20 mL/min and pulsatility index >5 predict technically inadequate grafts, mandating graft revision before leaving the operating theatre."

Despite adoption of intraoperative graft patency assessment in Europe and more than a hundred publications that attest to its value[2], no comparable United States guidelines for graft patency assessment exist.

In an intraoperative coronary graft assessment review, Dr. Michael Mack notes, "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."[3] He notes that this is based on a false assumption that a large majority of grafts produce good clinical outcomes, but data from the PREVENT

1 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

2 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.

3Mack, MJ, "Intraoperative Coronary Graft Assessment," Current Opinion in Cardiology 2008, 23: 568-572.

I. Why Measure Bypass Graft Flow cont.

B. Intraoperative Assessment Guidelines cont.

IV trial of 22,400 saphenous vein grafts showed a failure rate at one year of 25%.[1] Mack comments, "It is appropriate to presume that a large portion of those grafts fail early in the postoperative period. It also stands to reason that a significant number of these failures could be corrected by an intraoperative assessment of graft patency with immediate revision of the graft, if stenosed or occluded."[2]

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 fails to flow, life ends.

Whether a CABG is performed minimally-invasviely, off-pump, on-pump, or robotically, the end point is the same: to know how much blood flow is going through newly created anastomoses. Each anastomosis is best served by a definitive flow measurement. It takes only seconds to perform a measurement and greatly enhances the standard clinical observations of patient condition that include snappiness of the heart's contractions, MAP, EKG, CO, and BP. These are all secondary to the adequacy of the graft flows. Direct graft flow measurements will help the surgeon identify a problem's source more effectively and efficiently than any other parameter.

Yet, flow measurement is often not taken seriously or simply ignored. Precise flow measurement devices and technologies were not available until the mid-twentieth century. In their stead, surrogate measurement modalities took precedence. Pressure, used by the body to control flow, is routinely measured to assess hemodynamics. Pulses are felt. Doppler technology displays velocity of blood flow, not true flow. All are surrogates for knowing absolute volume flow, precisely measured by transit-time ultrasound technology and pioneered by Transonic® President Cornelis Drost[3].

1 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.

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I. Why Measure Bypass Graft Flow cont.

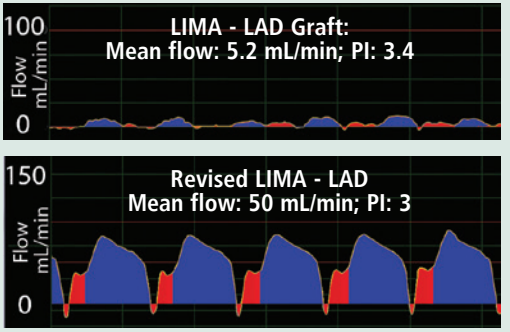
D. To Measure Is to Know

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 numbers provide valuable functional information. Just as a pilot must learn to fly by instruments to avoid crashing, it is incumbent on the clinician to value quantitative data and to rely on quantitative results in order to make objective clinical decisions.

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

A 67-year-old male patient with single-vessel coronary artery disease underwent off-CPB CABG. LIMA-LAD graft flow first measured 5.2 mL/min (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-LAD graft flow improved to 50 mL/min (PI: 3). The flow waveform (bottom) exhibited a classic LIMA-LAD 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-LAD graft. Flow improved dramatically after revision and the waveform exhibited a classic LIMA-LAD profile (bottom waveform).

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

I. Why Measure Bypass Graft Flow cont.

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 and 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

I. Why Measure Bypass Graft Flow cont.

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 of early graft patency, long-term outcomes are determined by many more factors that 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 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 grafts in their 2010 European Guidelines.[7]

In 2010, Di Giammarco and Rabozzu published a best evidence article entitled, *"Can transit-time flow measurement improve graft patency and clinical outcome in patients undergoing coronary artery bypass grafting?"* (See synopsis on previous page.) After surveying 102 papers, the authors chose ten publications they determined represented the best evidence to answer the clinical question.[1,8-14] They concluded that transit-time flowmetry is a reliable method to verify intraoperative graft patency and there is some evidence that checking graft patency intraoperatively may improve mid-term outcomes.

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[15]. 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.

I. Why Measure Bypass Graft Flow cont.

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II. Flow-based Graft Patency Assessment

A. Overview

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 twofold purpose for this handbook is to provide:

1) Basic flow measurement techniques to ensure successful measurements;
2) A protocol to correctly assess flow measurements to guarantee the best results for the patient.

Successful flow-based graft patency assessment during CABG requires skillful surgical technique coupled with astute on-the-spot decision making during the course of the surgery. Moreover, it is critical 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 page 9 for 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. A time-tested protocol is offered that lists all the conditions that must be taken into consideration for accurate graft assessment. An analysis of measured flows is provided. Addressed are: the cardinal importance of mean flow, how to determine whether a graft is in trouble, reasons (both physiologic and technical) for less than expected flows and other factors such as competitive flow, pulsatility index, the influence of pressure on flow, that should be taken into consideration. Flow measurements offer the surgeon an opportunity to correct otherwise undetectable flow restrictions before leaving the operating room, and ensure the best surgical outcome for the patient.

II. Flow-based Graft Patency Assessment cont.

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. Occlude the native coronary temporarily to assess the presence of competitive flow and to know the full flow capacity of the coronary artery and graft to the distal myocardial territory fed by that respective graft.

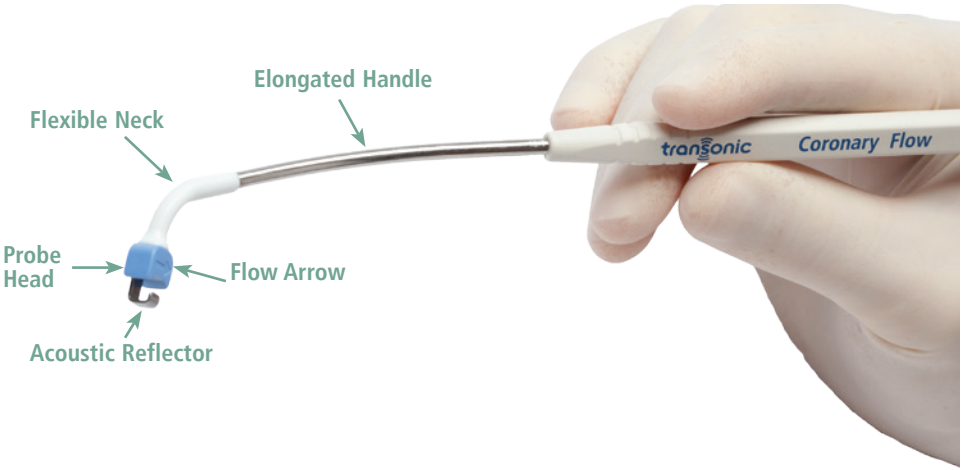


Fig. 2.1: Used for graft patency assessment, a Transonic Coronary Flowprobe's pliable neck bends as needed for positioning on the graft. Its elongated handle allows convenient positioning of the Probe around any coronary artery bypass graft..

II. Flow-based Graft Patency Assessment cont.

B. Measuring Coronary Bypass Graft Flow cont.

Step-by-Step Measurement Procedure

1. If using an internal mammary artery graft, skeletonize a 1.5 cm segment of the artery 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. Take care not to undersize the probe for the graft.
4. Apply ultrasound couplant (Aquasonic 100, Parker Labs) to the window of the Flowprobe.
5. Turn on FlowSound®. A low-pitch zero flow sound (“hum”) indicates that the Probe is properly connected to the Flowmeter, and that there is adequate ultrasound signal coupling for a measurement.
6. Place the Flowprobe on the graft, bending its flexible neck as needed. Avoid kinking the graft or placing the Flowprobe over surgical clips or sutures. The ultrasound’s signal quality is indicated on the AureFlo® Monitor or the Flowmeter’s front panel display.
7. Observe the contraction of the heart while listening to FlowSound. Listen for a strong diastolic flow component.
8. Note, after 10 seconds, the average (mean) flow displayed on the AureFlo screen or the front panel of the Flowmeter.
9. Occlude the native coronary artery and note any changes in the pitch and pattern of FlowSound. An increase in FlowSound pitch (i.e. mean flow) indicates the presence of competitive flow. If no competitive flow is observed, the occlusion may be released.
10. When flow has stabilized in 10 to 15 seconds, press PRINT on the Flowmeter, or tap SNAPSHOT or RECORD on AureFlo to document the measurement. Hold the probe steady on the graft until the printer stops.

II. Flow-based Graft Patency Assessment cont.

B. Measuring Coronary Bypass Graft Flow cont.

On-the-spot Measurement Quality Assurance

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

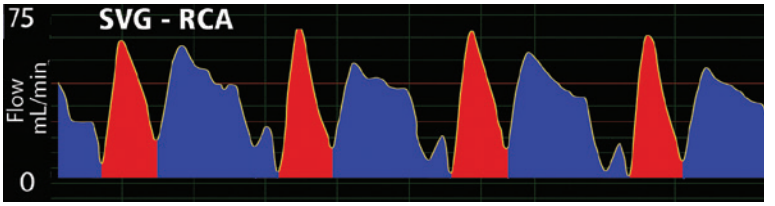


Fig. 2.2: Each flow beat should be an exact replica of the previous, without undue "noise" in the printout, without "jitter" in FlowSound.

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

Motion Artifacts (Figs. 2.3a, 2.3b)

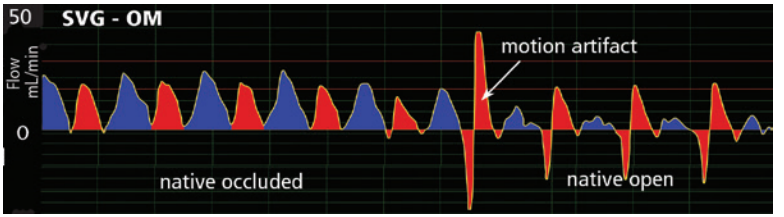


Fig. 2.3a: The left half of this trace is less repetitive due to motion caused by manual occlusion of the native coronary. A motion artifact (and change to repetitive flow pattern) is observed when the occlusion is released.

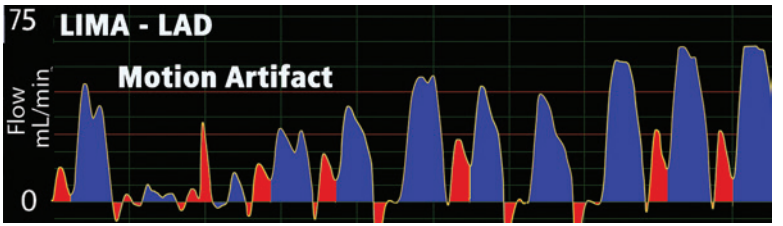


Fig. 2.3b: The non-repetitive left half of this LIMA - LAD waveform illustrates a motion artifact due to motion of the Flowprobe on the graft. As the Flowprobe is held steady on the graft, the waveform becomes more repetitive as shown on the right..

B. Measuring Coronary Bypass Graft Flow cont.

Probe Window Too Small for Vessel

A Flowprobe which compresses the graft induces its own waveform distortions with errors in mean flow and pulsatility index. 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.

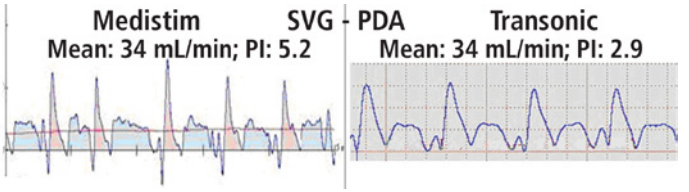


Fig. 2.4: These archival waveforms show a Medistim SVG - PDA waveform, on the left, recorded simultaneously with a Transonic SVG - PDA waveform. The pair exemplify how Pulsatility Index (PI) is affected by waveform integrity. Both waveforms record identical average flows of 34 mL/min, but the difference in PI (Meditim's 5.2 vs. Transonic's 2.9) 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.

II. Flow-based Graft Patency Assessment cont.

C. CABG Patency Assessment Protocol

Mean Flow is Paramount

Mean graft flow is the first consideration to confirm graft patency or to alert the surgeon to an undesirable condition. While flows greater than 20 to 30 mL/min indicate a good graft, flows under 5 mL/min indicate that there is a problem with the graft. A variety of conditions can limit bypass graft flow. First and foremost, the presence of competitive flow must be considered (pages 19-22).

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 must consider other factors that 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
   - Position of Probe on graft;
   - Use of IABP for ventricular support.

II. Flow-based Graft Patency Assessment cont.

C. CABG Patency Assessment Protocol cont.

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 37, 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.

> "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

Frequently Asked Question

How often does following the Flow-QC® protocol detect a technical error?

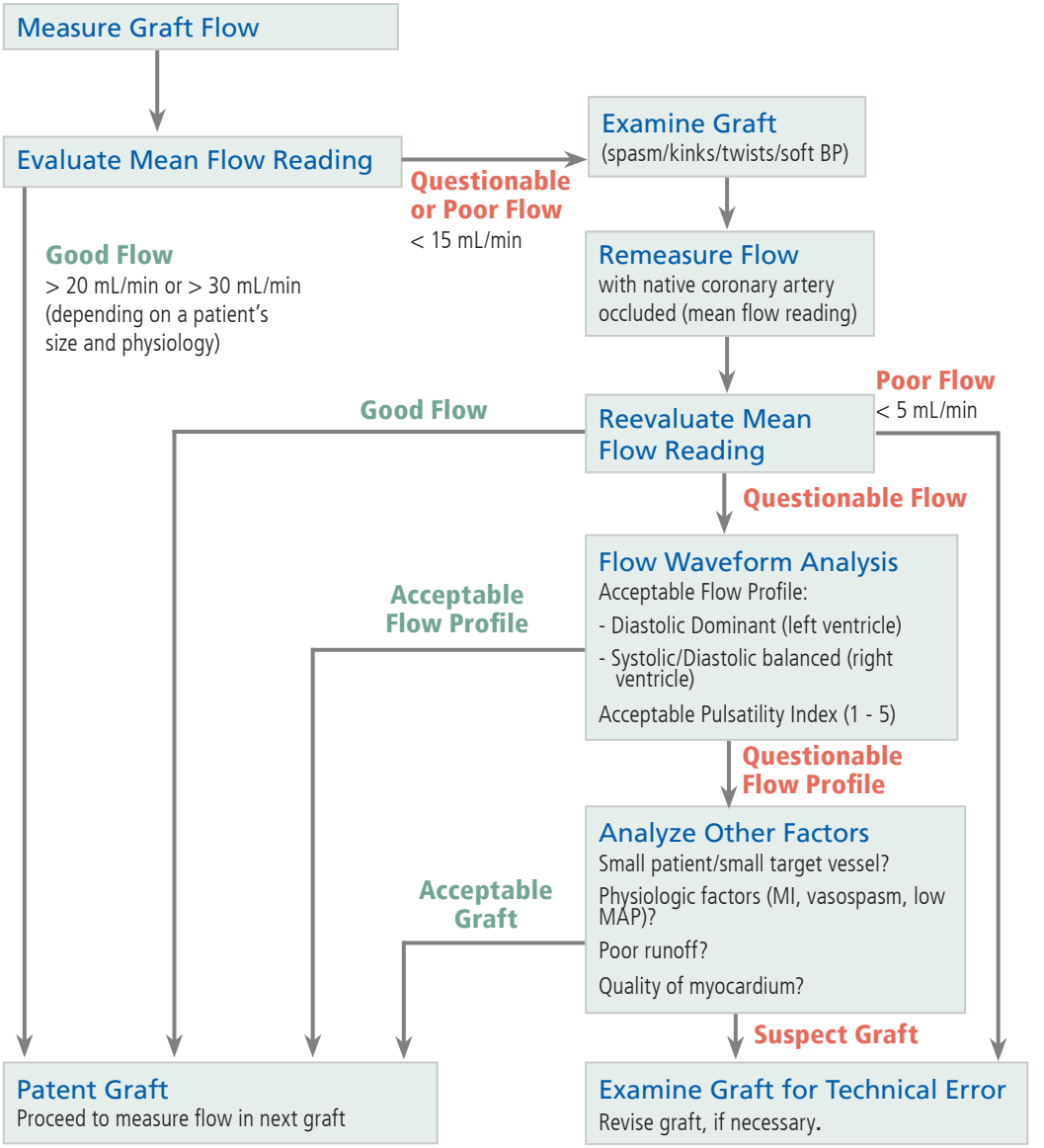
Early proponents of intraoperative flow measurement during beating heart surgery reported technical problems in 13.2%.[1] With experience, this percentage reduces to 5%.[2] Similar rates have been reported for technical errors during on-pump cases. To put this percentage in perspective: at 3.2 grafts per patient, a 5% technical error rate would mean that one in six patients would leave the OR with a correctable graft problem that may well create a complication during patient recovery.

[1] Possati G et al, "Systematic clinical and angiographic follow-up of patients undergoing minimally invasive coronary artery bypass," J Thorac Cardiovasc Surg. 1998 Apr;115(4):785-90.

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

II. Flow-based Graft Patency Assessment cont.

C. CABG Patency Assessment Protocol cont.



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

II. Flow-based Graft Patency Assessment cont.

D. 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 (pages 19-22).
- 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; Graft in Trouble

- 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 (pages 26, 27). For left ventricle grafts: look for a diastolic dominant waveform. For right-ventricle grafts, look for a systolic/diastolic balanced waveform.
- Assess other factors that may account for a lowered flow: (pages 32-43) such as small patient, small target vessel, small graft capacity, poor myocardial runoff.

II. Flow-based Graft Patency Assessment cont.

D. Mean Flow Assessment cont.

Mean flow is the primary determinant of graft quality. A high average flow always indicates a viable graft, and near-zero flow always indicates a graft in trouble. Mean flow alerts the surgeon to one of three graft conditions:

1. Mean flow falls within the normal range 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 (flow waveform analysis: pages 26, 27).

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	Any flow < 5 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	
SVG - OM1, OM2	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 in coronary grafts compiled from statistical averages of 589 transit-time flow measurements reported in the literature.

Frequently Asked Question

The mean flow table above lists only a small sampling of all coronary graft possibilities. Are there mean flow rules for other grafts?

Experience supports a mean flow of 30 mL/min to indicate acceptable patency. For small patients or small target vessels, this number can be reduced to 20 mL/min. The European Guidelines state: "Flow < 20 mL/min and pulsatility index >5 predict technically inadequate grafts, mandating graft revision before leaving the operating theatre."

II. Flow-based Graft Patency Assessment cont.

D. 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.

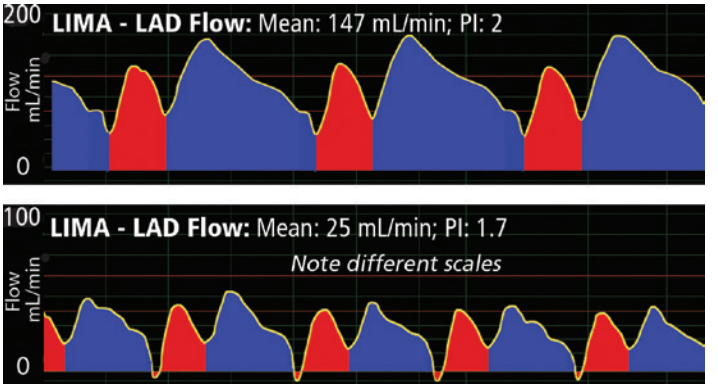


Fig. 2.5: Acceptable LIMA-LAD grafts in two patients demonstrate a range in average flows. The top graft can be considered patent based solely on mean flow (147 ml/min). The bottom graft required waveform analysis because of its questionable mean flow reading (25 ml/min). Its strong diastolic flow component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

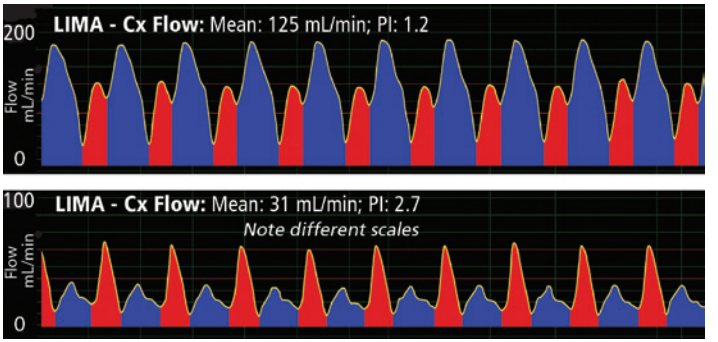


Fig. 2.6: LIMA to circumflex grafts in two patients also demonstrate a range of acceptable mean flows.

II. Flow-based Graft Patency Assessment cont.

Cut-off Values for Transit Time Flowmetry: Are the Revision Criteria Appropriate?

Une D *et al*, Card Surg 2013; 28(1): 3-7.

OBJECTIVE

To investigate whether other TTF values are more predictive of the saphenous vein graft (SVG) failure and/or clinical outcomes, and to reassess the TTF criteria used in GRIIP study and investigate whether any other factors were predictive of one-year SVG failure (MACE death, myocardial infarction, repeat revascularization).

METHODS

Retrospective study of a GRIIP imaging group (n - 44) included 65 SVGs, 41 arterial grafts.

- Novadaq SPY Imaging System imaged grafts after each distal anastomosis and proximally after separation from cardiopulmonary bypass (CPB).
- Transit-time ultrasound flow measurements (2-4 mm Flowprobes) were performed after CPB or completion of all grafts.

Study outcomes were graft patency at 12 months and major adverse cardiac events.

