

# Appendix



## A. Comparison of Measurement Modalities

	Transit-time Flow	Electro-magnetic	Angio-graphy	Color Doppler Ultrasound	Pen-tip Doppler	Observation of Pulse
Measured Parameter	Volume Flow	Volume Flow	Vessel cross-section	Velocity & cross-section	Flow Velocity	Tactile Sensation
Measurement Unit	mL/min	mL/min	mm	cm/sec, mm	Sound Pitch (kHz)	none
Measurement Tolerance	± 15%	± 15%	± 0.3 mm	± 30%, ± 0.3 mm	not, quantitative	not, quantitative
Sensitivity	high	medium	high	medium	medium	low
False Positive Rate	low	medium	medium	low	medium	high
Ease of Use	moderate	moderate	complex	complex	easy	easy
Time per Measurement	1 min	3 min	15-60 min	10-30 min	2 min	5 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?

### Intraoperative Angiography

When combined with other tests and clinical signs reported by the patient, angiography is the gold standard modality for stenotic disease. Although angiography has the appeal of authority and familiarity, the intraoperative intervention rate using angiography is much greater than with other modalities (e.g., 31%<sup>1</sup>, 15%<sup>2</sup>, 42%<sup>3</sup>). Calafiore<sup>4</sup> reports reversal of abnormalities detected with angiography, and Mack<sup>5</sup> recommends “practice of conservative management with observation, only if no ischemia is detected.”

### Transit-Time Flowmetry

Transit-time ultrasound flowmetry measures true volume flow (mL/min). While angiography detects constrictive lesions, flowmetry detects the combined effect of all lesions on flow to document the efficacy of the bypass procedure. Studies have documented that flowmetry is effective in detecting stenoses of 75% or more.<sup>6</sup> Sometime referred to as “Doppler,” transit-time flowmetry should not be confused with true Doppler.

<sup>1</sup>Lazarra et al, Ann Thorac Surg 1999  
<sup>2</sup>Elbeery et al, Ann Thorac Surg 1997  
<sup>3</sup>Goldstein et al, Ann Thorac Surg 1998

<sup>4</sup>Calafiore et al, J Card Surg 1998  
<sup>5</sup>Mack et al, Ann Thorac Surg 1999  
<sup>6</sup>Jaber et al, Ann Thorac Surg 1998

## A. Comparison of Measurement Modalities *cont.*

### Electromagnetic Flowmetry

Like transit-time ultrasound, electromagnetic (EM) flowmetry uses perivascular flow sensors to directly measure volume flow in mL/min. Its diagnostic capabilities match those of transit-time flowmetry, but EM suffers from zero-stability, motion artifacts, and interference from a heart's electrical activity, necessitating extra precautions to assure measurement quality.<sup>1</sup> Popular in the 1970s, this method has now been replaced by transit-time ultrasound.

### Color Doppler Ultrasound

Intraoperative color Doppler combines views of stenotic lesions with indirect measurement of flow. Its measurement accuracy is a compromise between angiography and transit-time flow measurement. Inferior intraoperative diagnostic precision has been reported.<sup>2</sup> Doppler's trans-sectional view is more localized and with less resolution than angiography, and the volumetric flow measurement capability is inferior to transit-time flowmetry. This is 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 patency. Its cost and measurement time are comparable to angiography.

### Pen-tip Doppler Ultrasound Sensors

These provide a sound related to blood flow velocity and the angle between probe and vessel. The method non-quantitative. The entire length of the vessel needs to be scanned to find possible lesions that would increase flow velocity. The velocity measurements are generally non-directional, and a constricted systolic flow pattern may sound similar to a non-constricted diastolic pattern. This method is less costly than transit-time, but more time-consuming with much lower diagnostic accuracy and precision.

### “Feel the Pulse”

The surgeon manually constricts the bypass. The pulse can be felt, and blood can be felt rushing through the constriction. The method is quick and inexpensive, but non-quantitative. No objective way of administering this “test” is documented in the scientific literature, and its results do not withstand scrutiny.<sup>3</sup>

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<sup>1</sup>Cancer et al, J Cardiothorac Surg 1997

<sup>2</sup>Elbeery et al, Ann Thorac Surg 1998

<sup>3</sup>D'Ancona et al, Heart Surgery Forum 2000

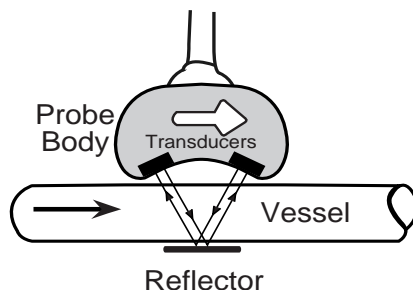
## B. Transit-Time Ultrasound Technology<sup>1</sup>

A Transonic® perivascular flowprobe (Fig. A-1) consists of a probe body which houses ultrasonic transducers and a fixed acoustic reflector. The transducers are positioned on one side of the vessel or tube under study and the reflector is positioned at a fixed position between the two transducers on the opposite side. Circuitry directs a flowprobe through upstream and downstream cycles.

