

# The Electromagnetic Flowmeter and Its Use in the Operating Room

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## *History of Blood Flow Measurement*

The first attempt to measure blood flow was by Chauveau, et al. in 1869.<sup>1</sup> This was a mechanical device in which the moving blood was made to strike a mechanical linkage which moved in relation to the velocity of the blood. A variety of other mechanical devices were designed to measure blood flow in the late 1800's including the Stromuhr of Carl Ludwig<sup>2</sup> and the differential pressure flowmeter designed by Otto Frank.<sup>3</sup> As late as 1942 an electromechanical rotameter was described by Gregg for measuring blood flow.<sup>4</sup>

All of the above methods had one common problem. It was necessary to cut the blood vessel in half, and insert cannulating tubing to bring the blood into the mechanical flowmeter and then back into the body. In addition, mechanical flowmeters interfered with the free movement of the blood. Consequently records were obtained which gave only an approximation of blood flow in ml/min, and did not show sudden flow changes with time. Because these mechanical flowmeter techniques required extensive surgical exposure and transverse section of the vessel to be studied, and produced moderate to severe obstruction of the flow, it was not possible to measure blood flow in human vessels.

The rapidly growing electronics industry paved the way for deBurgh-Daly in 1926<sup>5</sup> and Kolin in 1936,<sup>6</sup> who were the first to develop an extravascular, non traumatic electromagnetic flowmeter. This device was placed around the outside of an exposed vessel and did not require cutting or otherwise damaging the vessel. Kolin is generally credited with developing the first electromagnetic blood flowmeter, and this device is often used for blood flow measurement in animals and man at the time of surgery.

## *Principle of Electromagnetic Blood Flow Meters*

The principle of operating of an electromagnetic flowmeter is simple, but using it to measure blood flow has been a little more difficult. The basic principle is one commonly mentioned in an elementary physics course. It is called Faraday's Law, which states that when an electrical conductor moves at right angles to the lines of force of a magnetic field, a voltage is induced in the conductor.<sup>7</sup> This is expressed by Faraday's Law as  $e = blv \times 10^{-8}$  volts where B is the strength of the magnetic flux density in Gauss, l is the length of moving conductor, and v is the mean velocity of the moving conductor in cm/sec.

This principle is applied to blood flow as in Figure 1A. A cylinder is placed in the magnetic field. Two electrodes are placed at right angles to the flux, and a conducting liquid passed through the cylinder. That strip of liquid which appears

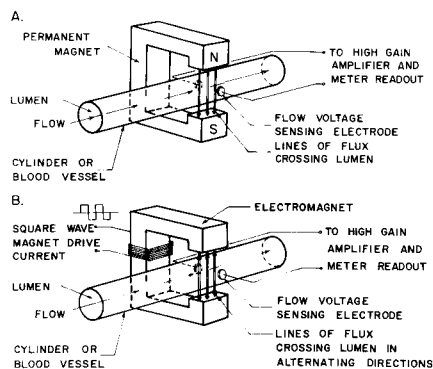


Figure 1—Schematic Diagram Showing Faraday's Principle Applied to Blood Flow Measurement

Figure 1-A shows the application of Faraday's Law using a permanent magnet to produce the magnetic field. The flow voltage is generated and picked up by the flow voltage sensing electrodes, as the conductive liquid moves through the field. This voltage will be of constant polarity for a given flow direction.

Figure 1-B shows a similar configuration except that the flux field is produced by an electromagnet and alternates with the square wave driving current. When there is flow of liquid through the alternating magnetic field, an alternating flow dependent voltage will be picked up by the electrodes. This is amplified and displayed as flow in ml/min.

between the electrodes at any given time will represent the moving conductor. The velocity of the liquid through the tube will determine  $v$  in Faraday's equation. The same principle applies if an unopened vessel is placed inside the cylinder, since the vessel wall is conductive. The voltage generated would be proportional to the flow velocity and would be detected by electrodes in contact with the vessel wall.