RESULTS

- Post-op angio: 21 SVGs occluded; 1 SVG, > 50% stenosis; all 41 arterial grafts patent.
- ROC curve analysis: TTF mean graft flow was significantly predictive of SVG failure (1 yr.).
- Mean graft flow of 31 mL/min was the best cut-off value ($p = 0.017$, sensitivity 63.6%, specificity 67.4%). The risk of graft occlusion was 14/28, 50% for grafts with mean flow <31 mL/min and 8/37, 21.6% for grafts with mean graft flow ≥ 31 mL/min.
- Mean flow was therefore a significant predictor of early SVG failure.
- Pulsatility Index (PI), diastolic filling (DF), other TTF values, patient comorbidities, and/or medication at discharge were not predictors of graft failure.
- TTF values were not predictive of MACE.

CONCLUSIONS

- TTF can identify non-functional grafts during CABG.
- TTF can predict one-year SVG patency.
- TTF has questionable value for improving one-year arterial graft patency.

OBSERVATIONS

- Study states that intraoperative graft assessment provides the surgeon with an opportunity to improve early graft patency through the identification of occluded parts of the graft.
- It underscores the importance of mean flow as an indicator of graft patency with a 31 mL/min optimum cut off threshold.

II. Flow-based Graft Patency Assessment cont.

D. Mean Flow Assessment cont.

Competitive Flow

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.

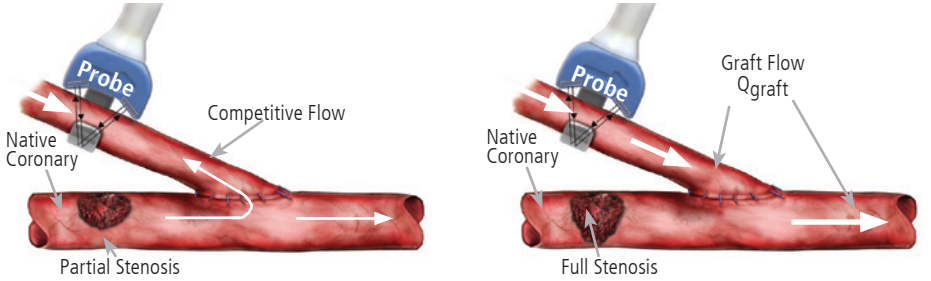


Fig. 2.7a: Measuring graft flow with occlusion of the native coronary proximal to the anastomosis allows for maximal flow through the graft.

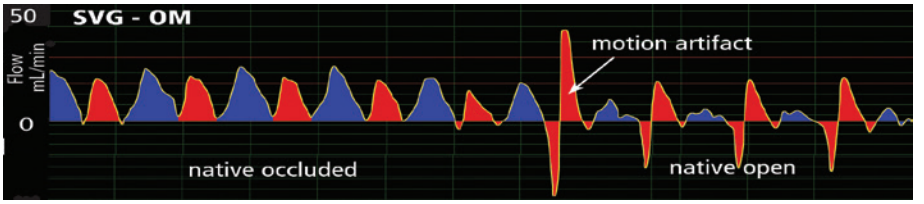


Fig. 2.7b: This trace demonstrates the advisability of taking flow measurements with and without occlusion of the native coronary. With the native open, mean flow approaches zero. With the native artery occluded, flow increased to approximately 15 ml/min with a good systolic/diastolic pattern (patent graft) which indicates that native flow was competing with graft flow. PI with native occluded is ~ 2.0. PI with native open is ~ 9.2.

II. Flow-based Graft Patency Assessment cont.

D. Mean Flow Assessment cont.

EXAMPLES OF COMPETITIVE FLOW

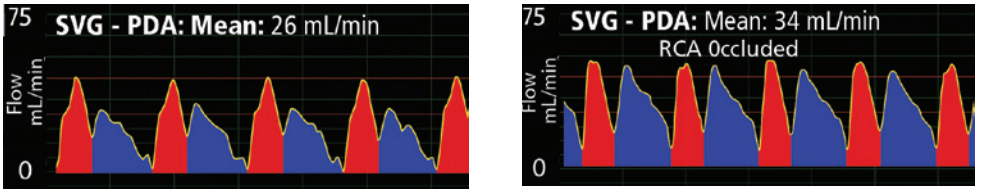


Fig. 2.8: SVG - PDA graft flow increased from 26 mL/min to 34 mL/min when the RCA was occluded.

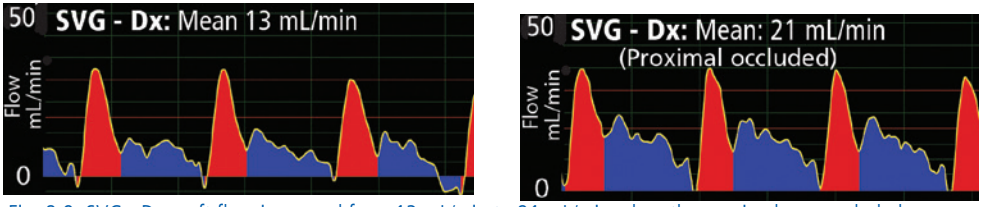


Fig. 2.9: SVG - Dx graft flow increased from 13 mL/min to 21 mL/min when the proximal was occluded.

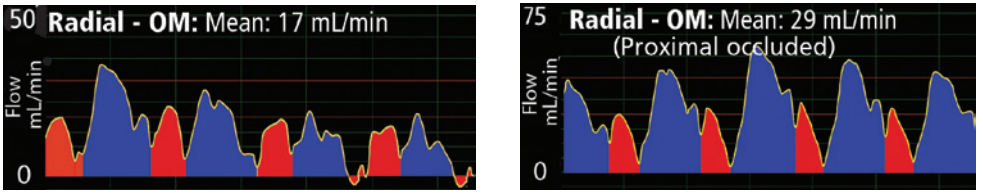


Fig. 2.10: Rad - OM graft flow increased from 17 mL/min to 29 mL/min when the proximal was occluded.

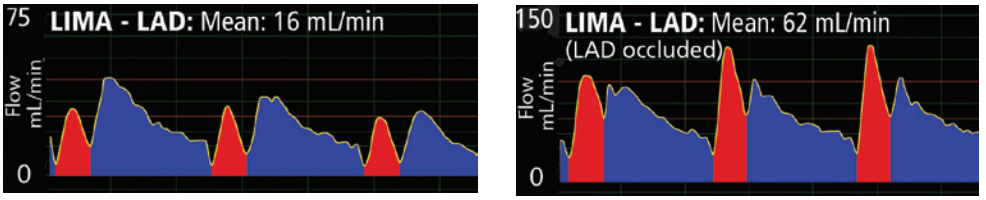


Fig. 2.11: LIMA - LAD graft flow increased from 16 mL/min to 62 mL/min when the proximal LAD was occluded.

II. Flow-based Graft Patency Assessment cont.

D. Mean Flow Assessment cont.

EXAMPLES OF COMPETITIVE FLOW CONT.

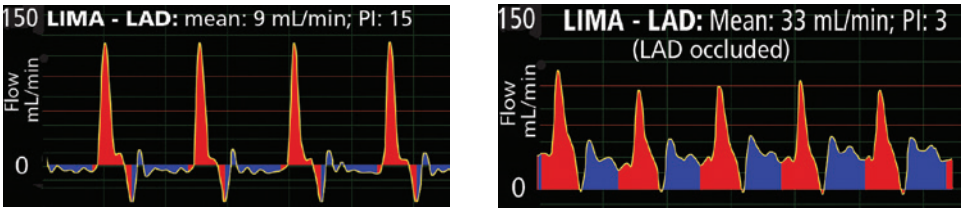


Fig. 2.12: LIMA - LAD graft flow increased from 9 mL/min to 33 mL/min when the LAD was occluded. Also note the change in waveform from an unacceptable negative diastolic to a more prominent diastolic phase.

Graft Patency Analysis with Competitive Flow Assessment

Two consecutive flow measurements are recommended: one without occlusion of the native coronary artery, 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 always identifies 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.

II. Flow-based Graft Patency Assessment cont.

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

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.

II. Flow-based Graft Patency Assessment cont.

E. Pulsatility Index Assessment

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

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

- 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. 2.13.

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). See flow waveforms on pages 19 and 21 where a high PI will drop by temporarily blocking competitive flow.

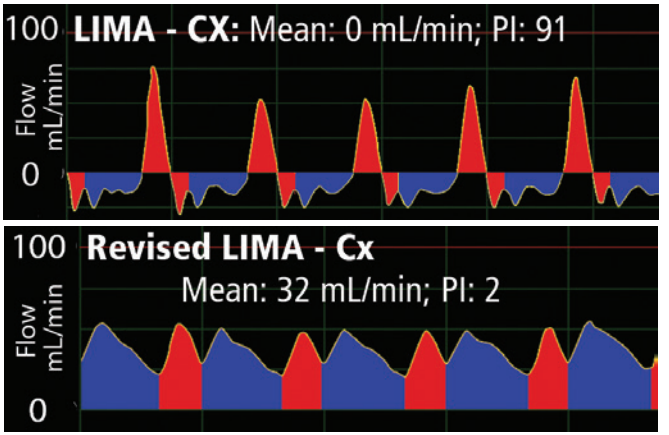


Fig. 2.13: Example: Trouble in a LIMA to circumflex graft with zero flow prior to revision is also indicated by a high PI (91). After revision, flow improved to 32 ml/min and PI became an acceptable 2.

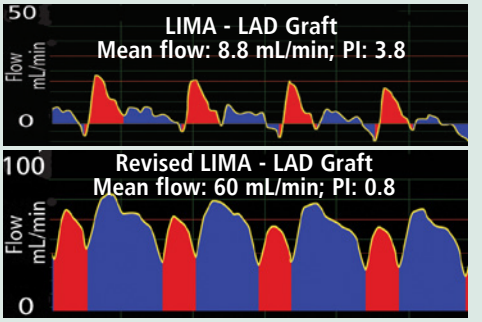
Conclusion: PI may be used as a secondary indication of graft patency, but a proper assessment must consider mean flow and waveform pulsatility separately. See Protocol on page 14.

II. Flow-based Graft Patency Assessment cont.

Case Report: PI < 5 False Positive in LIMA - LAD Graft

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) and was accompanied by a classic, diastolic dominant waveform profile (bottom waveform).



Flow in the top LIMA-LAD graft with a spiky systolic waveform profile is 8.8 mL/min (PI: 3.8). Following revision of the graft, flow increased to 60 mL/min (PI: 0.8) 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	Waveform	Analysis
Post-bypass	8.8	3.8	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?

Even though PI combines mean flow and waveform properties into one number, 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 flow waveform analysis second (if needed). 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).

II. Flow-based Graft Patency Assessment cont.

Pulsatility Index Variations Using Two Different Transit-time Flowmeters in CABG Surgery

Nordgaard HB *et al*, Eur J Cardiothorac Surg 2010; 37(5): 1063-7.

This study reports the findings of a study that compared measurements by the two Flowmeters (HT313 Flowmeter, Ithaca, NY; Medistim Flowmeter (VeriQ, Trondheim, Norway) in different patient populations (Italy and Norway). Coronary bypass graft flows values and pulsatility indexes (PI) were compared. Prior to the study, PI literature was analyzed that demonstrated that Transonic graft flow measurements had consistently lower PIs than the Medistim device.

STUDY

1) PI, as calculated by Transonic and Medistim Flowmeters, calculated simultaneously from 19 coronary grafts in 10 patients weaning from CP bypass and after administration of protamine, were compared. All patients were operated on by the same surgeon.
2) Changes in Medistim's flow curves and PIs at six different filter settings (5, 10, 20, 30 50, 100 Hz) of eight grafts in four patients, were evaluated.

RESULTS

Transonic HT313: Mean PI: 1.8 ± 0.6; Medistim VeriQ: Mean PI: 2.7 ± 1.2. The Transonic Flowmeter consistently arrived at lower PIs with the degree of difference between the Transonic and Medistim PIs depending on the flow pattern. A spiky flow curve with the Medistim Flowmeter produced a high PI and a greater difference between the two Flowmeters' measurements. A smoother flow pattern produced similar values. As PI increased, the difference between measurements by the two Flowmeters increased.

CONCLUSION

Transonic and Medistim measurements are not directly comparable because they use different filter settings (10 Hz vs 20 Hz) which presumably account for the different shapes of flow curves and different PI values. The authors note that the difference in waveforms could have important clinical repercussions when assessing the waveform to assess graft patency. They suggest that Medistim's spiky flow curves make it difficult to evaluate graft flow with that type of waveform, but that the lower Transonic filter setting might inadvertently make the graft assessment appear better than it is.

OBSERVATIONS

- Small sample: 19 grafts from 10 patients
- Probe styles were not considered. Medistim Probes are designed to compress the vessel, eliminating the need for couplant. Transonic Probes have a non-constrictive design.
- The primary cause of artifact is vessel compression.
- The authors concluded that Medistim and Transonic measurements were not comparable because of the different filter rates of their Flowmeters.
- Transonic calculates mean flow over 8 seconds; Medistim, over 2 seconds.
- A question remains, "Are higher flows from the Medistim Flowmeter actual physiological flows or are the result of spiky peaks from unfiltered electronic noise."

II. Flow-based Graft Patency Assessment cont.

F. 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.

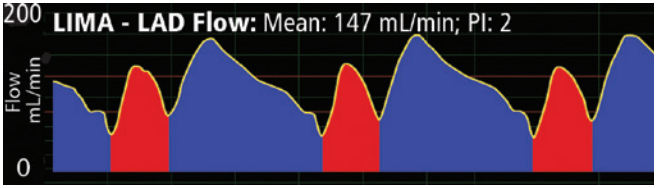


Fig. 2.14: LIMA-LAD: mean = 147 mL/min; diastolic dominant; PI =2.

Frequently Asked Question

Why, particularly in left ventricle grafts, is there less flow during systole?

There are two reasons:

1) Ostial obstruction: The anterior atrial valve leaflets open during systole and effectively block off the left and right coronary ostia.
2) Systolic compression: The coronary arteries are embedded in the muscular myocardium which contracts during systole, compressing inflow into the arteries. Certainly, some flow does get through, but it is limited.

Bypass grafting using mammary arteries and venous grafts replenishes blood supply to the coronaries and flow is greatly increased during diastole.

II. Flow-based Graft Patency Assessment cont.

F. Flow Profile Assessment cont.

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).

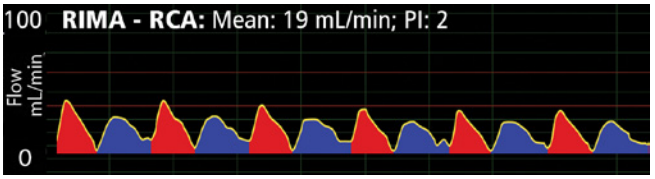


Fig. 2.15 RIMA - RCA: mean is 19 mL/min. systolic/diastolic balanced; PI=2

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 heart beat and diastole lasts two-thirds.

Stenotic Pattern

In partially stenotic vessels, a bypass graft delivers strong antegrade flow during systole, creating a dominant systolic peak. During diastole, significant native coronary flow will compete with the graft flow, reducing or even reversing flow measured within the graft by the Flowprobe. This negative (retrograde) flow is termed competitive flow, and can be seen in the waveforms below. This may be indicative of stenoses distal to the graft. Another graft should be considered.

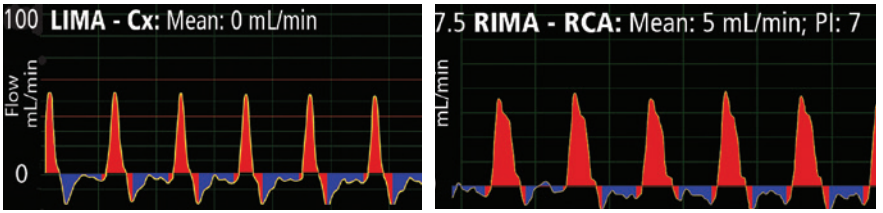


Fig. 2.16: Examples of grafts with stenotic flow profiles. In both the LIMA - Cx graft and the RIMA - RCA graft, the flow waveforms dipping below zero clearly indicate the presence of competitive flow.

II. Flow-based Graft Patency Assessment cont.

G. FlowTrace® ECG, Diastolic/Systolic Ratio (D/S), & Diastolic Filling Percentage (DF%)

AureFlo's 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:

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

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	0	1 - 2	>2
DF%	<50%	50% - 67%	>67%

G. FlowTrace® ECG, Diastolic/Systolic Ratio (D/S), & Diastolic Filling Percentage (DF%) cont.

Diastolic/Systolic Calculation Prerequisites for AureFlo®

In order to clearly delineate systolic and diastolic phases of a flow waveform, AureFlo's 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 HT300-Series Flowmeter
- Has a stable ECG signal that can be analyzed by FlowTrace software to identify systolic and diastolic phase demarcations.

ECG Signal Specifications Prerequisites

The AureFlo system has ECG signal input capability derived from any slaved device such as the anesthesia monitor, the TEE machine, or the defibrillator. The ECG signal source is connected to a compatible HT300-Series Flowmeter via a cable provided with the AureFlo 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 noted between the colorization points on the ECG and the corresponding points on an AureFlo 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.

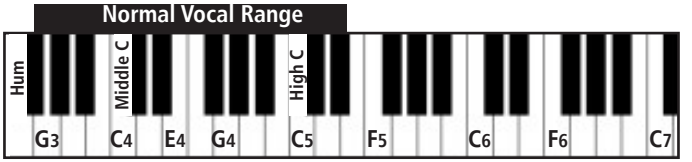
Note: For complete explanation of DS Ratio and DF%, see DS Ratio & DF% Technical Note (CV-54-tn).

II. Flow-based Graft Patency Assessment cont.

H. 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 anastmosis.

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.



Probe	Flow in mL/min									
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

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. 2:17: 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.

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

II. Flow-based Graft Patency Assessment cont.

H. 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

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.

I. Flow-Limiting Conditions

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 grafts, especially 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).

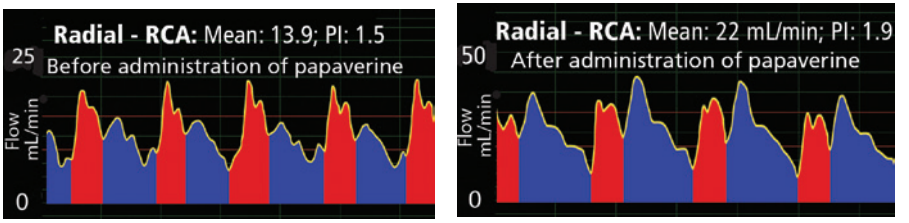


Fig. 2.18: Following administration of papaverine, flow improved from 13.9 mL/min to 22 mL/min. A strong improvement in diastolic flow pattern is observed, and the graft was considered patent.

Improvement with Time

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

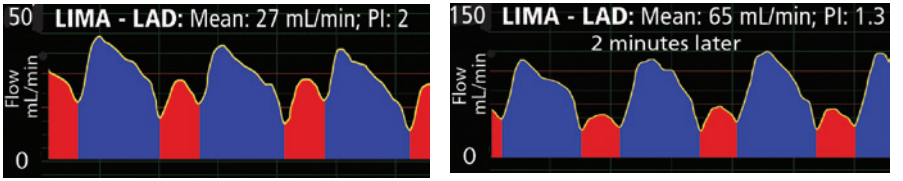


Fig. 2.19: Within two minutes, flow in this LIMA - LAD graft increased from 27 mL/min to 65 mL/min.

I. 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.

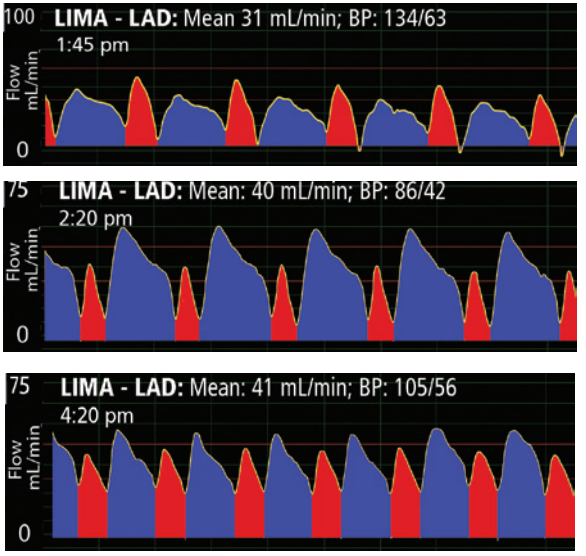


Fig. 2.20: During the case illustrated above, flow increased to 40 ml/min although BP dropped from 134/63 to 86/42 within the first half hour following grafting. Two hours later flow remained stable although BP had increased to 105/56.

I. Flow-Limiting Conditions cont.

Physiologic Factors cont.

Run-off Quality of the Myocardium

An anastomosis can be technically perfect, but if there is high downstream resistance due to myocardial infarction and/or vessel disease as seen in diabetics, flow will be relatively low. The lower contractility of diseased myocardium will alter the systolic/diastolic flow profile of the graft (Figs. 2.21, 2.22).

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

Fig. 2.22: 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.

I. 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

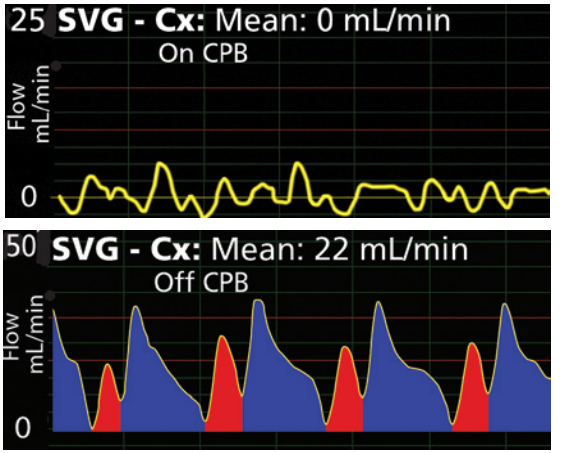


Fig. 2.23: When flow in this SVG - Cx graft registered zero mL/min and had a poor waveform profile, the surgeon investigated and discovered a twist in the graft. Once the graft was untwisted, flow improved to 22 mL/min.