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 flow and total transit time is decreased by the same flow-dependent amount. The Transonic flowmeter subtracts the downstream transit time from the upstream transit time utilizing wide-beam ultrasonic illumination. This difference of integrated transit times is a measure of volume flow.

### Upstream Transit-Time Measurement Cycle

An electrical excitation causes the downstream transducer to emit a plane wave of ultrasound. This ultrasound wave intersects the vessel or tubing under study in the upstream direction, then bounces off the fixed "acoustic reflector," again intersects the



**Fig. A-1:** Schematic view of the perivascular ultrasound volume flowsensor. 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 took 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 measurement of volume flow, not velocity.

<sup>1</sup>Drost, C.J., "Vessel Diameter-Independent Volume Flow Measurements Using Ultrasound", Proceedings San Diego Biomedical Symposium, 17, p.299-302, 1978. U.S. PATENT 4,227,407, 1980.

## B. Transit-Time Ultrasound Technology *cont.*

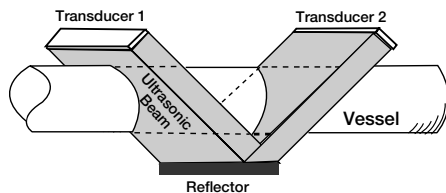
vessel and is received by the upstream transducer where it is converted into electrical signals. From these signals, the flowmeter derives an accurate measure of the "transit-time" it took for the wave of ultrasound to travel from one transducer to the other.

### Downstream Transit-Time Measurement Cycle

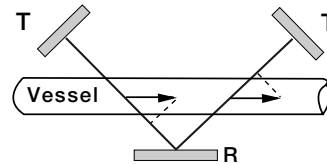
The same transmit-receive sequence is repeated, but with the transmitting and receiving functions of the transducers reversed so that the flow under study is bisected by an ultrasonic wave in the downstream direction. The flowmeter again derives and records from this transmit-receive sequence an accurate measure of transit time.

### Wide Beam Illumination

One ray of the ultrasound beam undergoes a phase shift in transit time proportional to the average velocity of the liquid times the path length over which this velocity is encountered. With wide-beam ultrasound illumination (Fig. A-2), the receiving transducer sums (integrates) these velocity-chord products over the vessel's full width to yield 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 (Fig. A-3). Ultrasound 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 probes even when the vessel is smaller than the acoustic window.



**Fig. A2:** The vessel is placed 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.



**Fig. A3:** Angle insensitivity of the flowprobe:  
T = transducer; R = reflector  
The ultrasound beam intersects the vessel twice on its reflective pathway. During each intersection, the transit time of the beam is modified by a vector component of the flow. The full transit time of the ultrasound beam senses the sum of these two vector components, that is, the flow itself.

## C. Abstract

### **REDUCTION OF TECHNICAL GRAFT PROBLEMS UTILIZING ULTRASONIC FLOW MEASUREMENTS<sup>1</sup>**

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**Purpose:** Graft patency is the crucial end point in CABG surgery. Factors leading to graft failure are well documented with technical errors remaining the most frustrating. In an effort to detect unacceptable grafts in the operating room, where correction can be accomplished, ultrasonic flow measurements have been introduced.

**Method:** Once flow has been established in a graft, measurements are performed utilizing ultrasonic technology. The probes are placed around the graft and the volume of flow is measured by ultrasonically intersecting the entire width of the vessel both in an upstream and downstream cycle. A printout and acoustic signal are generated which are able to be interpreted. If flow is inadequate, an algorithm is established to determine the cause of the problem. The effects of poor run-off, competitive flow and possible spasm are differentiated from technical errors. The latter are then corrected. In patients done on CPB in isolated or combined procedures graft flows are 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 can be instituted at that time. All patients have oximetric Swan-Ganz catheters, TEE probes and ECG event analysis in place during the entire procedure. Curves representing poor flow are correlated with these parameters.

**Results:** This technique has been utilized in over 1,000 cases. The most recent 500 cases were analyzed in an effort to eliminate effects of learning curve or interpretation of the data. There were 3.2 grafts/patient. Ninety-five (95%) percent of the isolated CABGs were done as OPCABS. Of the 1,600 grafts evaluated, 248 demonstrated questionable curves: 82 technical problems, 93 with competitive flow, 73 poor run-off. Revision of the 82 technical problems resulted in improvement in all grafts; however, one patient died of an MI directly related to that graft. 17 of the competitive flow grafts and 25 poor run-off grafts were revised in the early portion of the series with no significant change in flow — over the past 300 cases this pattern of curves have become more identifiable and revision is avoided. The majority of technical problems occurred in arterial grafts - 67/82. Proximal anastomotic problems occurred in 4 cases — 3 of which were “Y” grafts. The LAD system was involved in 45, the circumflex 19, and RCA, 18. The only death directly related to an intra-op MI occurred with a CX problem that was corrected but not in a timely fashion. 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 complication 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.