This was basically the technique used by Kolin in 1936.<sup>6</sup> At that time the first of several problems became apparent. With a constant flux field and with blood flow always in the same direction through the cylinder, one of the electrodes would always be positive and the other one always negative. This produced polarization at the electrodes with migration of the ions in the blood to the oppositely charged electrode. This would mean that charged particles in the blood would collect near the electrodes, interfering with the flow measurement and also may precipitate clotting. In addition to this problem, permanent magnets were not very strong thus the voltages generated by normal blood flow velocities were quite small and difficult to measure. These problems were solved by using an electromagnet instead of the permanent magnet. This is shown in Figure 1-B. The magnet is driven by a pulsed square wave current such that the direction of the magnetic field alternates in time, and an alternating voltage is produced at the electrodes. This alternating voltage is still linearly related to the velocity of the blood. This "flow signal" voltage which is directly proportional to blood flow through the magnetic field, is amplified, averaged and displayed by a direct reading meter.

Commercial blood flowmeter systems have two basic parts, as shown in Figure 2. The flowmeter is the metal cabinet that has the electronic circuitry which supplies the current to energize the electromagnet and the high gain amplifier that amplifies the small flow voltages picked up by the electrodes. The flowmeter also has some complex circuitry which removes artifacts and error signals, and converts the flow signal to a volume flow in ml/min which is displayed on a flow indicator meter, or as a digital readout. The second part of a flowmeter system is the flow probe. This is the electromagnet and electrodes encapsulated in epoxy, with a lumen in which the vessel is placed as in Figure 2-A. The flowprobe has a flexible cable, and a connector to connect it to the flowmeter as also shown in Figure 2-A.

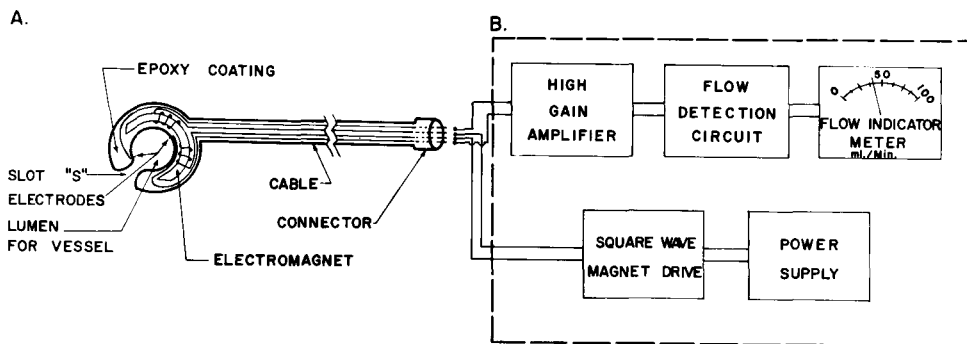


Figure 2-A.—*Electromagnetic Flowprobe*

Pictorial diagram of an electromagnetic flowprobe, with an electromagnet to produce the magnetic field, two platinum or silver flow voltage sensing electrodes and a flexible cable with a connector for connecting the flowprobe to the flowmeter. The blood vessel is slipped into the lumen through the slot "s".

Figure 2-B—*Block Diagram of Electromagnetic Flowmeter*

The dotted line represents the metal cabinet which is the flowmeter and contains the necessary electronic circuits and the flow indicator meter. There is a high gain differential amplifier to amplify the microvolt signal picked up by the electrodes, and a square wave magnet drive current source. The flow indicator meter has a scale calibrated to read flow in ml/min. Some flowmeters have a digital readout which displays the flow value in ml/min.

### Measurement of Blood Flow

The basic principles of blood flow measurements will be described, which apply to any of the commercially available electromagnetic blood flowmeters. A flowprobe is selected which has a lumen approximately 5% smaller than the outside diameter of the vessel to be studied. The blood vessel is dissected out and cleaned of excess adventitia, and then slipped into the lumen of the flowprobe through the slot "S" shown in Figure 2-A. The blood vessel must fit tightly in the lumen of the probe so that the electrodes make good electrical contact with the vessel wall. However, the probe should not fit so tightly that the vessel is stenosed more than 10% as turbulence may be produced. Therefore, a number of probes are normally purchased with a range of lumen diameters to closely match the outside diameter of the vessel to be studied.