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

I. 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

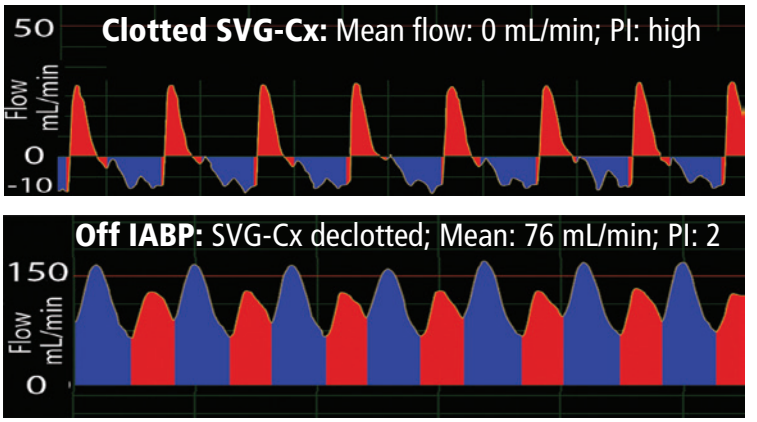


Fig. 2.24: The first flow measurement of this SVG - Cx graft registered zero flow indicating a problem with the graft. Investigation revealed a clot. As the graft was declotted, intra-aortic balloon pumping (IABP) was initiated. Graft flow increased to 85 ml/min. When the IABP was removed, graft flow measured 76 ml/min.

II. Flow-based Graft Patency Assessment cont.

I. Flow-Limiting Conditions cont.

Examples of Technical Problem and Revisions

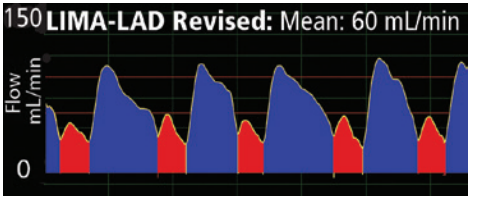
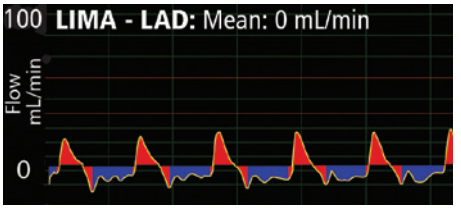


Fig. 2.25: Following graft revision LIMA - LAD mean flow increased from -1 mL/min to 60 mL/min.



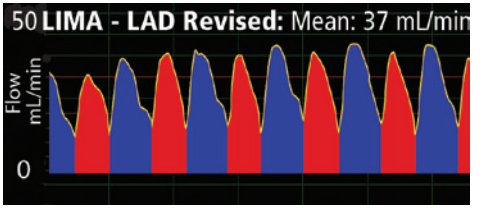
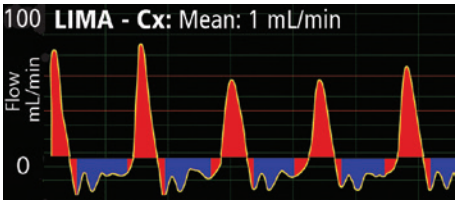


Fig. 2.26: Following graft revision LIMA - LAD mean flow increased from 0 mL/min to 37 mL/min.



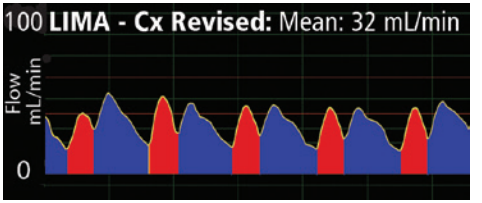
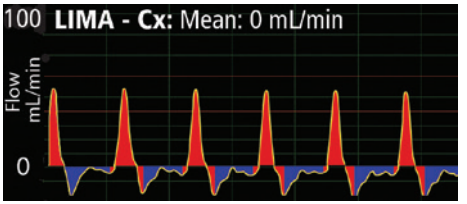


Fig. 2.27: Following graft revision LIMA - Cx mean flow increased from 1 mL/min to 32 mL/min.



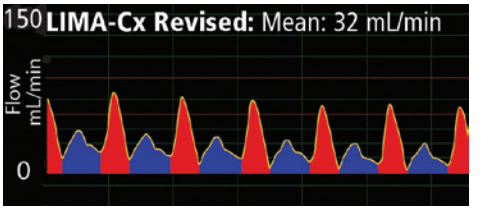
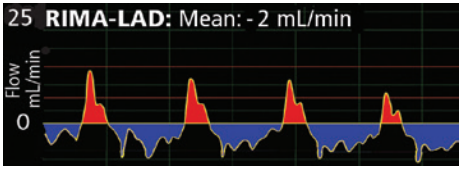


Fig. 2.28: Following graft revision LIMA - Cx mean flow increased from 0 mL/min to 32 mL/min.



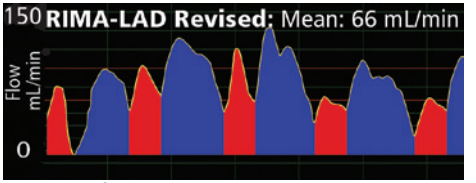
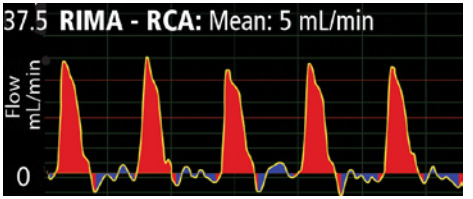


Fig. 2.29: Following graft revision RIMA - LAD mean flow increased from -2 mL/min to 66 mL/min.

II. Flow-based Graft Patency Assessment cont.

I. Flow-Limiting Conditions cont.

Examples of Technical Problem and Revisions cont.



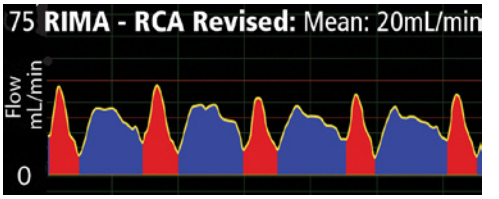


Fig. 2.30: Following graft revision RIMA - RCA mean flow increased from 5 mL/min to 20 mL/min.

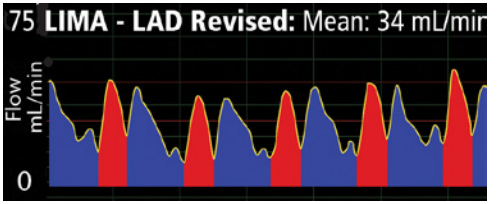
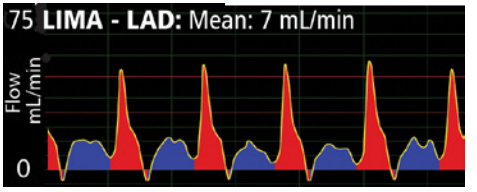


Fig. 2.31: Following graft revision LIMA - LAD mean flow increased from 8 mL/min to 34 mL/min.



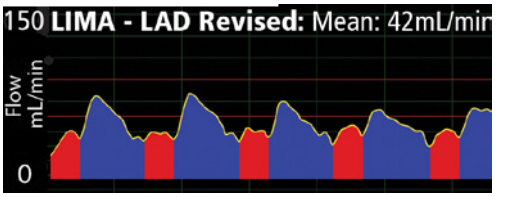


Fig. 2.32 Following graft revision LIMA - LAD mean flow increased from 7 mL/min to 42 mL/min.

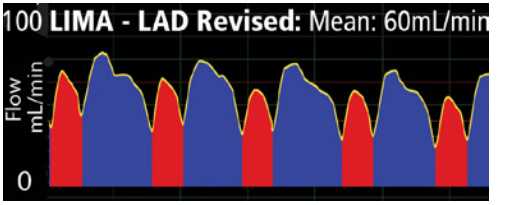


Fig. 2.33: Following graft revision LIMA - LAD mean flow increased from 9 mL/min to 60 mL/min.

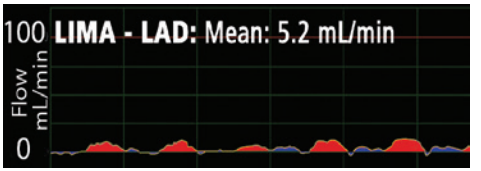


Fig. 2.34: Following graft revision LIMA - LAD mean flow increased from 5 mL/min to 50 mL/min.

I. 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.

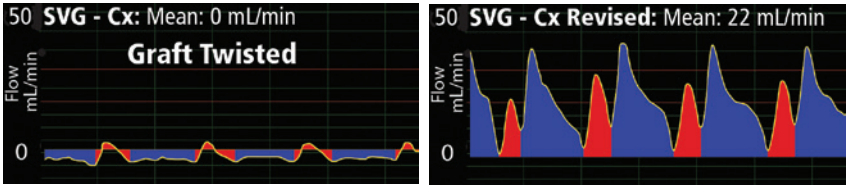


Fig. 2.35: Following chest closure, changes in the patient's hemodynamic parameters can give cause for alarm. Upon re-opening the chest, graft flow can be rechecked. A near-zero flow, as with this vein graft, indicates possible twisting of the graft. When a twist was discovered and corrected in this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

II. Flow-based Graft Patency Assessment cont.

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 is 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/patient. Ninety-five (95%) percent of the isolated CABGs were performed as OPCABS. 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

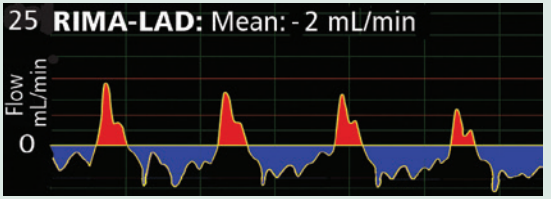
The intraoperative use of flow measurements provide invaluable information in a timely, accurate, cost-effective manner allowing for the surgical correction of a surgical problem. This has significantly reduced the complications related to early technically induced graft failure. In an era of rapidly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

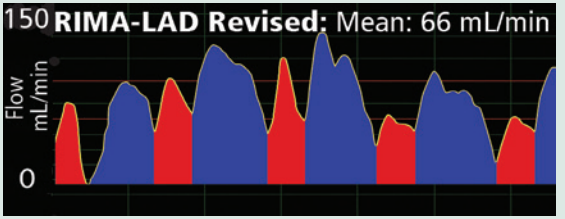
II. Flow-based Graft Patency Assessment cont.

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**	**Waveform Analysis**	**Analysis**
1) Post bypass	-2	29	Poor waveform	Requires attention
2) After revision	66	2.4	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.				

I. 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 B.), 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.

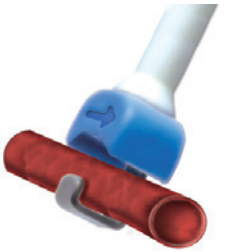


Fig. 2.36: For optimal measurements, the Flowprobe should be positioned on the graft so that the graft fills between 75 - 100 % of the Probe's ultrasonic window and the graft lies parallel to the Probe's reflector.

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.

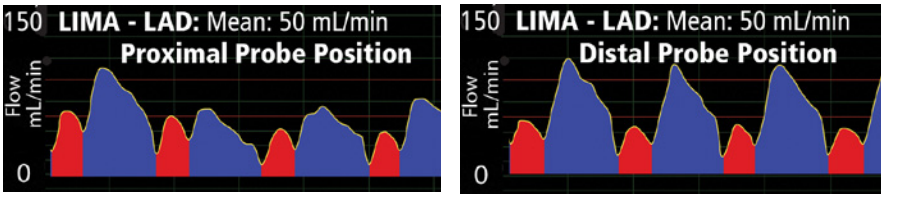


Fig. 2.37: These two LIMA - LAD waveforms demonstrate the effect of changing the site of a Flowprobe on a bypass graft. As shown in the right waveform, the flow profile is more diastolic-dominant when the Flowprobe is placed near the distal anastomosis. Note that the repetitive quality and the general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

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

I. 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 when low output syndrome occurs after CABG.

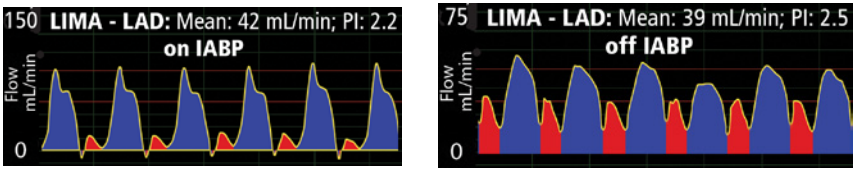


Fig. 2.38: LIMA-LAD mean graft flow dropped marginally from 42 mL/min to 39 mL/min.

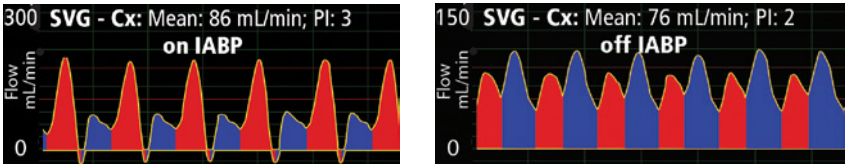


Fig. 2.39: Off IABP, SVG-Cx mean flow decreased from 86.4 mL/min to 76.2 mL/min.

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

Two recent 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.

II. Flow-based Graft Patency Assessment cont.

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 the time to examine the waveform, after eliminating competitive flow as a factor. A patent graft exhibits a good flow waveform.

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 (see section of Charge Flow). 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.

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 10% 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.

II. Flow-based Graft Patency Assessment cont.

Intraoperative Bypass Flow Measurement Reduces the Incidence of Postoperative Ventricular Fibrillation and Myocardial Markers after Coronary Revascularization

Bauer, SF *et al*, Thorac Cardio Surg 2005; 53: 217-22.

STUDY

The incidence of postoperative ventricular fibrillation and myocardial infarction were compared in two groups.

- One group of surgeries (n = 3421) used transit time flow measurements to assess the quality of the coronary bypass grafts.
- The other group of surgeries (n = 4321) were performed before transit-time flow measurement technology became available at the institution.

REPORTED RESULTS

Intraoperative measurement	Number	Post-operative Fibrillation	Subsequent Mortality
Transit time Ultrasound	3,421	0.44%	12.2%
No Measurement	4,321	0.66%	30%

The rate of insufficient bypass flow detected by angiography, was reduced by 66%.

CONCLUSION

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.

COMMENT

This paper attests to the value of using intraoperative flow measurements during coronary artery bypass grafting (CABG) to assess the quality of the bypass graft.

II. Flow-based Graft Patency Assessment cont.

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 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 (beaker/stopwatch method).

III: Physiology of Graft Flow cont.

Coronary graft flow is a function of cardiovascular status, myocardiac pathology, surgical procedures and graft patency.[1]

A. Introduction

The purpose of CABG surgery is to restore flow to the myocardium so that the heart can meet the body's metabolic demands. Flow-based intraoperative graft patency assessment verifies a coronary bypass graft's capacity to supply flow. Poor graft mean flows and waveforms can indicate severe impairment to a graft's functionality (caused by over 75% constriction).[1]

This chapter presents a review of the physiologic principles which govern coronary flow in order to assist the surgeon in developing a feel for "normal" and "questionable" graft flows and flow waveforms.

A number of mechanical processes determine coronary bypass flow.[2] By applying basic principles to the coronary circulation augmented with a bypass, rules can be formulated for a simple graft flow measurement protocol. A surgeon using this protocol would be alerted to potential technical error in the bypass which could result in graft failure early in the postoperative period.

1 Jaber SF et al, "Eur J Cardiovasc Surg 1998; 14: 476-9
2 Guyton, 1971, Chapters 13, 14, 18, 31

III: Physiology of Graft Flow cont.

B. CABG Graft Flow

Figure 3.1 presents a simple coronary circulation model with a bypass graft.

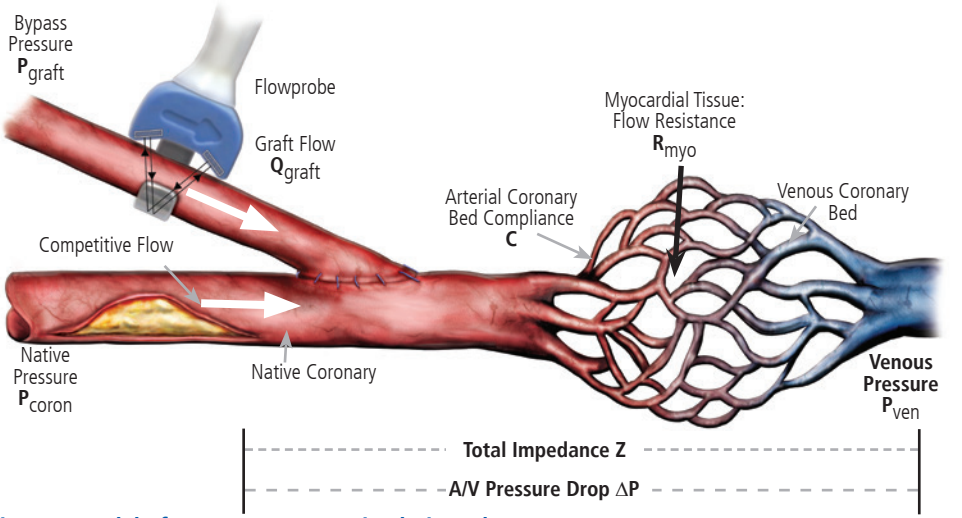


Fig. 3.1: Model of Coronary Bypass Circulation where:

Qgraft = Graft flow passing through the Flowprobe

ΔP = Arterio-venous pressure difference

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:

Rmyo = Flow resistance of the myocardial tissue

C = Vascular compliance downstream of the Flowprobe: graft segment + small coronary arteries

Flow through a graft is driven by a pressure (Pgraft), which differs from the pressure at the root of the aorta (Pcoron) feeding the coronary arteries.

Graft patency is determined by analyzing whether the graft exhibits the capability for uninhibited flow into the myocardium. As demonstrated by the diagram above, blood flow may be inhibited by competitive flow from the native coronary. In the following analysis we will consider only the case where graft flow is maximized by blocking competitive flow.

Flow to the target coronary and myocardium consists of two distinct components, each with unique characteristics:

B. CABG Graft Flow cont.

1. Myocardial Flow (Q_{myo}) is the flow passing through the myocardium. The myocardium has a certain amount of flow resistance (R_{myo}). Flow through the myocardium is expressed as the pressure across the myocardium divided by the myocardial resistance:

$$Q_{myo} = \frac{\Delta P}{R_{myo}} \qquad (1)$$

2. Charge Flow (Q_{charge}) is the flow associated with expansion and contraction of the coronary vessels with each heart beat.

   During systole, most of the cardiac ejection is stored in the arterial tree by expansion of arterial diameters. This change in arterial volume requires a flow: the arteries are "charged" (larger diameter, increased pressure) during systole. During diastole, these same vessels release their blood charge. Due to pressure wave propagation, this continual charge/discharge process converts the pulsatile output of the heart into the arterial waveforms with which we are familiar.[1,2]

   Charge flow contributes to the flow measured by a Flowprobe positioned on a coronary graft. This results from the changes in volume of the segment of the graft distal from the Flowprobe, and the coronary branches between the anastomotic site and the myocardium. $\mathbf{Q}_{charge}$ flow results from changes in pressure:

$$Q_{charge} = [\Delta P] \times C \qquad (2)$$

   $[\Delta P]$ = pressure change over time (the time-derivative of pressure)
   C = compliance of the blood vessels: their ability to expand in response to pressure changes.

   These two components, myocardial flow and charge flow, are indicated in Figure 3.2 (on the next page) as separate "circuit branches." Competitive flow is shown occluded in this figure: the relationship between the flow components is then:

$$Q_{graft} = Q_{charge} + Q_{myo} \qquad (3)$$

[1]Berne, Levy, "Physiology" Mosby, St. Louis 1998.
[2]Olsson, RA, Bünger, R., Spaan, JAE, "Coronary Circulation, " The Heart and Cardiovascular System, Second Edition, edited by H.A. Fozzard et al. Raven Press. Ltd., New York 1992.

III: Physiology of Graft Flow cont.

B. CABG Graft Flow cont.

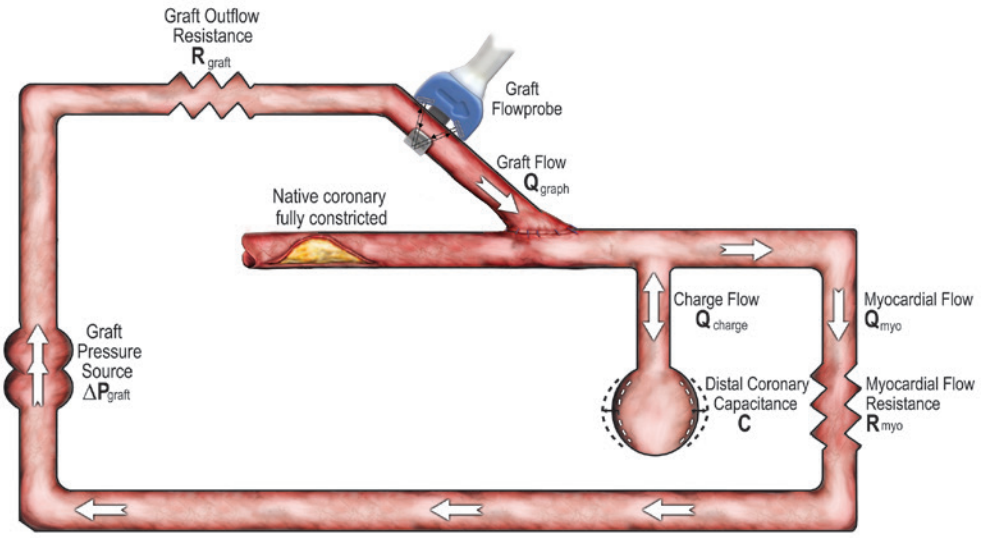


Fig. 3.2: Schematic of the Bypass and Coronary Flow Circuit where:

C is a storage vessel: when pressure rises, a positive Qcharge flows to expand its volume. When pressure drops, the stored blood is released as a negative Qcharge.