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<sup>1</sup>Mindich et al, NY Thorac Society, 2001

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## F. List of Flow Waveforms

### Native Vessels

LIMA	Left Coronary Artery	Right Coronary Artery
Fig. 5-1 (p 42)	Fig. 5-2 (p 42)	Fig. 5-2 (p 42)

### Grafts → LAD

#### LIMA → LAD

Fig. 2-8 (p 9); Fig. 2-9 (p 9); Fig. 2-16 (p 13);  
Fig. 2-20 (p 15); Fig. 3-2 (p 16); Fig. 3-8 (p 22);  
Fig. 3-13 (p 26); Fig. 3-14 (p 27);  
Fig. 3-16 (p 27); Fig. 3-18 (p 28);  
Fig. 3-19 (p 29); Fig. 3-20 (p 30);  
Fig. 3-22 (p 33); Fig. 3-26 (p 36);  
Fig. 3-27 (p 37); Fig. 4-3 (p 40); Fig. 5-4 (p 43);  
Fig. 5-5 (p 43); Fig. 6-1 (p 53); Fig. 6-4 (p 56);  
Fig. 6-6 (p 58); Fig. 6-8 (p 60); Fig. 6-10 (p 62)

#### RIMA → LAD

Fig. 3-22 (p 22); Fig. 5-9 (45)

#### RAD → LAD

Fig. 3-22 (p 22); Fig. 5-9 (45)

#### SVG → LAD

Fig. 5-16 (p 47)

### Grafts → Cx

#### LIMA → Cx

Fig. 2-8 (p 9); Fig. 2-9 (p 9); Fig. 3-9 (p 22);  
Fig. 3-10 (p 23); Fig. 3-22 (p 33);  
Fig. 5-7 (p 44);

#### RIMA → Cx

Fig. 5-10 (p 45)

#### RAD → Cx

Fig. 5-14 (p 46)

#### SVG → Cx

Fig. 3-21 (p 31); Fig. 3-24 (p 35);  
Fig. 3-27 (p 37); Fig. 5-17 (p 47);  
Fig. 6-2 (p 54)

### Grafts → Dx

#### LIMA → Dx

Fig. 5-6 (p 44)

#### RIMA → Dx

Fig. 3-20 (p 30); Fig. 5-12 (45)

#### RAD → Dx

Fig. 3-20 (p 30); Fig. 5-12 (45)

#### SVG → Dx

Fig. 3-13 (p 26); Fig. 4-2 (p 39);  
Fig. 4-4 (p 40); Fig. 5-25 (p 51);  
Fig. 6-9 (p 61); Fig. 6-10 (p 62)

### Grafts → OM

#### LIMA → OM

Fig. 5-8 (p 44)

#### RIMA → OM

Fig. 5-8 (p 44)

#### RAD → OM

Fig. 5-15 (p 46)

#### SVG → OM

Fig. 2-6 (p 8); Fig. 3-5 (p 20); Fig. 3-12 (p 25);  
Fig. 4-2 (p 39); Fig. 5-18 (p 47);  
Fig. 5-25 (p 51); Fig. 5-26 (p 52);  
Fig. 6-8 (p 60); Fig. 6-9 (p 61); Fig. 6-10 (p 62)

### Grafts → RCA

#### RIMA → RCA

Fig. 2-20 (p 15); Fig. 3-23 (p 34);  
Fig. 5-20 (p 48); Fig. 6-5 (p 57);

#### RAD → RCA

Fig. 2-15 (p 12); Fig. 2-16 (p 13);  
Fig. 3-17 (p 28); Fig. 5-13 (p 46);  
Fig. 5-19 (p 48)

#### SVG → RCA

Fig. 2-11 (p 10); Fig. 2-13 (p 11);  
Fig. 3-4 (p 20); Fig. 3-6 (p 20); Fig. 3-15 (p 27)  
Fig. 3-15 (p 27); Fig. 5-21 (p 49);  
Fig. 6-3 (p 55); Fig. 6-9 (p 61); Fig. 6-10 (p 62)

### Grafts → PDA

#### RAD → PDA

Fig. 6-6 (p 58)

#### SVG → PDA

Fig. 3-13 (p 26); Fig. 5-23 (p 50);  
Fig. 5-24 (p 50); Fig. 6-7 (p 59); Fig. 6-8 (p 60)

### Grafts → PVB

#### SVG → PVB

Fig. 2-13 (p 11); Fig. 5-22 (p 49)

### Grafts → PLV

#### SVG → PLV

Fig. 2-17 (p 13); Fig. 6-7 (p 59)