There are several electronic adjustments to be made before each flow measurement, which are similar on most commercial flowmeters. First there are artifact voltages produced by the changing magnetic field, and these are minimized by adjusting a knob on the flowmeter usually called a "Null." This is adjusted until the meter reads zero or near zero. This means that artifact and error signals have been "nulled" or minimized. A second adjustment is made which establishes a zero setting, or zero reference. This consists of adjusting a second knob, normally called a "zero" control, until the flow indicator meter reads zero flow. Finally, one turns a function switch to the "flow" position and blood flow through the intact artery can be determined in ml/min from the flow indicator meter scale or on a digital readout. In addition to reading the average or mean flow in ml/min most flowmeters have an output cable that permits one to couple the output of the flowmeter into a high impedance DC direct writing recorder. This allows one to obtain phasic or beat by beat recordings of blood flow comparable to the way the electrocardiogram is recorded.

With most commercial flowmeters, the probes can be purchased precalibrated. This means that when certain adjustments are made on the flowmeter the actual

flow can be measured without a special calibration procedure being first performed by the operator. However, there is no guarantee that the electronic equipment will maintain the accuracy of the factory precalibration. Therefore, it is strongly recommended that the individual responsible for the operation of the flowmeter periodically check the calibration as described below.

### *Probe Calibration and Accuracy Checks*

In order to insure accuracy in blood measurements on patients the flowprobe calibration should be checked approximately every 4 to 6 weeks. In addition, by going through the calibration procedure the operator becomes more familiar with the characteristics and use of the flowmeter. A typical calibration method is shown in Figure 3. The flow probe is first placed in the saline bath and the null and zero adjustments are made. Then with the flowmeter function switch in the flow position, the flowprobe is swished back and forth so that saline passes back and forth through the lumen of the flowprobe. This should produce an oscillation of the flow indicator meter, and back and forth movement of the pen in the direct writing recorder as

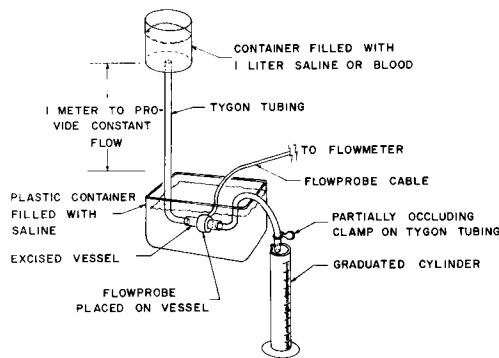


Figure 3—*Calibration of Electromagnetic Flowprobe*

Pictorial diagram of a flowprobe calibration technique. The flowprobe is placed on a section of excised artery of suitable size which is attached at both ends to tygon tubing of appropriate size. The artery and its associated tygon inflow and outflow tubing, along with the flowprobe are submerged in a saline bath. The reservoir of blood or saline is placed approximately 1 meter above the artery to provide a suitable head of pressure to produce a relatively constant flow. There must be sufficient pressure within the artery to cause it to fit snugly inside the lumen of the flowprobe. The blood or saline is allowed to pass through the probe at various rates by adjusting the partially occluding clamp, and collected over timed intervals in the graduated cylinder.

shown in Figure 4-A. The flow signal produced shows flow above and below the zero reference point as the liquid is going in two directions through the lumen of the probe. Then the probe is held stationary in the saline and with the flowmeter function switch still in the flow position, the meter should read zero flow. This occurs because with the probe stationary, there is no saline passing through the lumen and the flow velocity is zero. If one reduces the velocity term in Faraday's equation to zero, then there is zero flow voltage generated and the flowmeter circuits have no flow induced voltage to measure. To check the accuracy of the zero reference in the flowmeter, one notes the meter reading with the probe at rest and then switches the flowmeter function switch to the "zero" position. This is an electronic zero built into most commercial flowmeters that allows one to determine the zero reference point without the necessity of stopping the flow through the vessel. There should be agreement within  $\pm 5\%$  between the electronic zero reading and the zero reading obtained with the flow probe at rest in the saline.