Qmyo flows into the resistive load of the myocardial tissue, **R**myo.

Δ**P**graft: the arteriovenous pressure difference causing flow.

Rgraft: the total of all outflow resistances upstream of the probe such as vasospasm and proximal anastomotic constriction.

The variability of all these "circuit elements" (ΔPmyo, Rgraft, C, and Rmyo) accounts for the range of Qgraft values and waveforms observed during CABG surgery. The properties of these elements will be discussed on the following pages.

III: Physiology of Graft Flow cont.

C. Pressure

A pressure waveform varies throughout the cardiovascular circuit. As one moves farther away from the root of the aorta, the initial systolic pressure peak is time-delayed and is followed by a second pressure peak, the dicrotic notch (Fig. 3.3).[1] Bypass grafts interpose an additional length of flow conduit between the heart and a coronary anastomosis. This extra length of conduit produces a similar delay in the systolic pressure peak, and may give rise to a similar second pressure peak during the middle of diastole.

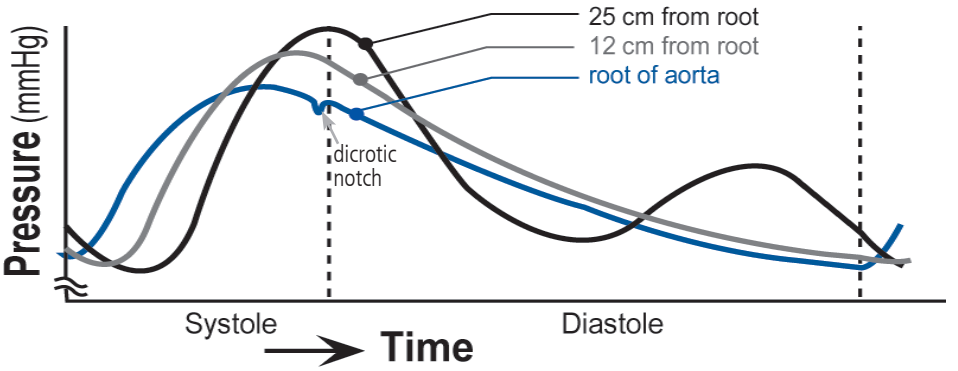


Fig. 3.3: Pressure Waveforms: The blue curve is a typical pressure waveform at the root of the ascending aorta; this is the pressure that drives the flow through a patent coronary artery. The gray line (12cm from the root) and black line (25 cm from root) show the time delay and change in waveform as the pressure pulse travels down the arterial tree. The gray line may indicate pressure at the anastomosis of a short vein or IMA graft; the black line may indicate the same for a longer graft conduit.[1].

[1] McDonald, Blood Flow in Arteries, Williams & Williams, Baltimore 1974

III: Physiology of Graft Flow cont.

D. Myocardial Flow Resistance

The heart's pattern of contraction and relaxation modulates its myocardial resistance. During systolic contraction, flow resistance is higher and less blood flow perfuses the myocardium (Fig. 3.4). This effect is pronounced in the left ventricle where the high flow resistance during systole reduces myocardial flow close to zero. When the left ventricular myocardium is diseased, its contractions will be weaker, further diminishing the difference in between systolic and diastolic perfusion. Graft flow is limited by afterload, due to runoff, elasticity, and degree of atherosclerosis, in addition to systolic compression, or preload.

The effect is less in coronaries perfusing the right ventricle and the atria: perfusion of these tissues continues throughout the cardiac cycle.

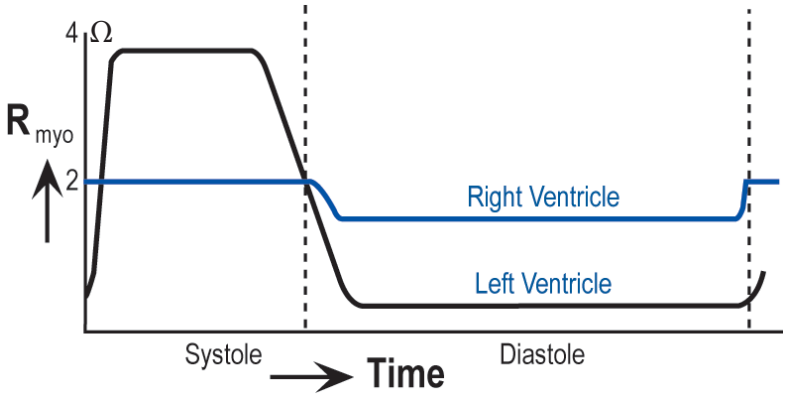
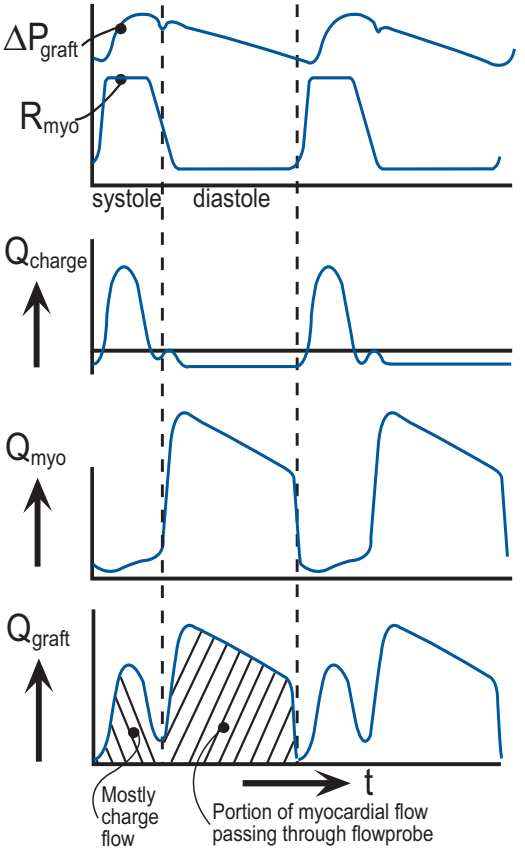


Fig. 3.4: Variations in Myocardial Flow Resistance. Systolic contraction of the heart greatly increases flow resistance of the left ventricular myocardium. Systolic myocardial flow decreases proportionally per:
$\mathbf{Q}_{myo} = \Delta\mathbf{P}_{graft} / \mathbf{R}_{myo}$.

E. CABG Flow Profiles

Left Ventricle

These graft flow profiles are characterized by a disparity in systolic and diastolic flow to the myocardium. The graft flow profile is explained by the beat-to-beat profiles of pressure and resistance (Fig. 3.5).



ΔPgraft: time-delay from the pressure at the root of the aorta, due to the length of the flow conduit to the anastomosis and its compliant properties.

Rmyo: the left-ventricular resistance with large difference between systole and diastole caused by strong muscle contraction.

Qcharge: the time-derivative of **ΔPgraft.** This flow is maximum during rapid rise of pressure, zero at the peaks and valleys of the pressure wave and negative when the pressure drops.

Qmyo: tracks the pattern of **ΔPgraft**, but with steps in scaling at the systolic and diastolic transitions.

Qgraft = Qcharge + Qmyo
Graft flow exhibits a diastolic dominant pattern. The ratio between systolic peak and diastolic peak flow may vary over a wide range, but the diastolic blood volume (right shaded area) is greater than the systolic volume (left shaded area).

Fig. 3.5: Components (ΔPgraft, Rmyo, Qcharge, Qmyo) of left ventricular graft flow, and its sources.

E. CABG Flow Profiles cont.

Left Ventricle cont.

Systolic & diastolic flow patterns of left ventricular grafts are illustrated in Figure 3.6.

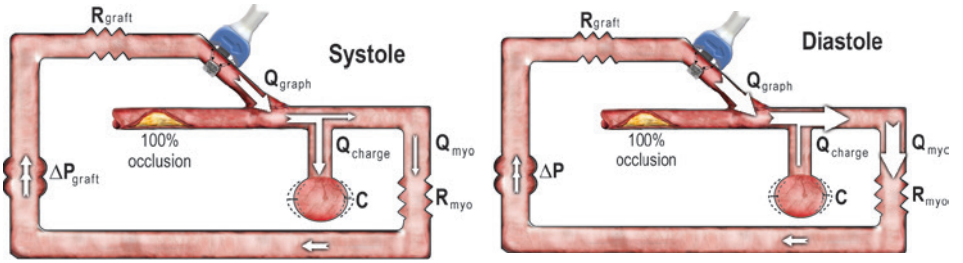


Fig. 3.6: Graft Flow Distribution to the Left Ventricle. During systole, the Flowprobe primarily senses charge flow. During diastole the Probe senses the greater portion of myocardial flow. The widths of the white arrows indicate their proportional ratios.

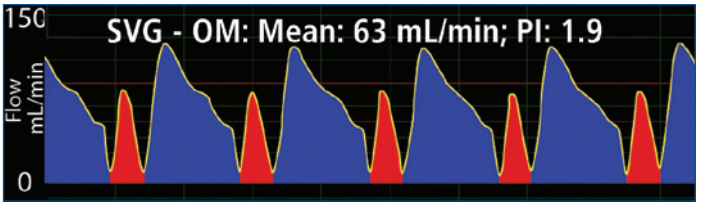


Fig. 3.7: Case example of a SVG-OM flow waveform, generated by the flow sources illustrated in Fig. 3.6. Systolic is denoted in red; diastolic in blue.

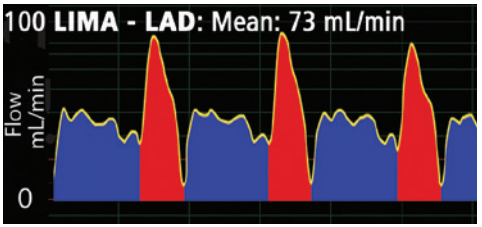
The flow pattern derived in Figure 3.6 and illustrated in Figure 3.7 is one of many possibilities.

E. CABG Flow Profiles cont.

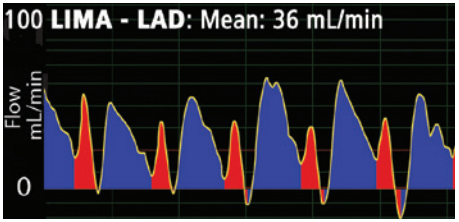
Left Ventricle cont.

The ratio between Q_{charge} and Q_{myo} may change (Fig. 3.8) and Q_{charge} will be greater (with a corresponding reduction in diastolic component) if Q_{graft} is measured on the proximal side of the graft. The ΔP waveform may be time shifted more toward diastole; in such instances a graft's systolic flow pulse will blend into the diastolic flow wave (Fig. 3.9).

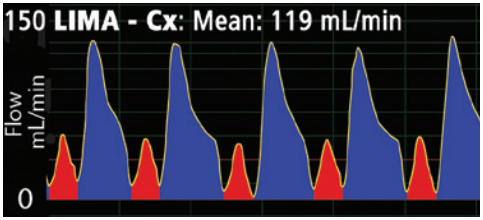
Examples of Grafts to the Left Ventricle



Mean Q_{graft} = 73 mL/min

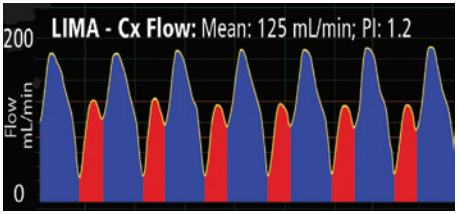


Mean Q_{graft} = 36 mL/min



Mean Q_{graft} = 119 mL/min

Fig. 3.8: Variations in systolic/diastolic peak graft flows in patent grafts to the left ventricle.



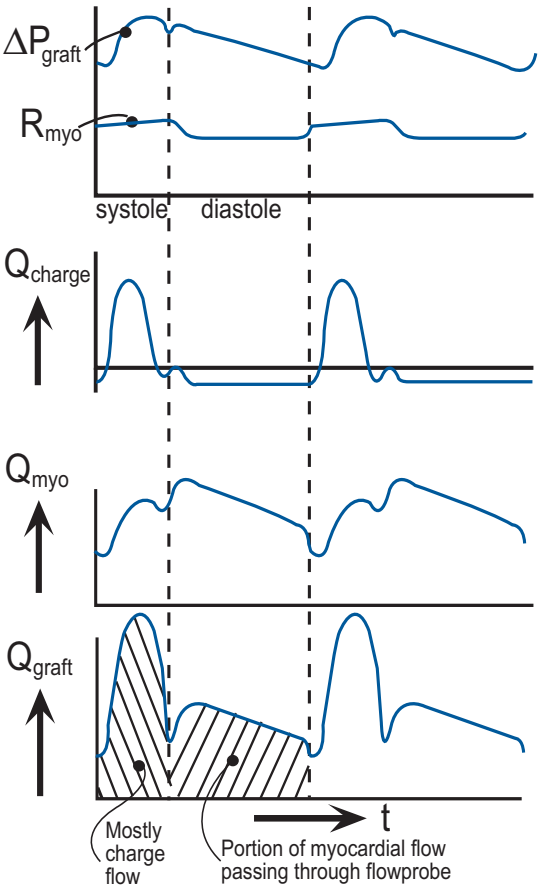
Mean Q_{graft} = 125 mL/min

Fig. 3.9: Time shift of the systolic pressure peak in patent grafts to the left ventricle, resulting from a delayed systolic pressure peak.

E. CABG Flow Profiles cont.

Right Ventricle

The flow in these grafts is characterized by a balanced systolic/diastolic flow profile similar to profiles seen in other organs of the body. The graft flow profile is explained by the beat-to-beat profiles of pressure and resistance (Figs. 3.10 & 3.11).



ΔPgraft is time-delayed from the pressure at the root of the aorta, due to the length of the flow conduit to the anastomosis and its compliant properties.

Rmyo is the right-ventricular resistance with only minor differences between systole and diastole from muscle contraction.

Qcharge: the time-derivative of **ΔPgraft.**
This flow is maximum during rapid rise of pressure, zero at the peaks and valleys of the pressure wave and negative when the pressure drops (as in the left ventricle).

Qmyo tracks the pattern of **ΔPgraft**, but with minor steps in scaling at the systolic and diastolic transitions.

Qgraft = Qcharge + Qmyo
Graft flow exhibits a balanced systolic/diastolic pattern. The delivered systolic blood volume (left-hatched area) may exceed the diastolic volume (right-hatched area) but the profile will include a proportionally sized diastolic contribution.

Fig. 3.10: Components (ΔPgraft, Rmyo, Qcharge, Qmyo) of right ventricular graft flow, and its sources.

E. CABG Flow Profiles cont.

Right Ventricle cont.

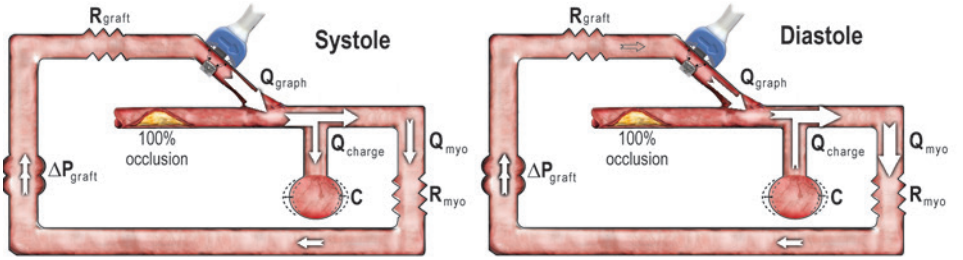


Fig. 3.11: Graft Flow Distribution to the Right Ventricle. During systole, the flowprobe senses a combination of charge flow and myocardial flow. During diastole, the probe senses the large part of myocardial flow only. The width of the white flow arrows indicate their proportional quantities.

Typical systolic & diastolic flow patterns of a RV graft is illustrated in Figure 3.12.

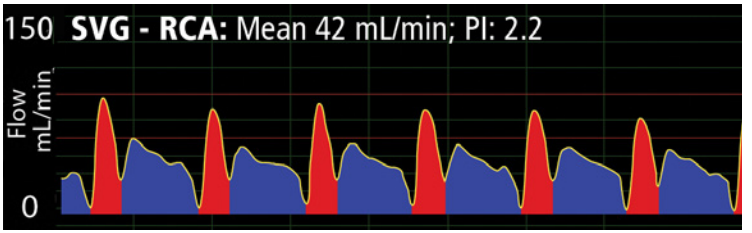


Fig. 3.12: Case example of a SVG-RCA waveform, generated by the flow sources illustrated in Fig. 3.10 and Fig. 3.11.

E. CABG Flow Profiles cont.

Right Ventricle cont.

The flow profile derived in Figure 3.10 and illustrated in Figures 3.12 & 3.13 will also be encountered with a range of variants in ratio between systolic/diastolic peak, and systolic/diastolic timing (Fig. 3.14).

Examples of Grafts to the Right Ventricle

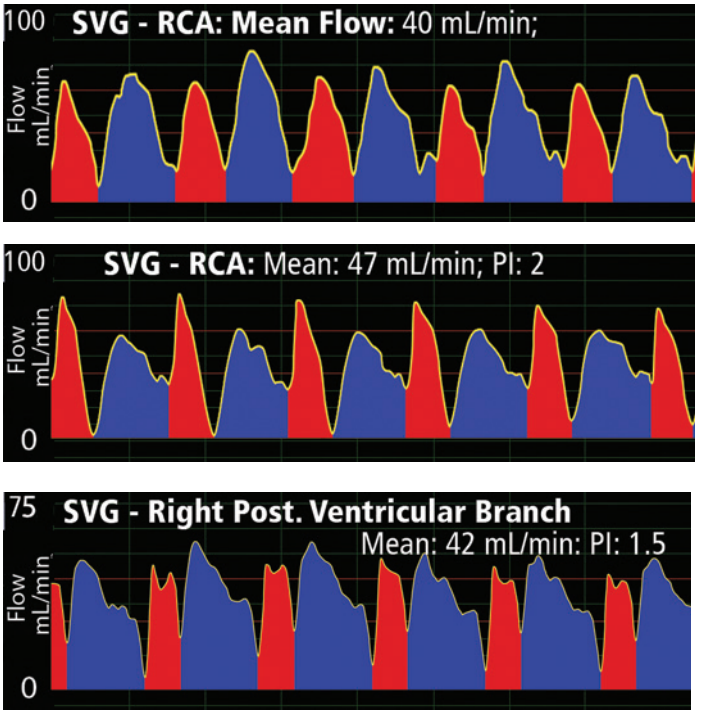
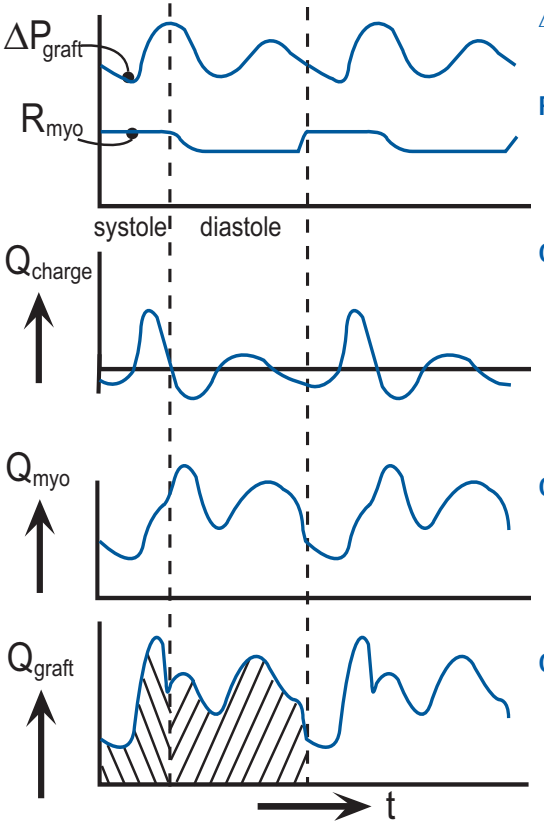


Fig. 3.13: Alternate normal flow profiles in right ventricular grafts, with altered systolic/diastolic flow peak ratio and timing.

E. CABG Flow Profiles cont.

Additional Profile Phenomena

The flow profile derivations in Figures 3.5 and 3.10 both 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 Figure 3.14. While these are RV waveforms, similar pattern changes are observed in LV graft flow traces.



ΔPgraft: time-delay from the pressure at the root of the aorta, with a second pressure peak (dicrotic wave).

Rmyo: the right-ventricular resistance with only minor differences between systole and diastole from muscle contraction.

Qcharge: the time-derivative of **ΔPgraft.** Because the pressure wave oscillates at twice the heart rate, **Qcharge** also oscillates at twice the heart rate.

Qmyo tracks the pattern of **ΔPgraft**, but with steps in scaling at the systolic and diastolic transitions. It becomes an oscillating flow as well.