A section of excised blood vessel is attached to tygon tubing as illustrated in Figure 3. The probe is then placed on the section of excised vessel and blood or

saline is passed through the vessel at several rates and collected for timed intervals in a graduated cylinder. For example, if 50 ml of saline is collected in 30 seconds, then the flow rate =

$$F = \frac{\text{ml collected}}{\text{no. of seconds}} \times 60 = \frac{50 \text{ ml}}{30 \text{ sec.}} \times \frac{60 \text{ sec.}}{\text{min.}} = 100 \text{ ml/min}$$

The phasic flow record is shown in Figure 4-B. The flow indicator meter should also indicate a mean flow between 90 and 105 ml/min if the precalibration is working properly. Figure 4-C shows the phasic record obtained when the flow rate is doubled to 200 ml/min, and Figure 4-D shows the phasic flow obtained when the saline is sent through the vessel in the opposite direction at a rate of 100 ml/min. These records show that the flowmeter measures flow linearly in both directions. The values obtained with this type of calibration procedure can be plotted on the y axis of the record as shown on the left of Figure 4-A and may be used later to determine the average flow in ml/min when the probe is placed on blood vessels.

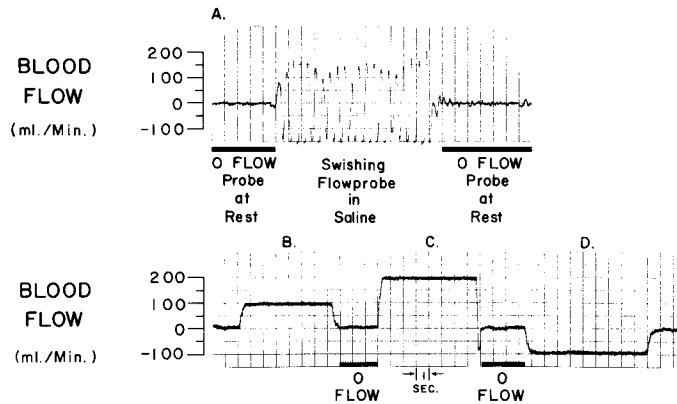


Figure 4-A—Flow Patterns Produced During Testing and Calibration

Phasic flow obtained by coupling the output of the flowmeter to a direct writing recorder, with the flowprobe at rest in the saline bath. In the center of the panel, the flowprobe is swished back and forth in the saline, causing the saline to move back and forth through the lumen of the flowprobe. This produces a characteristic flow signal which alternates above and below the zero line as saline is flowing through the probe in both directions. When the probe is again held stationary the flowprobe should read zero flow.

Figure 4-B

Phasic flow record obtained during the calibration procedure. Panel B shows the record obtained when 50 ml of saline were collected in 30 seconds. This is calculated to be a flow of 100 ml/min and is plotted on the y axis of Panel B. Panel C shows the record obtained when the flow was 200 ml/min and in Panel D the flow was 100 ml/min in the reverse direction. This information was used to graph the calibration scale shown on the left of Panel A and B.

### Phasic Arterial Blood Flow Patterns

The primary advantage of the electromagnetic flowmeter is that it can measure flow velocities that may change rapidly with time. This might be compared to measuring arterial pressure using a column of mercury, which would respond very slowly to changes in pressure and using the newer pressure transducers with a direct writing recorder system which gives a rapid and faithful reproduction of the changes in systolic and diastolic pressure with time. For example, if the flowprobe is placed on the femoral artery of a dog, the flow changes throughout the cardiac cycle as shown in Figure 5-A.