Qgraft = **Qcharge** + **Qmyo**
The graft flow pattern becomes "reverberant." The systolic and diastolic peak can each become a double peak..

Fig. 3.14: Components of left ventricular graft flow, driven by a bi-phasic pressure wave.

E. CABG Graft Flow Profiles cont.

Reverberant Waveform Phenomena cont.

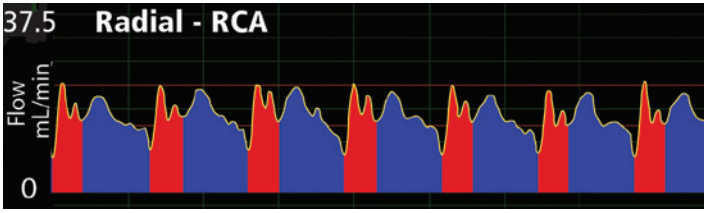


Fig. 3.15: Case example of Radial-RCA flowtrace, generated by the flow sources illustrated in Fig. 3.14.

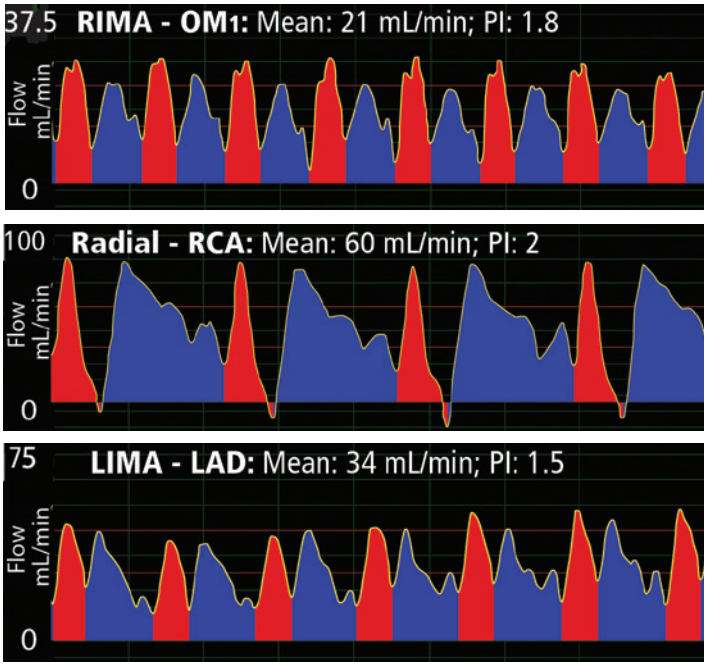


Fig. 3.16: Additional examples of reverberant flow patterns. Both systolic and diastolic flow phase may become double-peaked (RIMA - OM_1). The decaying slope of the diastolic flow wave often exhibits an oscillating pattern (Radial - RCA, LIMA - LAD).

E. CABG Graft Flow Profiles cont.

Additional 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 (Fig. 3.17).

Fig. 3.17: Typical flow profile in a graft supplying both left and right ventricular tissue (systolic/diastolic balanced).

III: Physiology of Graft Flow cont.

F. Competitive Flow

Competitive flow will obscure some of the flow capacity of the graft. It is, therefore, a wise practice to occlude competitive flow when measuring the flow patency of a graft.

This section describes the mechanism responsible for a typical flow pattern seen in the graft when competitive flow is present. Figure 3.18 illustrates the flow circuit components responsible for competitive flow.

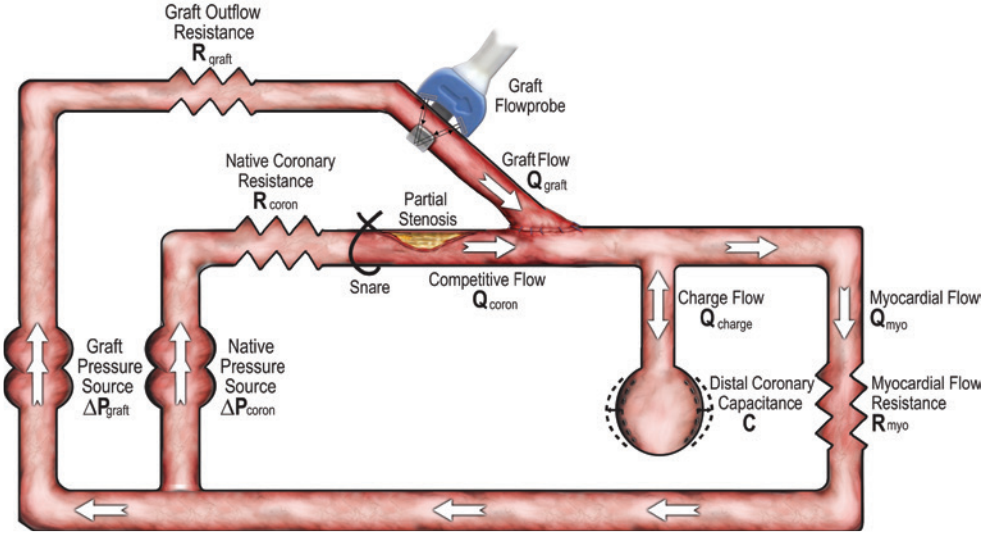


Fig. 3.18: Schematic of a bypass flow circuit when competitive flow is present. Flow through the target myocardium is now driven by two distinctly different pressures. Differences between these pressures account for unique features in the graft flow waveform.

When a stenosis in the native coronary is less than 100%, flow into the target myocardium is supplied by two branches, each with its own pressure profile P_{graft} and P_{coron}.

The coronary branch offers a shorter path to the root of the aorta. Therefore, the systolic pressure pulse will typically reach the graft's distal anastomosis, first via the native coronary artery branch, then via the graft branch. Figure 3.19 shows typical pressure waves at this point.

F. Competitive Flow cont.

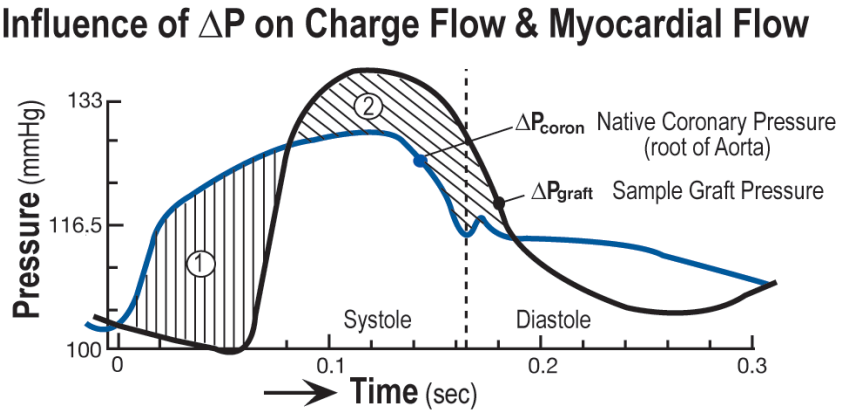


Fig. 3.19: ΔP_{coron} and ΔP_{graft} will typically differ in phase. When native coronary pressure exceeds the graft pressure (1), flow is forced back into the graft producing negative graft flow. When downstream coronary pressure becomes lower than graft pressure (2), graft flow becomes positive.

As illustrated in Figure 3.19, flow is being forced backward into the graft when native coronary pressure at the anastomosis exceeds graft pressure. This negative flow is exhibited by the flow waveform dipping below zero (Fig. 3.20).

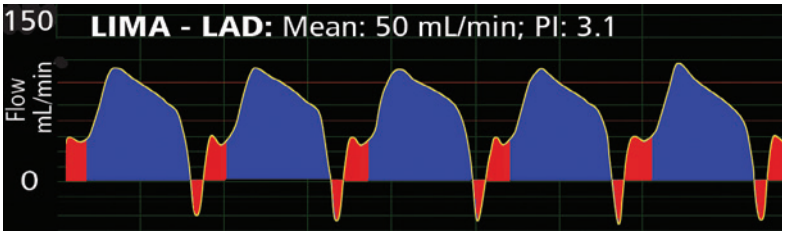


Fig. 3.20: This LIMA-LAD graft has sufficient competitive flow from the native coronary to force a negative graft flow at the onset of systole. The systolic waveform thus becomes bi-phasic, first negative and then positive.

III: Physiology of Graft Flow cont.

F. Competitive Flow cont.

The influence of the competitive flow on graft flow depends on the magnitude of the resistances R_{coron} and R_{graft}. R_{coron} is largely a function of the severity of the stenosis. R_{graft} includes factors such as graft length and size, vasospasm, and technical errors. Figure 3.21 of a RIMA-RCA graft presents an example of the effect of competitive flow on mean graft flow. Without occluding the native RCA, flow through the graft is 20 mL/min. If the native coronary is occluded, graft flow triples to 63 mL/min.

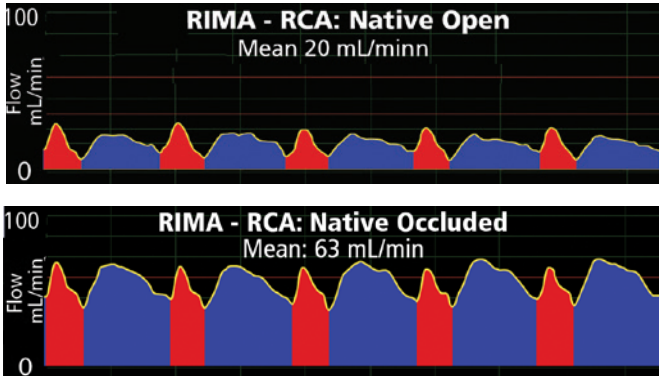


Fig. 3.21: Competitive flow, without a negative systolic peak, is indicated by an increase in mean flow from 20 mL/min to 63 mL/min when the native coronary artery is occluded. Graft flow, during native coronary artery occlusion, conclusively demonstrates graft patency.

IV. Representative Graft Flow Profiles

This chapter presents representative examples of coronary bypass graft flow and analyses of characteristic flow waveforms. Presented first are native flow profiles of the left internal mammary artery (LIMA), left (LAD) and right (RCA) coronary arteries. These are followed by examples of graft waveforms to the left ventricle, and then graft waveforms to the right ventricle.

A. Native Arterial Flow Profiles

The amount and profile of flow through arteries and grafts is highly dependent upon the properties of the organ being perfused. A graphic example of this is the native flow in the internal mammary artery (IMA) (Fig. 4.1). Its flow profile changes dramatically when it is used as a coronary graft (Fig. 4.4). A patent coronary graft will transport flow in a pattern similar to a native coronary artery 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 the different myocardial thicknesses.

In Situ (native) LIMA Flow

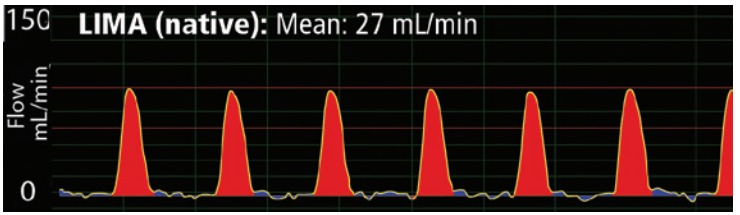


Fig. 4.1: Note that this LIMA flow is entirely in systole. LIMA flows are generally low in the native state because the artery is supplying the chest wall, a high resistance bed. Free flow from an open LIMA graft typically exceeds 90 mL/min, since there is then no resistance.

IV. Representative Graft Flow Profiles cont.

A. Native Arterial Flow Profiles cont.

In Situ LAD (Coronary Flow to the Left Heart)

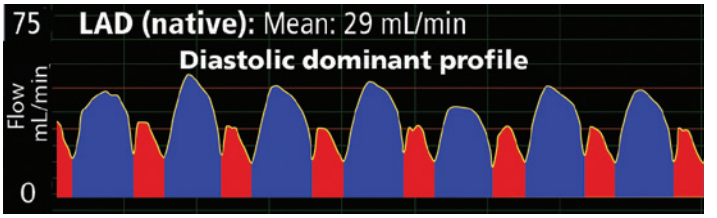


Fig. 4.2: The native left anterior descending coronary artery (LAD) exhibits a bi-phasic systolic/diastolic "M"-shaped flow pattern in contrast to the *in situ* LIMA's mono-phasic systolic profile.

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

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

- Mean flow is in the "Normal" range or higher (table, page 16) or
- Mean flow is in the "Questionable" range but flow is "diastolic-dominant."

IV. Representative Graft Flow Profiles cont.

B. Bypass Grafts to the Left Ventricle

Representative waveforms of left ventricle grafts include:

Left Internal Mammary Artery (LIMA) Grafts

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

LIMA - LAD Graft

LIMA - LAD Flow (classic diastolic profile)

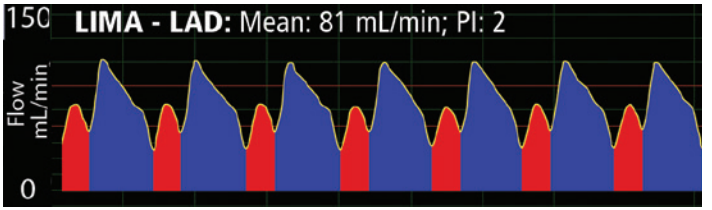
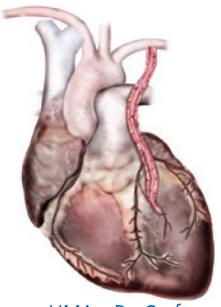


Fig. 4.4: This waveform exhibits a classic LIMA - LAD flow profile. Mean flow is 81 ml/min, the pulsatility index is 2; and the flow profile exhibits diastolic dominance. Note that diastole is consistent with the one-third (systole) to two-thirds (diastole) rule of thumb.



LIMA - Dx Graft

LIMA -Dx Flow (classic diastolic profile)

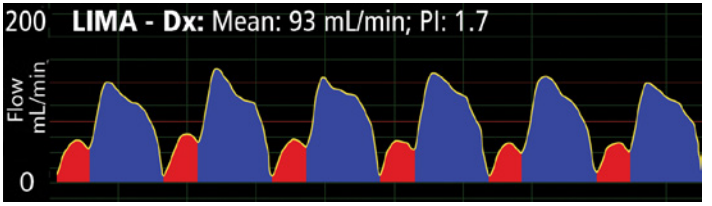


Fig. 4.5: This LIMA - Dx waveform exhibits a diastolic dominant flow profile. Mean flow is 93 mL/min, the pulsatility index is 1.7.

IV. Representative Graft Flow Profiles cont.

B. Bypass Grafts to the Left Ventricle cont.

Left Internal Mammary Artery Grafts cont.

LIMA - Cx Graft

LIMA -Circumflex (Cx) Flow

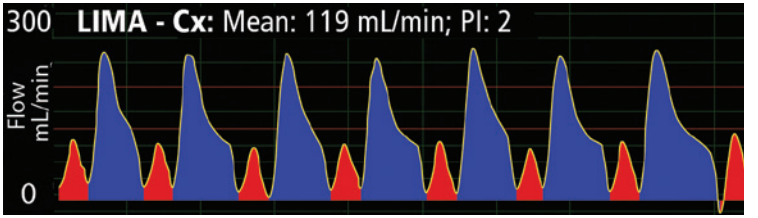


Fig. 4.6: This waveform exhibits a diastolic-dominant profile with excellent mean flow of 119 mL/min and a PI of 2.

LIMA - OM Graft

LIMA - Obtuse Marginal (OM) Flow

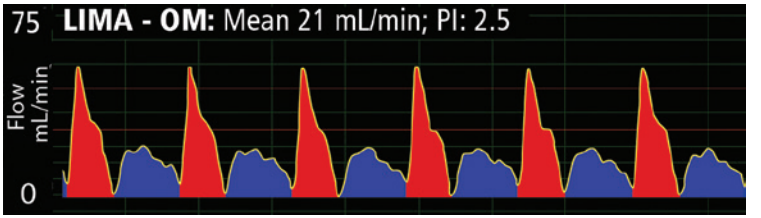


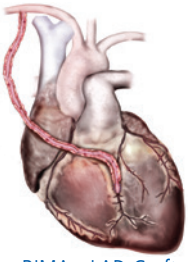
Fig. 4.7: Although waveform analysis reveals a balanced systolic/diastolic profile more representative of right heart grafts than a diastolic dominant profile seen in left heart grafts, the graft was accepted based on its good diastolic component and mean flow. The acceptable PI supported this decision.

IV. Representative Graft Flow Profiles cont.

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 the end (approximately 1.5 cm) of the graft, similar to the LIMA.



RIMA - LAD Graft

RIMA - LAD Flow

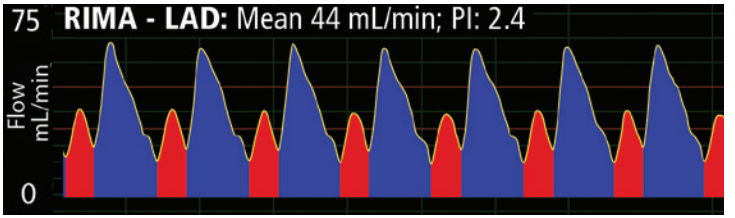
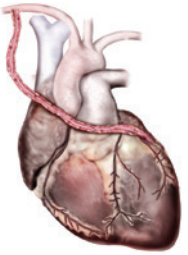


Fig. 4.8: The good RIMA - LAD mean flow indicates patency which is confirmed by the classic diastolic dominant waveform profile and 2.4 PI.



RIMA - Cx Graft

RIMA - Circumflex (Cx) Flow

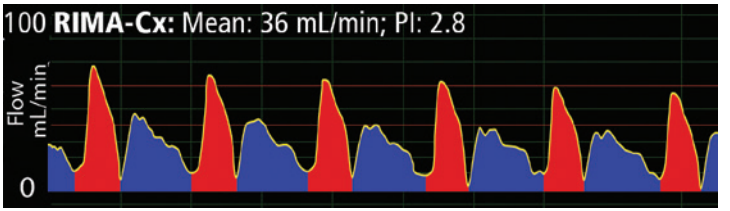
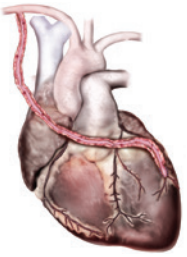


Fig. 4.9: Good mean flow (36 mL/min) indicates patency. Balanced waveform and acceptable PI confirm an acceptable graft.



RIMA - OM Graft

RIMA - Obtuse Marginal (OM) Flow

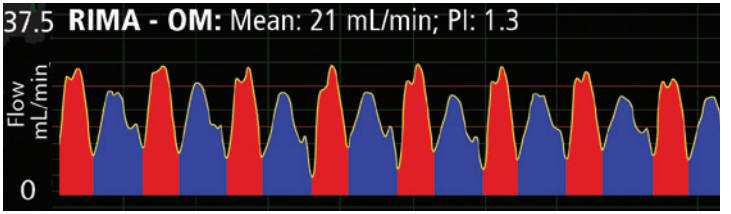
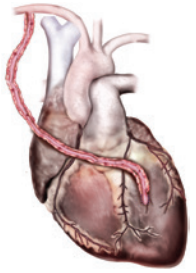


Fig. 4.10: The mean flow (21 mL/min), the diastolic waveform component and an acceptable PI of 1.3 indicate an acceptable graft.

IV. Representative Graft Flow Profiles cont.

B. Bypass Grafts to the Left Ventricle cont.

RIMA Graft Flows cont.



RIMA - Dx Graft

RIMA - Diagonal (Dx) Flow

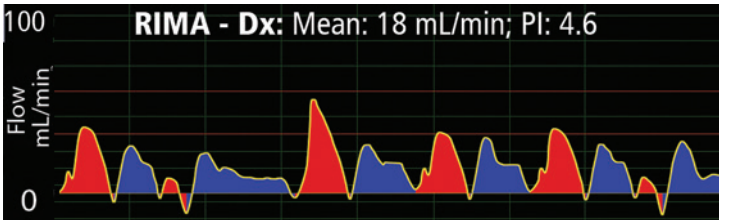
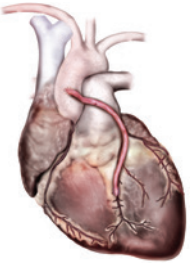


Fig. 4.11: This waveform exhibits a characteristic pattern of poor runoff into the myocardium. The graft was considered patent given the clear diastolic component of the waveform and the stage of the myocardial disease.

Radial (Rad) Graft Flows



Rad - LAD Graft

Rad - LAD Flow

Fig. 4.12: This graft profile indicates a patent graft with an acceptable (30 mL/min) mean flow. Note the high scale in relation to the waveform. This occurs when using a larger Flowprobe.

IV. Representative Graft Flow Profiles cont.

B. Bypass Grafts to the Left Ventricle cont.

Radial (Rad) Graft Flows cont.

RAD - Cx Graft

Rad - Circumflex (Cx) Flow

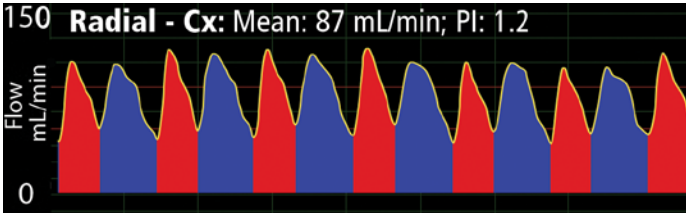
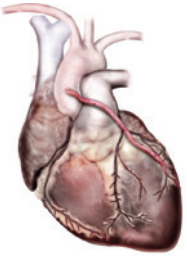


Fig. 4.13: The high mean flow indicates an acceptable graft.



RAD - OM Graft

Rad - Obtuse Marginal (OM) Flow

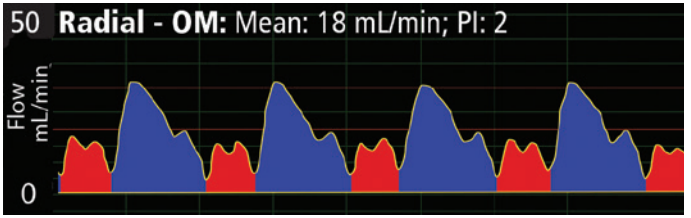
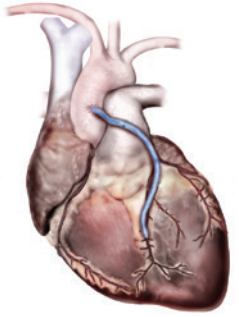


Fig. 4.14: The strong diastolic waveform profile and PI indicate an acceptable graft.

IV. Representative Graft Flow Profiles cont.

B. Bypass Grafts to the Left Ventricle cont.

Mean flow and waveform assessment rules for vein grafts are similar to those for arterial grafts. When a graft to the PDA supplies the left heart, the waveform also exhibits a diastolic dominant pattern (see Fig. 4.18).



SVG - LAD Graft

SVG - LAD Grafts

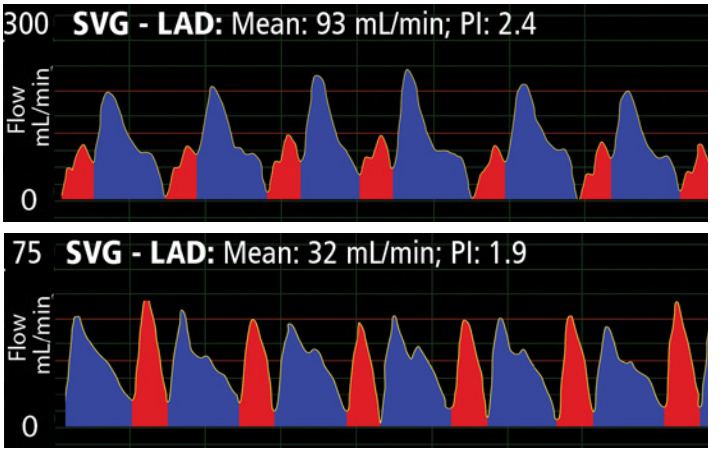


Fig. 4.15: Each of these two SVGs is anastomosed to the LAD in two respective patients. Both grafts indicate graft patency, based on their good mean flows, diastolic-dominant flow profiles, and low PIs.

SVG - Ramus Graft

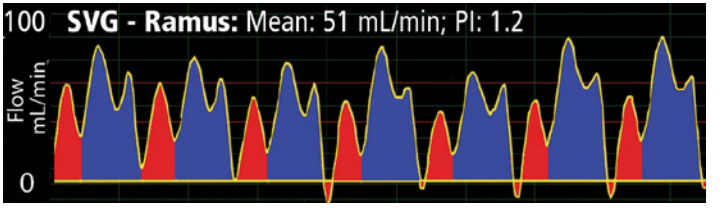
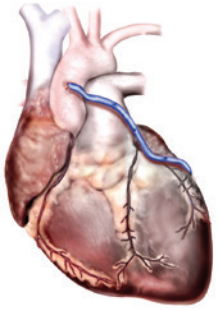


Fig. 4.16: The 51 mL/min mean flow, diastolic-dominant flow profile, and low PI of this SVG - Ramus bypass graft indicates graft patency. The ramus intermedius is a variant coronary artery resulting from trifurcation of the left main coronary artery. It is present in ~20% (range 15-30%) of the population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

IV. Representative Graft Flow Profiles cont.

B. Bypass Grafts to the Left Ventricle cont.



SVG - Cx Graft

SVG - Circumflex (Cx)

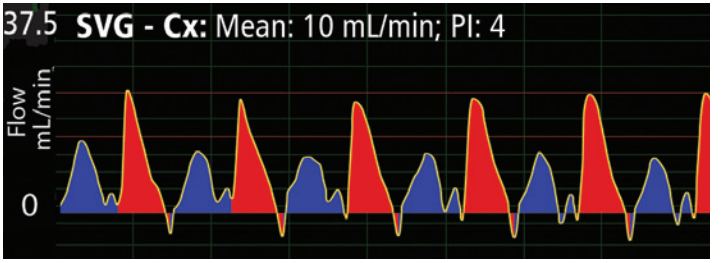
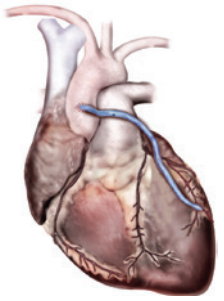


Fig. 4.17: Low mean flow (10 ml/min) accompanied by a fair waveform profile raised questions about the patency of this graft. The negative troughs at the end of systole indicate competitive flow. A repeat measurement is recommended with the native coronary occluded..



SVG - OM Graft

SVG - Obtuse Marginal (OM)

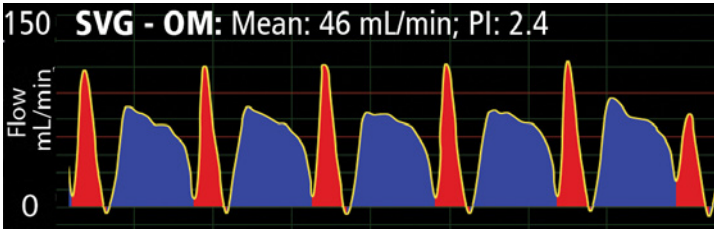


Fig. 4.18: Good mean flow (46 mL/min) with a strong diastolic profile indicate an acceptable SVG - OM graft.

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..

IV. Representative Graft Flow Profiles cont.

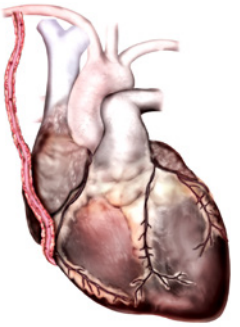
C. Bypass Grafts to the Right Ventricle

The right heart exerts less resistance during systole. Therefore, patent graft flow patterns to the right heart follow the arterial pressure waveform (Fig. 3.10), 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."

Arterial Grafts to the Right Ventricle



RIMA - RCA Graft

RIMA - RCA Graft Flows

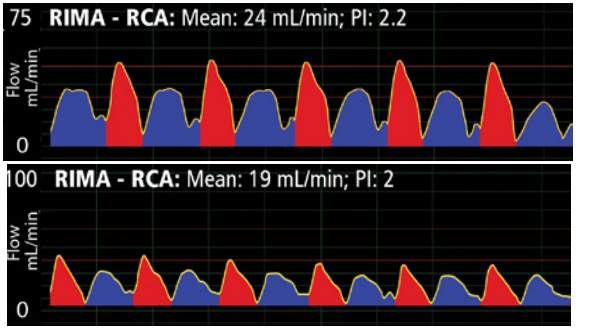


Fig. 4.20: The two waveforms above demonstrate balanced flow distributions between systole and diastole, common graft flow patterns to the right ventricle. These systolic/diastolic balanced profile indicates acceptable grafts despite rather low mean flows.

Radial (Rad) - RCA Flow

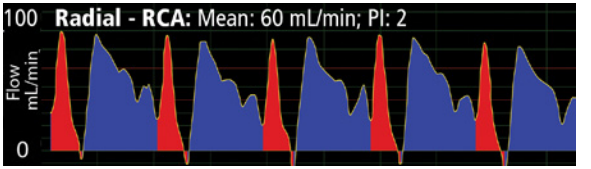
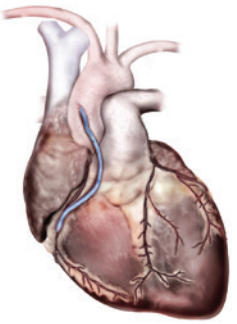


Fig. 4.21: The high mean flow (60 mL/min), good waveform and acceptable PI indicate an acceptable graft.

IV. Representative Graft Flow Profiles cont.

C. Bypass Grafts to the Right Ventricle cont.

Vein Grafts to the Right Ventricle



SVG - RCA Graft

SVG - RCA Graft Flows

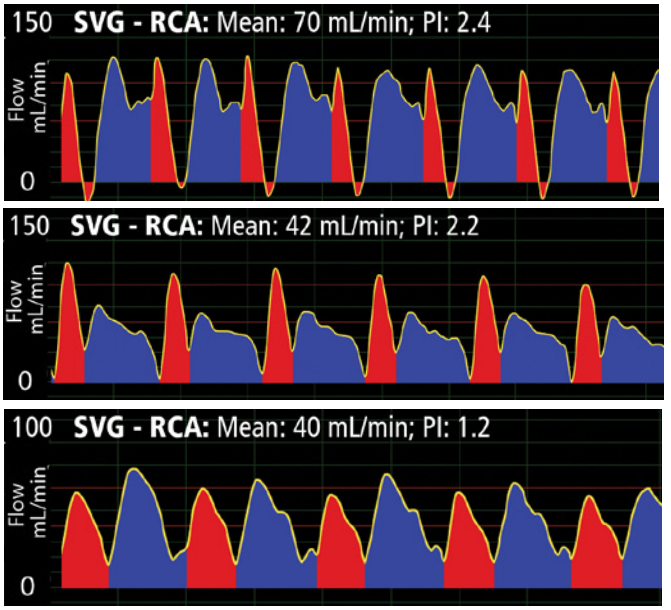


Fig. 4.22: All three of these SVG -RCA grafts have good mean flows that indicate acceptable grafts. The flow profiles illustrate some of the variations that may be encountered with acceptable grafts.

SVG - Post-Ventricular Branch Graft Flow

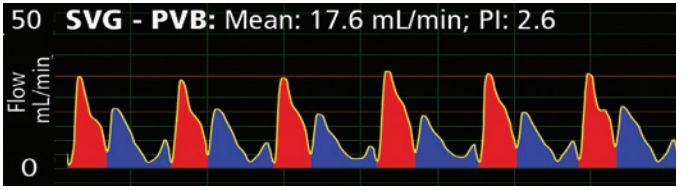


Fig. 4.23: Mean flow of this SVG to the post-ventricular branch coronary artery is questionable, but the systolic/diastolic balanced waveform profile indicates a patent graft. An acceptable PI supports this conclusion.

IV. Representative Graft Flow Profiles cont.

C. Bypass Grafts to the Right Ventricle cont.

Vein Grafts to the Right Ventricle cont.

SVG - PDA Graft Flows

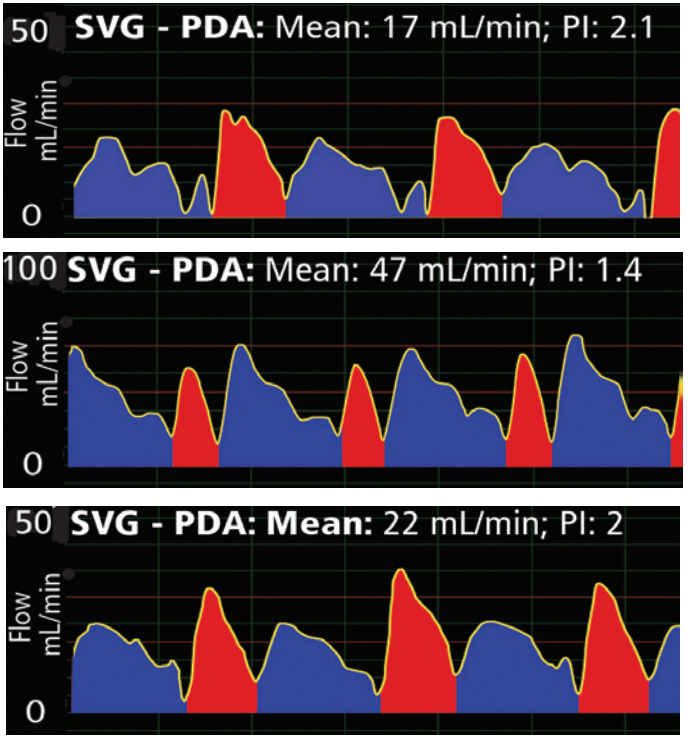


Fig. 4.24: All three of these SVG - PDA grafts have acceptable mean flows that indicate acceptable grafts. The variations in flow profiles illustrate some that may be encountered with acceptable grafts to the right heart.

IV. Representative Graft Flow Profiles cont.

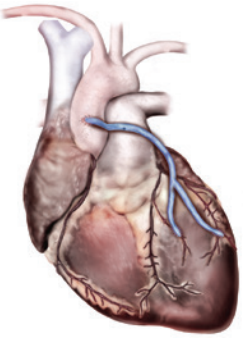
D. Composite Grafts

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 ventricle 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 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

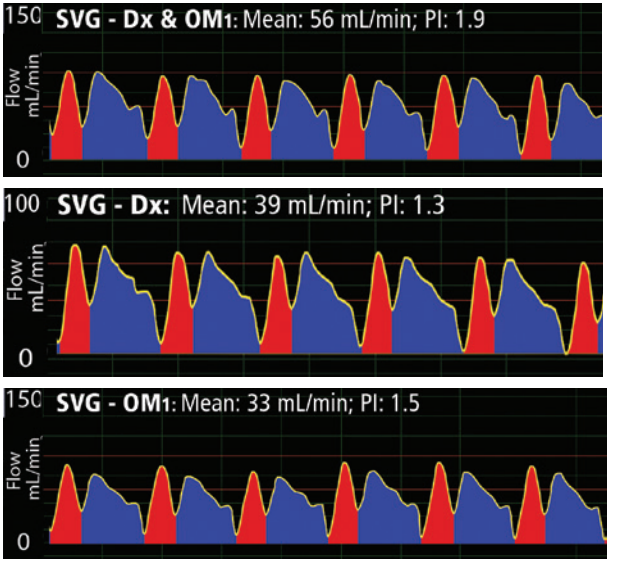
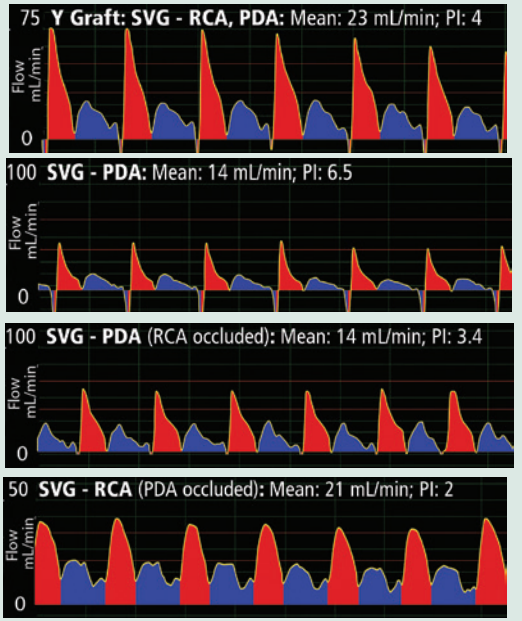


Fig. 4.25: Flow through the two branches (top trace) of the Y graft indicates graft functionality at the proximal anastomosis. Individual measurements of the diagonal (middle trace) and OM1 (bottom trace) branch reveal good mean flows, diastolic-dominant flow profiles to indicate patency for each branch.

IV. Representative 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.

IV. Representative Graft Flow Profiles cont.

D. Composite Grafts cont.

Sequential Grafts

To measure the patency of a sequential graft, the Flowprobe is applied to the main trunk of the graft and flow is measured. Then, remeasure flow 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

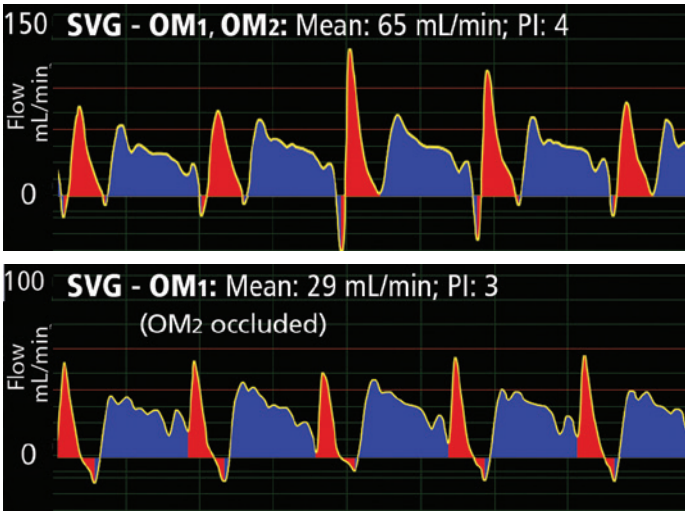


Fig. 4.26: Mean flow of the sequential SVG to OM1 and OM2 graft was 65 mL/min. When the OM2 was occluded, flow from the SVG to OM1 graft was 29 mL/min, indicating OM1 patency. OM2 patency is inferred from the drop in flow: at least 65 - 29 = 36 ml/min perfused the OM2 during the OM1 & OM2 measurement.

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.

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.

V. CABG Case Reports

This 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. All cases reports are courtesy of The Valley Hospital, Ridgewood, NJ.

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.

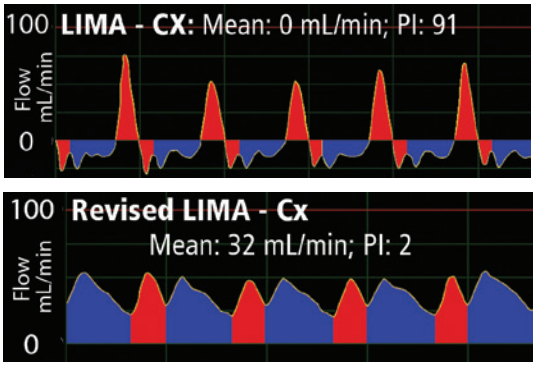


Fig. 5.1: The top waveform exhibited a spiky systolic profile, which, accompanied by zero mean flow, called for the surgeon to revise the LIMA-Cx graft without hesitation. Flow improved to 32 mL/min after revision and the waveform exhibited a balanced LIMA-Cx profile (bottom waveform).

Summary: Off-CPB CABG; LIMA-Cx Graft 78-year-old female, single-vessel coronary artery disease				
Flow Measurement	**Mean Flow** (mL/min)	**Pulsatility Index (PI)**	**Waveform**	**Analysis**
Post-bypass	0	91	Spiky systolic profile	Revision demanded
After revision	32	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 24/7 demonstrating the cascade of sequelae triggered by flow.

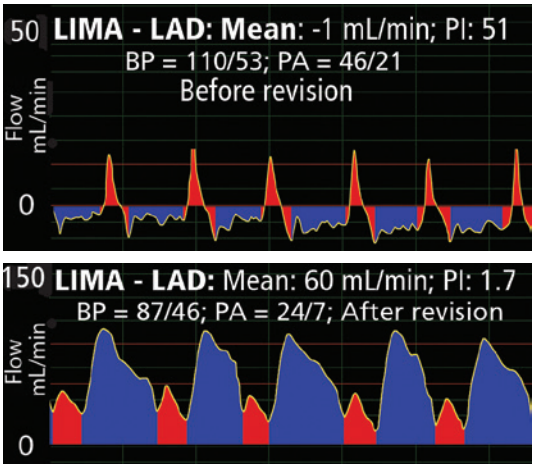


Fig. 5.2: The zero mean flow of the first flow measurement demonstrated a graft that required immediate attention. Mean flow was -1 mL/min. The LIMA to LAD anastomosis was revised and mean flow improved to 60 mL/min with a excellent diastolic flow pattern.

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.						

V. CABG Case Reports cont.

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 (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 (PI: 1.7) and was accompanied by a diastolic dominant waveform.

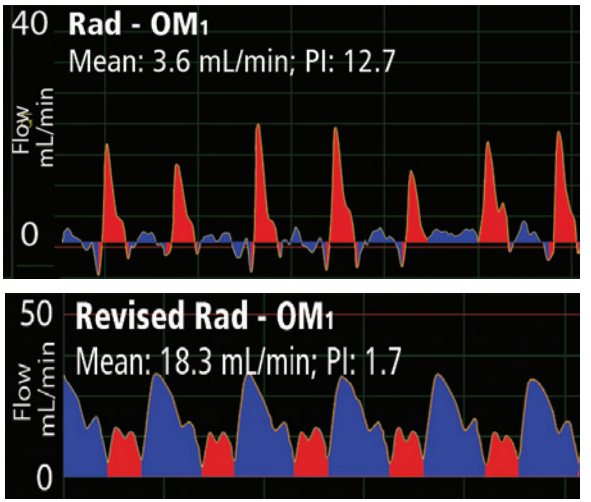


Fig. 5.3: The top waveform with a spiky systolic profile shows initial Rad-OM1 graft flow of 3.6 mL/min. Following revision of the graft, flow increased to 18.3 mL/min and was accompanied by a diastolic dominant waveform profile (lower waveform).

Summary: Off-CPB CABG; RAD-OM1 Graft 48-year-old male, multi-vessel coronary artery disease				
Flow Measurement	**Mean Flow (mL/min)**	**Pulsatility Index (PI)**	**Waveform**	**Analysis**
Post RAD - OM1 bypass	3.6	12.7	Systolic dominant waveform.	Revision warranted
After revision	18.3	1.7	Repetitive 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 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 (PI: 29) indicating that revision of the graft was warranted (upper waveform).

After revision, graft flow improved to 77.5 mL/min (PI: 3). The flow was accompanied by a repetitive systolic/diastolic waveform profile (lower waveform).