Femoral arterial pressure was obtained by inserting a cannula into the artery and the flow was obtained by placing a flowprobe of appropriate size on the artery

proximal to the pressure cannula. The pressure cannula was attached to a Statham p-23 pressure transducer and the flow is measured with a 3 mm flowprobe and a Statham SP 2201 electromagnetic flowmeter. The flow and pressure were then recorded on a Sanborn 150 direct writing recorder. As noted in Figure 5-A the changes in pressure throughout the cardiac cycle can be graphically displayed. There is a zero pressure reference point marked on the left of Figure 5, which is determined by turning off the pressure cannula and exposing the pressure transducer to atmospheric pressure. The pressure transducer and recorder are calibrated so that each 10 mm of pen deflection indicates an 80 mm Hg increment in pressure. If the pressure in the artery should go negative or below atmospheric pressure, the pen would deflect below the zero line. The phasic pressure pattern obtained shows how pressure in the artery varies with time.

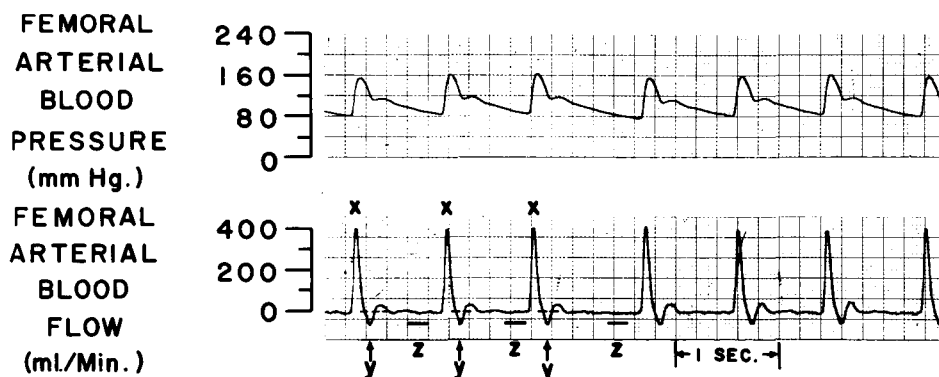


Figure 5—Femoral Arterial Blood Flow and Blood Pressure Changes

Femoral arterial blood pressure in an anesthetized dog obtained by placing a 20 gauge needle into the exposed femoral artery and attaching it to a pressure transducer. A flowprobe of suitable size is placed proximally on the artery and the flow and pressure recorded on a Sanborn direct writing recorder. Peak systolic pressure and maximum forward blood flow in the femoral artery occur at the points marked x. At the points marked y there is retrograde flow back up the femoral artery, and at points z the femoral artery flow is essentially zero.

The flow probe measures variation in blood flow velocity with time in a similar manner. A positive deflection from zero represents an increase in forward flow down the femoral and into the leg. Conversely any deflection of the recorder pen below the zero flow line represents retrograde flow back up the femoral as measured by the flowmeter. Peak systolic femoral arterial pressure and maximum forward flow velocity through the femoral artery occurs at points "x" in Figure 5. Early in the diastolic period at points "y", the flow in the femoral artery goes below the zero line representing retrograde flow up the femoral artery. This backflow is thought to occur because there is a pressure wave which is reflected back from the arteries in the leg and causes the pressure in the femoral artery to be momentarily greater than that in the central aorta. A pathologic cause of femoral arterial backflow was noted in patients with severe aortic insufficiency.<sup>8</sup> This backflow in the femoral artery was believed to be the cause of Duroziez's murmur in patients with severe aortic insufficiency. Any backflow in the femoral or any other artery would not be detected if one only used the flow indicator meter on the flowmeter, and did not measure the phasic flow on a recorder. The meter only reads the average flow of 48 ml/min without showing variations in flow direction. At points z in Figure 5 the flow has fallen to near zero late in diastole and coincides with the zero flow time. This is often seen in an anesthetized dog with the leg at rest. In an unanesthetized chronically instrumented dog who is exercising, the flow in the femoral artery is considerably greater.