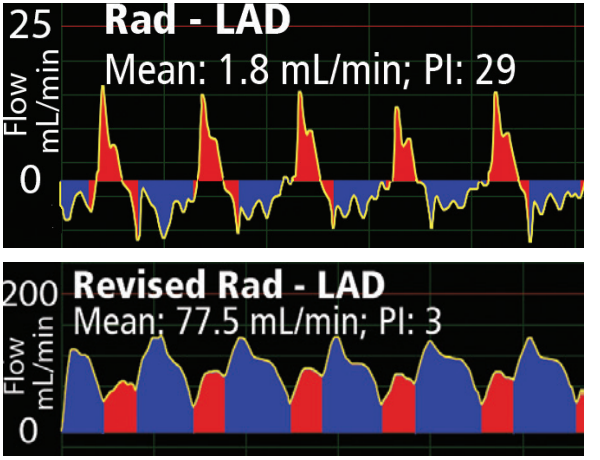


Fig. 5.4: The upper Rad-LAD waveform exhibits a spiky systolic profile and is coupled with an initial graft flow of 1.8 mL/min. Following revision of the graft, flow increased to 77.5 mL/min and was accompanied by a diastolic dominant waveform (bottom).

Summary: Off-CPB CABG; RAD-LAD Graft 71-year-old male, single vessel coronary artery disease				
Flow Measurement	**Mean Flow (mL/min)**	**Pulsatility Index (PI)**	**Waveform**	**Analysis**
Post RAD-LAD bypass	1.8	29	Atypical diastolization although pulse and pressure appeared functional	Revision warranted
After revision	77.5	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 Revision 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.

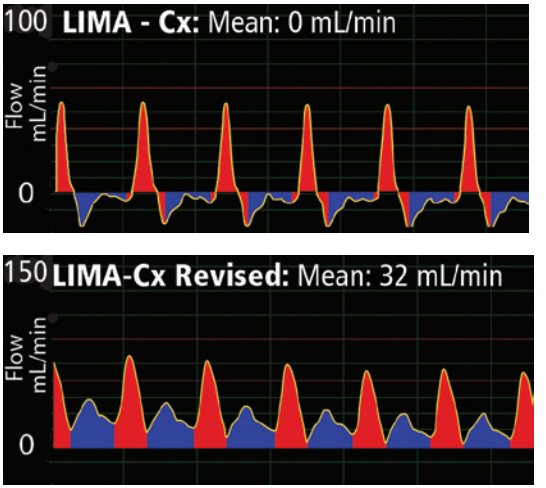


Fig. 5.5: The upper spiky systolic waveform profile shows initial 0 mL/min LIMA - Cx graft flow following anastomosis of the bypass. After the graft was revised, flow increased to 32 mL/min and was accompanied by a more balanced diastolic/systolic profile (lower waveform).

Summary: Off-CPB CABG; LIMA - Cx Graft 78-year-old male				
Flow Measurement	**Mean Flow (mL/min)**	**Pulsatility Index (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 76 mL/min (PI: 2).

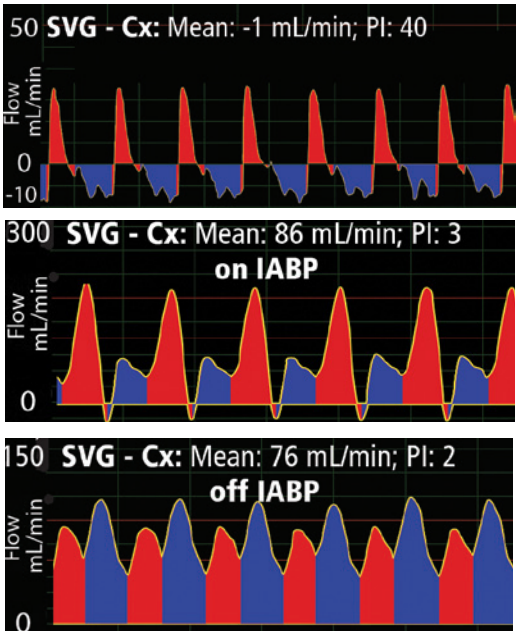


Fig. 5.6: This SVG - Cx graft first registered zero flow indicating a problem. Investigation revealed a clot. The second and third grafts show flow on and off IABP after declotting the graft.

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

V. CABG Case Reports cont.

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

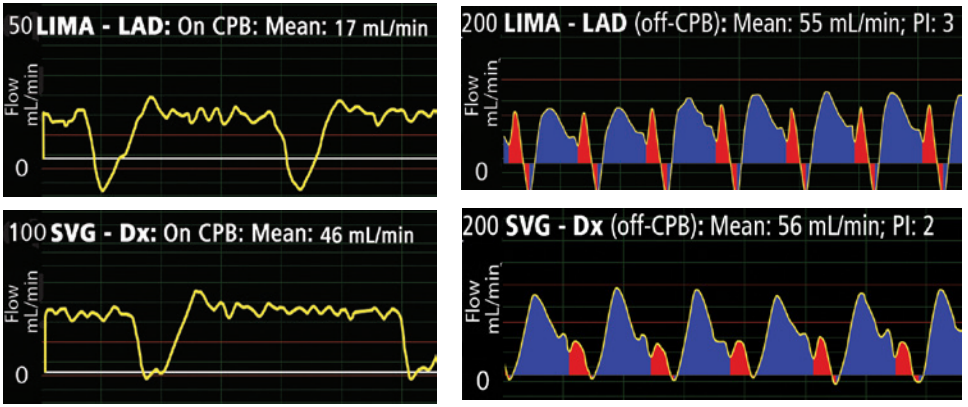


Fig. 5.7: Two good on CPB flows (LIMA - LAD: 17 mL/min, SVG - Dx: 46 mL/min) predict excellent off-CPB flows (LIMA - LAD: 55 mL/min; SVG - Dx: 56 mL/min). Also, SVG - OM flow was 53 mL/min off CPB.

Case Summary: 81-year-old male; Three Grafts: LIMA - LAD, SVG - OM, SVG - Dx				
	On CPB	Off-CPB	Off-CPB	Off-CPB
Grafts	Mean Flow (mL/min)	Mean Flow (mL/min)	PI	Waveform Analysis
LIMA - LAD	17	55	3	Excellent diastolic dominant profile
SVG - OM	31	53	3	Systolic/diastolic balanced profile
SVG - Dx	46	56	2.2	Systolic/diastolic balanced profile
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.

V. CABG Case Reports cont.

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

On-, Off-CPB Graft Flows with Heart Fibrillating

SVG - RCA Graft Flows

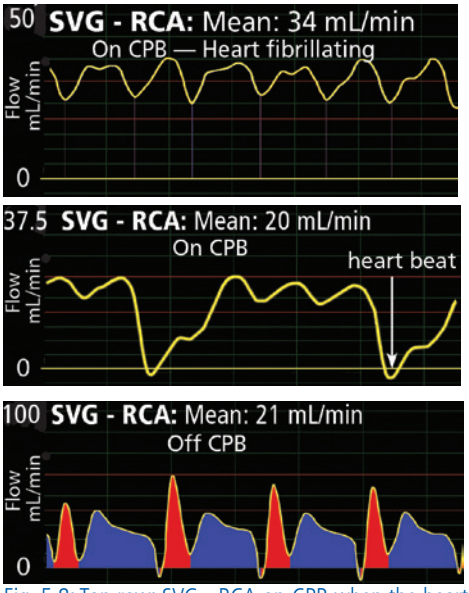


Fig. 5.8: Top row: SVG - RCA on-CPB when the heart is fibrillating; 2nd row: SVG - RCA on-CPB without fibrillation. Acceptable on-CPB SVG - RCA mean flow foreshadowed an acceptable off-bypass flow and waveform (third row).

SVG - Dx Graft Flows

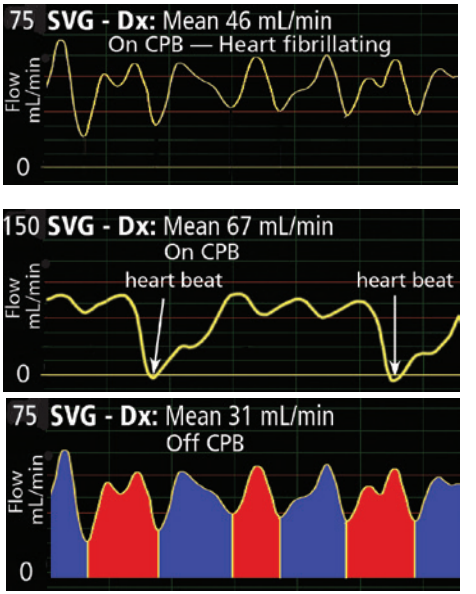


Fig. 5.9: Top row: SVG - Dx on-CPB when the heart is fibrillating; 2nd row: SVG - Dx on-CPB without fibrillation. Acceptable on-CPB SVG - Dx flow foreshadowed an acceptable off-bypass flow (third row).

Case Summary: 73-year-old male; Two Grafts: SVG - RCA; SVG - Dx				
	On CPB (fibrillating)	**On CPB** (not fibrillating)	**Off-CPB** (not fibrillating)	
Grafts	**Mean Flow** (mL/min)	**Mean Flow** (mL/min)	**Mean Flow** (mL/min)	**Waveform Analysis**
SVG - RCA	34	20	21	Good systolic diastolic balance
SVG - Dx	46	67	31	Good systolic diastolic balance
Case illustrates how fibrillation affects flow.				

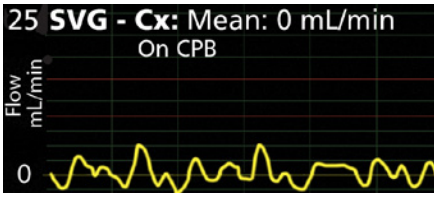
V. CABG Case Reports cont.

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.

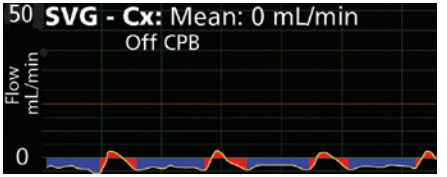
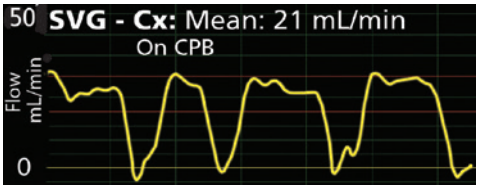


Fig. 5.10: Zero mean flows on & off CPB.

3.



4.

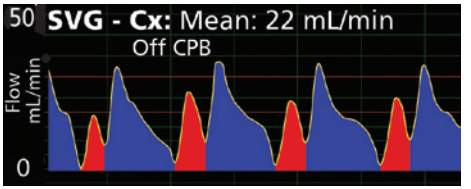


Fig. 5.11: When graft is untwisted, on-CPB flow increased to 21 mL/min; off-CPB flow was 22 mL/min.

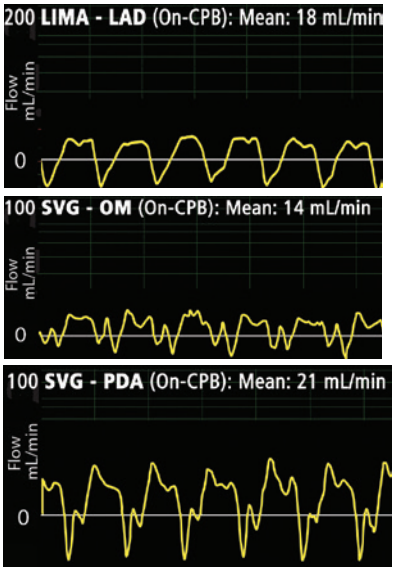
Case Summary: CABG: 73-year-old male; SVG - Cx Graft				
Flow Measurement	**Mean Flow** (mL/min)	**PI**	**Waveform Analysis**	**Action**
1) On CPB	0		Poor waveform supports 0 mL/min mean flow	Remeasure off CPB
2) Off CPB	0		Poor waveform corroborates on-CPB measurement	Graft needs to be revised
Graft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

V. CABG Case Reports cont.

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

Vein Grafts Questionable: LIMA - LAD Graft Good

On-CPB Graft Flows



Off-CPB Graft Flows

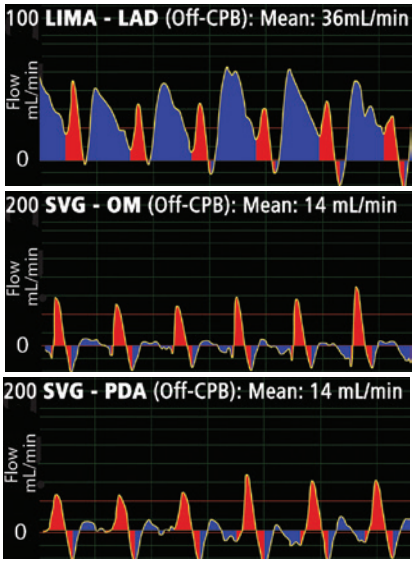


Fig. 5.12: LIMA - LAD graft flows on total CPB registered 18 mL/min. Off bypass LIMA - LAD flow measured 36 mL/min with a characteristic 2/3 diastolic, 1/3 systolic waveform profile. However, both SVG grafts, to the OM had questionable on-pump measurements of 14 mL/min. Even with systolic/diastolic balanced 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; Three Grafts: LIMA - LAD, SVG - OM, SVG - PDA				
	On CPB	Off-CPB	Off-CPB	Off-CPB
Grafts	Mean Flow (mL/min)	Mean Flow (mL/min)	PI	Waveform Analysis
LIMA - LAD	18	36	3	Classic LIMA - LAD profile
SVG - OM	14	14	15	Systolic dominant, competitive flow?
SVG - PDA	21	14	14	Systolic dominant, competitive flow?
Case illustrates how on-CPB flows can mirror off-CPB flows.				

V. CABG Case Reports cont.

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

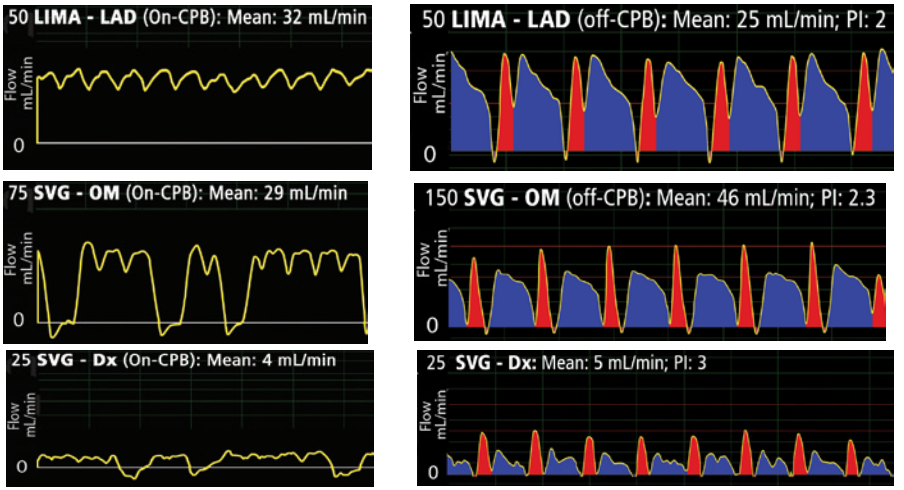


Fig. 5.13 On CPB, LIMA - LAD graft flows registered 32 mL/min. Off bypass LIMA - LAD flows measured 25 mL/min with a characteristic 2/3 diastolic, 1/3 systolic waveform profile. Similarly, the SVG - OM graft flow of 29 mL/min foreshadowed excellent off-CPB flow (46 mL/min). Moreover, poor on-CPB SVG - 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; Three Grafts: LIMA - LAD, SVG - OM, SVG - Dx				
	On CPB	Off-CPB	Off-CPB	Off-CPB
Grafts	Mean Flow (mL/min)	Mean Flow (mL/min)	PI	Waveform Analysis
LIMA - LAD	32	25	2	Classic LIMA - LAD profile
SVG - OM	29	46	2.3	Systolic/diastolic balanced
SVG - Dx	4	5	3 (false positive)	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.

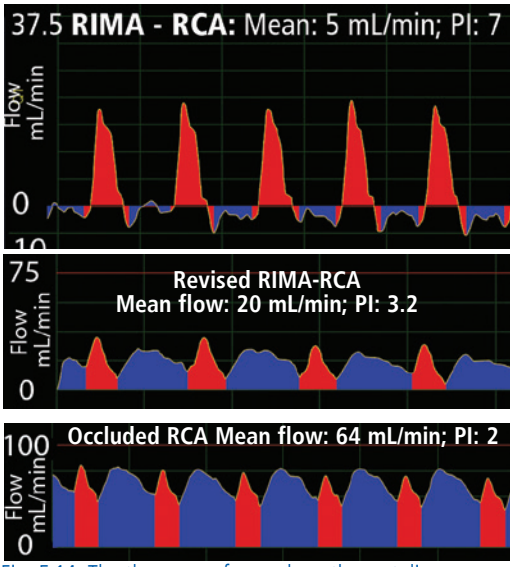


Fig. 5.14: The three waveforms show the systolic dominant profile of the RIMA-RCA graft before revision (top), the systolic/diastolic flow waveform profile following revision of the graft (middle), and the similar graft waveform with the proximal RCA occluded (bottom).

Case Summary: Off-CPB CABG; RIMA-RCA Graft; 60-year-old male				
Flow Measurement	**Mean Flow (mL/min)**	**Pulsatility Index (PI)**	**Waveform**	**Analysis**
Post RIMA - RCA bypass grafting	5	7	Systolic	Revision called for
After revision	20	3.2		Possible competitive flow; occlude proximal RCA
Proximal RCA Occlusion	64	2	Diastolic dominant	
Case demonstrates the presence of significant competitive flow from the native RCA.				

V. CABG Case Reports cont.

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.

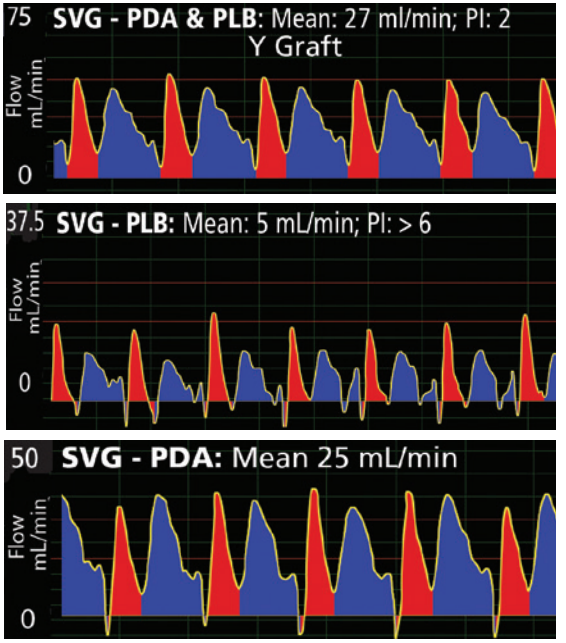


Fig. 5.15: The three waveforms show the acceptable flow waveforms of a Y graft to the PDA and PLB, even though flow to the PLB was low (5 mL/min) due to competitive flow from the native coronary artery.

Case Summary: Off-CPB CABG; Y Graft to PLB, PDA; 66-year-old male			
Flow Measurement	**Mean Flow (mL/min)**	**Pulsatility Index (PI)**	**Waveform & Flow**
1. Y Graft to PDA, PLB	27	2	Repetitive systolic/diastolic
2. Y Graft to PLB	5	>6	Good waveform; poor flow
3. Y Graft to PDA	25	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.			

V. CABG Case Reports cont.

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]

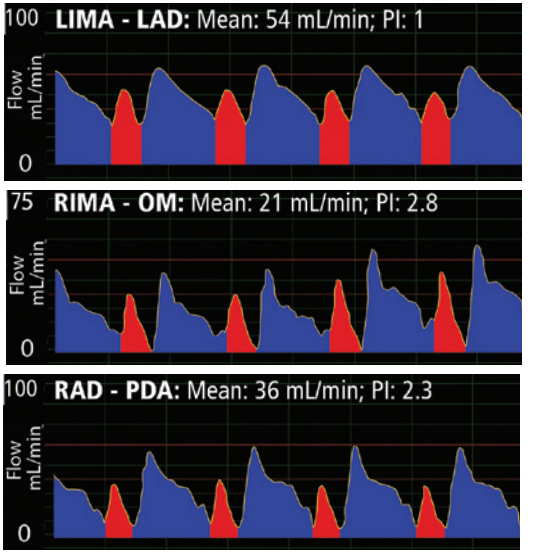


Fig. 5.16: These three arterial graft all exhibit good flows, acceptable PIs and excellent waveform profiles.

Case Summary: Off-CPB CABG; Three Arterial Grafts; 70-year-old male			
Flow Measurement	**Mean Flow** (mL/min)	**Pulsatility Index (PI)**	**Waveform**
LIMA - LAD	54	1	Excellent
RIMA - OM	21	2.8	Good
Radial - PDA	36	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.

V. CABG Case Reports cont.

C. Interesting Cases cont.

Left and Right Heart Waveform Comparisons

Case #1 Right Heart Waveforms Case #2

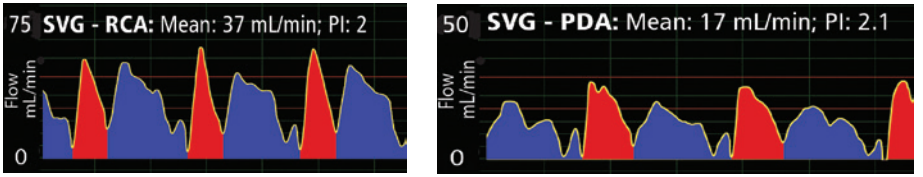


Fig. 5.17: Right heart grafts (SVG - RCA in Case #1, and SVG - PDA in Case #2) both demonstrate the balanced systolic/diastolic waveform profiles typical of bypass flows to the right heart.

Case #1 Left Heart Waveforms Case #2

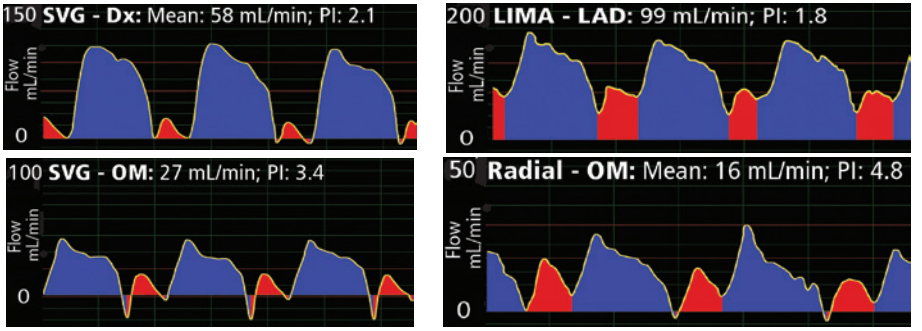


Fig. 5.18: Left heart grafts (SVG - Dx & SVG - OM in Case #1, and LIMA - LAD & Rad - OM in Case #2) all demonstrate strong diastolic dominant profiles typical of left heart bypass flows.

Case Summary: Two Elderly Males: 1 bypass to the right heart, 2 to the left heart							
Case #1				Case #2			
Graft	Mean Flow (mL/min)	PI	Waveform	Graft	Mean Flow (mL/min)	PI	Waveform
Right Heart							
SVG - RCA	37	2	Balanced	SVG - PDA	17	2.1	Balanced
Left Heart							
SVG - Dx	58	2.1	Diastolic Dominant	LIMA - LAD	99	1.8	Diastolic Dominant
SVG - OM	27	3.4	Diastolic Dominant	Rad - OM	16	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.

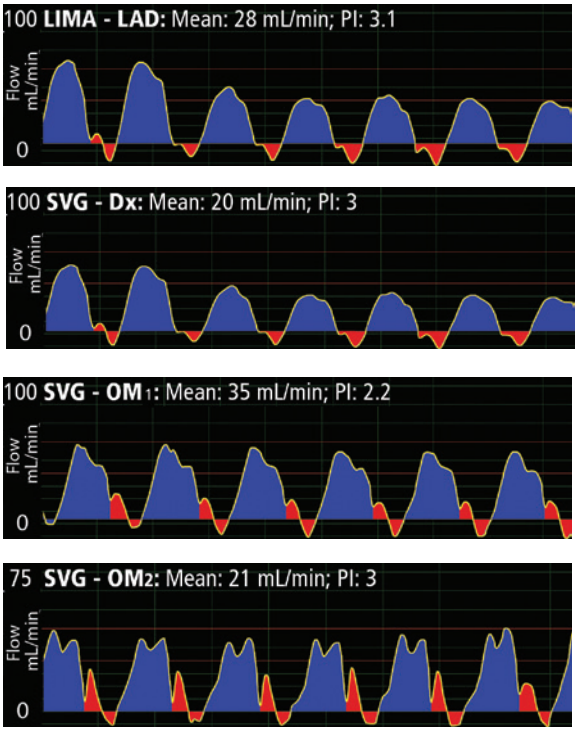


Fig. 5.19: Four grafts with acceptable mean flows and PIs but unusual waveforms with large diastolic components.

Case Summary: Off-CPB CABG; Four Bypass Grafts; 66-year-old male			
Flow Measurement	**Mean Flow** (mL/min)	**Pulsatility Index (PI)**	**Waveform**
LIMA - LAD	28	3.1	Unusual but acceptable
SVG - Dx	20	3	Unusual but acceptable
SVG - OM1	35	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.

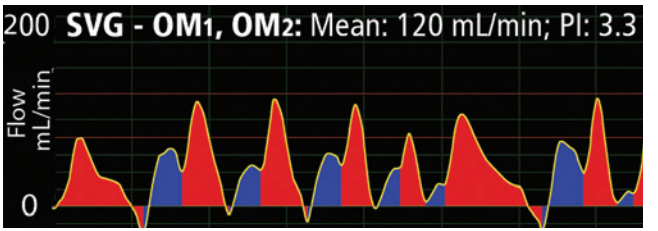


Fig. 5.20: This 17-year-old Y graft to the OM1, OM2 exhibited phenomenal flow of 120 mL/min in a 90-year-old woman.

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.

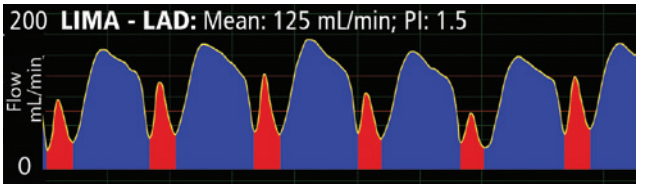


Fig. 5.21: Excellent LIMA - LAD graft flow and diastolic dominant waveform in a 58-year old patient.

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.

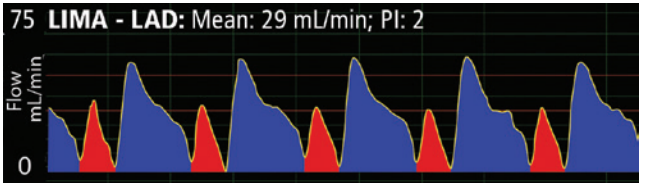


Fig. 5.22: LIMA - LAD graft flow in a 66-year old patient was accompanied by a classic diastolic dominant left heart waveform.

V. CABG Case Reports cont.

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).

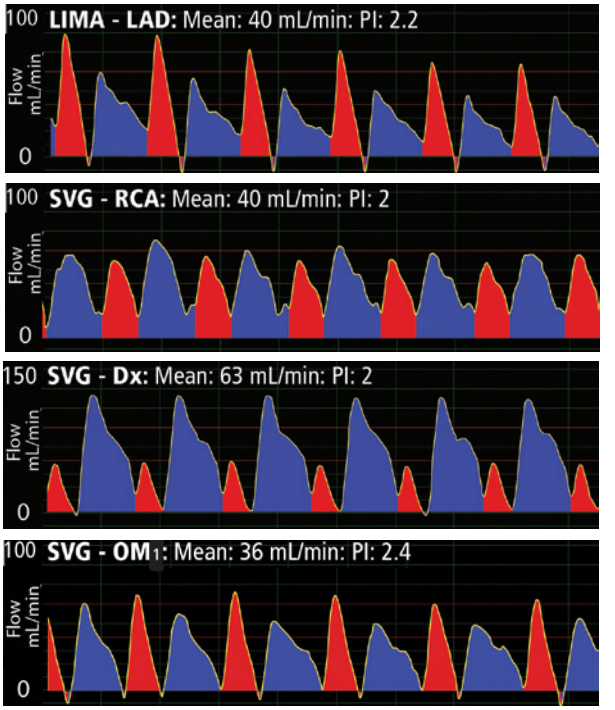


Fig. 5.23: All four grafts in this CABG patient exhibits good flow, acceptable PIs and excellent waveforms.

Case Summary: CABG: 83-year-old female with multi-vessel disease				
Flow Measurement	**Post Bypass Mean Flow** (mL/min)	**PI**	**Waveform Analysis**	**Analysis**
LIMA - LAD	40	2.2	Systolic/diastolic profile	Good graft
SVG - RCA	40	2	Systolic/diastolic profile	Good graft
SVG - Dx	63	2	Systolic/diastolic profile	Good graft
SVG - OM1	36	2.4	Systolic/diastolic profile	Good graft

V. CABG Case Reports cont.

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.

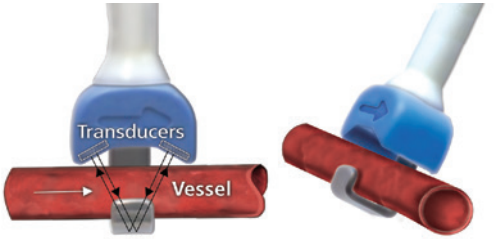
Appendix A: Transit-time Ultrasound Technology

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.

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.



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.

DOWNSTREAM TRANSIT-TIME CYCLE

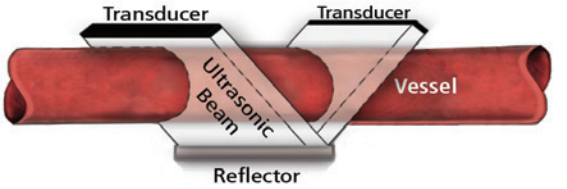
The same sequence is repeated, but with the transducers transmitting

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.

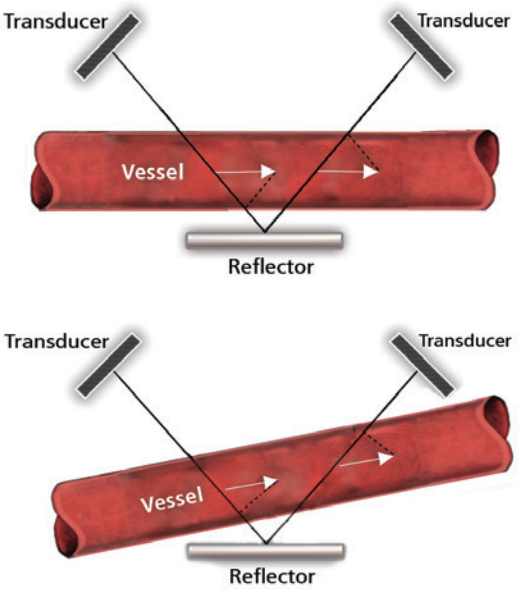
and receiving functions reversed so that the flow is bisected by an ultrasonic wave in the downstream direction. The Flowmeter derives and records from this transmit-receive sequence an accurate measure of the transit time it takes for the wave of ultrasound to travel from one transducer to the other.

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.



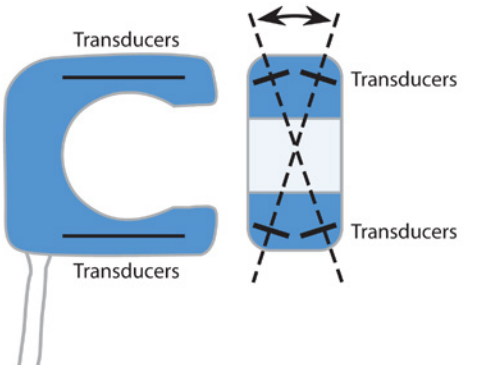
The vessel is positioned within a beam that fully and evenly illuminates the entire blood vessel. The transit time of the wide beam then becomes a function of the volume flow intersecting the beam, independent of vessel dimensions.



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: Comparison of Modalities

Surgical exposure presents an opportunity to analyze and safeguard the quality of surgery. Surgeons who follow best practices call for using this opportunity to evaluate the quality of each newly constructed bypass. Coronary artery bypass graft assessment methods include: intraoperative angiography, transit-time ultrasound and intraoperative fluorescence imaging (IFI). Other assessment methods might include pencil-tip Doppler, intraoperative color Doppler, or simply tactile assessment of the pulse and the bruit of the flow, simple inspection of the quality of the anastomosis and the course of the bypass conduit. The chart below compares and contrasts these primary modalities used by surgeons to assess the quality of a new graft bypass. Descriptions of each modality follow including color Doppler Ultrasound, pencil-tip Doppler and Observation of Pulse.

Modality	Intraoperative Angiography	Transit-time Ultrasound	Intraoperative Fluorescence Imaging (IFI)
Parameter	Velocity & Cross-section	Volume Flow	Velocity & Cross-section
Advantages[1]	Gold Standard	Proven, objective, simple, safe, cost effective, widely available	Simple, safe, expeditious, repeatable
Limitations[1]	Needs "hybrid" OR and catheter skills.	Non-visual, assessment impacted by other factors than graft patency such as competitive flow, blood pressure and peripheral resistance	Only semi-quantitative assessment of graft flow; does not show precise anastomotic quality, suboptimal image of pedicled grafts and intramyocardial coronary arteries, limited experience
Unit of Measurement	subjective	mL/min	subjective
Sensitivity	high	high	high
False Positive Rate	subjective	rare	occasional
Time per measurement	15-60 min	1 min	15-60 min

Sensitivity: How well the test identifies the presence of a correctable technical problem.
False Positive Rate: Does the test indicate a problem with a graft when none exists?

Appendix B: Comparison of Modalities cont.

Intraoperative Angiography

Conventional intraoperative angiography is considered the gold standard modality for detection of stenotic disease and is used to determine the need for bypass grafts. Although angiography has the appeal of authority and familiarity, the intraoperative intervention rate using angiography is much greater than with other modalities (e.g., 15%[2], 42%[3]). Calafiore[4] reports reversal of abnormalities detected with angiography, and Mack[5] recommends "practice of conservative management with observation, only if no ischemia is detected." With this method the surgeon can only assess indirectly (from how fast the contrast medium travels through the vessels) the level of flow though the bypasses.

Transit-Time Ultrasound

Transit-time ultrasound flowmetry provides quick, direct (real-time), quantitative measurements of pulsatile and average flow by applying a Perivascular Flowprobe around an exposed vessel or bypass graft. Non-constrictive Flowprobes require no direct contact with the vessel or graft. While angiography detects constrictive lesions, flowmetry detects their effect on flow. Transit-time ultrasound flowmetry documents the efficacy of surgery. Studies have reported that flowmetry is effective in detecting stenoses of 75% or more[6].

Intraoperative Fluorescence Imaging (IFI)

IFI evaluates anatomy. Based on the fluorescent properties of indocyanine green (ICG) dye, IFI captures the fluorescence with a near infrared video camera after 1 mL of ICG has been injected into a central venous catheter, ascending aorta, or bypass circuit. After activation of the laser power, images of the graft and native coronary arteries are immediately captured. A major limitation to this technique is that it requires direct "line of sight" so that the heart needs to be moved from its native position. Other issues include limited tissue penetration and imprecise imaging of an anastomosis.[1]

Color Doppler Ultrasound

Intraoperative color Doppler combines views of stenotic lesions with direct measurement of flow. Its measurement accuracy is a compromise and inferior intraoperative diagnostic precision has been reported.[1] The transsectional view is more localized and of a lesser resolution than angiography, and its volumetric flow measurement capability is inferior to transit-time flow because the device measures flow velocity and vessel diameter separately to calculate volume flow. However, a trained operator will find benefits in having flow velocity (cm/sec), volume flow (mL/min) and cross sectional data all considered in the analysis of bypass

Appendix B: Comparison of Modalities cont.

patency. Its cost and time to take a measurement is comparable to angiography.

Pencil-tip Doppler Ultrasound Sensors

Pencil-tip ultrasound sensors provide a "swoosh-swoosh" sound related to blood flow velocity and angle between probe and vessel. The method is non-quantitative, and the whole length of the vessel would need to be scanned with a pencil-tip sensor to find possible lesions that would increase flow velocity. Such velocity measurements are generally non-directional, and a constricted systolic flow pattern may sound similar to a non-constricted diastolic pattern. Pencil-tip Doppler is less costly than transit-time, but has much lower diagnostic accuracy and precision.

Feel the Pulse

A pulse only indicates that a vessel connects to the heart. It is quick and inexpensive, but non-quantitative. No objective way of administering this "test" is documented in the scientific literature[7] and its results do not withstand scrutiny. If a partial occlusion exists, the proximal pulse will increase, the distal pulse will decrease. Determining arterial obstruction from the pulse is a tenuous art form at best, but may provide the experienced surgeon with qualitative information in cases where the vessel can be palpated.

1. Mack MJ, "Intraoperatiive Coronary Graft Assessment," Curr Opin Cardiol 2008; 23: 568-572.
2. Elbeery JR et al, "Intraoperative MIDCABG Arteriography via the Left Radial Artery: A Comparison with Doppler Ultrasound for Assessment of Graft Patency," Ann Thorac Surg 1998; 66: 51-5.
3. Goldstein JA et al, Intraoperative angiography to assess graft patency after minimally invasive coronary bypass. Ann Thorac Surg 1998; 66(6): 1978-82.
4. Calafiore AM et al, "Left Anterior Small Thoracotomy (LAST): Midterm Results in Single Vessel Disease," J Cardiac Surg 1998; 13: 306-9.
5. Mack MJ et al, "Results of graft patency by immediate angiography in minimally invasive coronary artery surgery, Ann Thorac Surg. 1999; 68(2): 383-9.
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7. Canver C et al, "Clinical Importance of Measuring Coronary Graft Flows in the Revascularized Heart. Ultrasonic or Electromagnetic?" J. Cardiovasc Surg (Torino)1997; 38(3): 211-5.
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Appendix C: Catalog of Waveforms

Native Vessels

LIMA: Fig. 4.1, p. 65

LAD: Fig. 4.2, p. 66

RCA: Fig. 4.3 p. 66

Bypasss Grafts

Grafts to the LAD

LIMA - LAD: Case example, p. 3; Fig. 2.3b, p. 10; Fig. 2.5, p. 17; Fig. 2.11, p. 20; Fig. 2.12, p. 21; Case example, p. 24; Fig. 2.14, p. 26; Fig. 2.19, p. 32; Fig. 2.20, p. 33; Fig. 2.21, p. 34; Figs. 2.25-2.26, p. 37; Figs. 2.31-2.34, p. 38; Figs. 2.37, p. 42; Fig. 2.38, p. 43; Figs. 3.8, 3.9, p. 55; Fig. 3.16, p. 60; Fig. 3.20, p. 63; Fig. 4.4, p. 67; Fig. 5.2, p. 82; Fig. 5.7, p. 87; Fig. 5.12, p. 90; Fig. 5.13, p.91; Fig. 5.16, p. 94; Fig. 5.18, p. 95; Fig. 5.19, p. 96; Figs. 5.21, 5.22, p. 97; Fig. 5.23, p. 98.

RIMA - LAD: Fig. 2.29, p. 37; Case example, p. 41, Fig. 4.8, p. 69.

RAD - LAD: Fig. 4.12, p. 70; Fig. 5.4 p. 84.

SVG - LAD: Fig. 4.15, p. 72.

Grafts to the Cx

LIMA - Cx
Figs. 2.6, p. 17; Fig. 2.13, p. 23; Fig. 2.16, p. 27; Figs. 2.27, 2.28 p. 37; Figs. 3.8, 3.8, p. 55; Fig. 4.6, p. 68; Fig. 5.1, p. 81; Fig. 5.5, p. 85.

RIMA - Cx: Fig. 4.9, p. 69.

RAD - Cx: Figs. 4.13, p. 61.

SVG - Cx: Fig. 2.23, p. 35; Fig. 2.24, p. 36; Fig. 2.35, p. 39; Fig. 2.39, p. 43; Fig. 4.17, p. 73; Fig. 5.6, p. 86; Fig. 5.10, 5.11, p. 89.

Grafts to the Dx

LIMA - Dx: Fig. 4.5, p. 67.

RIMA - Dx: Fig. 2.22, p. 34; Fig. 4.11, p. 70;

SVG - Dx: Fig. 2.9, p. 20; Fig. 4.25, p. 77; Fig. 5.7, p. 87; Fig. 5.9, p. 88; Fig. 5.13, p. 91; Fig. 5.18, p. 95; Fig. 5.19, p. 96; Fig. 5.23, p. 98.

Grafts to the OM

LIMA - OM: Fig. 4.7, p. 68.

RIMA - OM: Fig. 3.16, p. 60; Fig. 4.10, p. 69; Fig. 5.16, p. 94.

RAD - OM: Fig. 2.10, p. 20; Fig. 4.14, p. 71, Fig. 5.3, p. 83, Fig. 5.18, p. 95.

SVG - OM: Fig. 2,3a, p. 10; Fig. 2.7b, p. 19; Fig. 3.7, p. 54; Fig. 4.18, p. 73; Fig. 4.25, p. 79; 5.12, p. 90; Fig. 5.13, p. 91; Fig. 5.18, p. 95; Fig. 5.19, p. 96; Fig. 5.20, p. 97; Fig. 5.23, p. 98.

Graft to the Ramus

Fig. 4.16, p. 72

Grafts to the RCA

RIMA - RCA: Fig. 2.15, p. 27; Fig. 2.16, p. 27; Fig. 2.30, p. 38; Figs. 3.21, p. 64; Fig. 4.20, p. 74; Fig. 5.14, p. 92.

RAD - RCA: Fig. 2.18, p. 32; Fig. 3.15, p. 60; Fig. 4.21, p. 74.

SVG - RCA: Fig. 2.2, p. 10; Fig. 2.15, p. 26; Fig. 3.12, p. 57; Fig. 3.13, p. 58; Fig. 4.22, p. 75; Case example p. 78; Fig. 5.8, p. 88; Fig. 5.17, p. 95; Fig. 5.23, p. 98.

Grafts to the PDA

RAD - PDA: Fig. 4.18, p. 61; Fig. 5.16, p. 94.

SVG - PDA: Fig. 2.4, p. 11; Fig. 2.8, p. 20; Fig. 4.24, p. 76; Fig. 5.12, p. 90; Fig. 5.17, p. 95; Case example p. 78.

SVG - LPDA: Fig. 4.19, p. 73.

Grafts to the PVB

SVG - PVB: Fig. 3.17, p. 61; Fig. 4.19, p. 73; Fig. 4.23, p. 75; Fig. 5.15, p. 93.

Y Grafts

SVG - Dx, OM: Fig. 4.24, p. 77.

SVG - PDA & PLB: Fig. 5.15, p. 93.

SVG - RCA & PDA: Case example p. 78.

SVG - OM1, OM2: Fig. 5.20, p. 97.

Sequential Grafts

SVG - OM1, OM2: Fig. 4.25, p. 79.

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