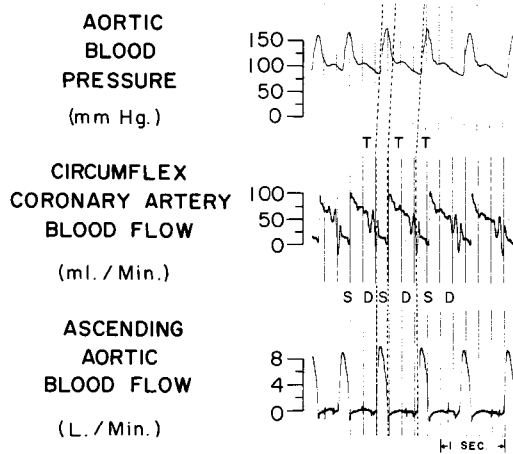


Figure 6—*Phasic Coronary and Aortic Blood Flow Patterns and Aortic Blood Pressure With Time*

The phasic changes in aortic blood pressure, aortic blood flow and circumflex coronary blood flow in a dog. The characteristic changes in aortic blood pressure are shown at the top of the panel and are delayed slightly in time due to the time lag in the pressure catheter system. Therefore the time lines "t" are offset to correlate flow and pressure events. Aortic flow at the bottom of the panel is high during the systolic period marked "s" when the aortic valve is open, and the stroke volume is being ejected. During the diastolic period marked with a "d" when the aortic valve is normally closed, aortic flow is zero, as there is no blood flow through a normal closed valve. The coronary blood flow shows a characteristic pattern of high flow during diastole and reduced flow during systole. This is caused by the increased coronary vascular resistance produced by transmural compression of the left coronary arteries during systole.

Figure 6 shows the phasic blood flow patterns recorded from flowprobes placed on the ascending aorta and the circumflex coronary artery in a dog, and how they compare to the more familiar pattern of descending aortic blood pressure. The bottom of the figure shows the flow pattern through a normal aortic valve. During diastole, the aortic valve is closed and there should be no blood flow through the aortic valve, and therefore no flow through the ascending aorta. These periods of zero diastolic aortic flow coincide with diastolic aortic pressure. These areas are marked with a "d" in Figure 6. However, when systole occurs, and the aortic valve opens, there can now be forward flow through the aortic valve as the stroke volume is ejected and this is seen on the aortic flow tracing, in the areas with an "s". The area under the curve represents the stroke volume for that beat. Aortic flow has been measured in man by placing a flowprobe of suitable lumen diameter on the ascending aorta at the time of surgery.<sup>9</sup> Flow patterns similar to that shown in Figure 6 have been repeatedly observed in man. It has also been shown that when the aortic valve leaks during diastole, such as with aortic insufficiency there is flow below the zero line. This regurgitant flow can be quantitated and the amount of aortic insufficiency determined.<sup>10</sup> The aortic blood pressure recording in Figure 6, is slightly delayed in time because of the time lag produced in the length of tubing connecting the aortic pressure catheter to the pressure transducer. Therefore vertical lines "t" were drawn offset to show how systolic and diastolic aortic pressure are related to blood flow events in the cardiac cycle.

Coronary flow, shown in the center of Figure 6 also has a characteristic phasic pattern. Left coronary arterial blood flow is unique in that it is low during systole and high during diastole; whereas all other arterial flow patterns in the body show high flow during systole and lower flow during diastole. This change in left coronary flow occurs because during systole, when the cardiac muscle is contracting the branches of the left coronary arteries which go into the wall of the heart are pinched off. These vessels therefore have a high resistance to flow during systole, but with diastole, when

the cardiac muscle is relaxing, the coronary arteries can dilate and have a low resistance and permit a high diastolic coronary flow.

### Blood Flow Studies in Man

The electromagnetic flowmeter is an excellent means of evaluating the effects of arterial reconstructive or revascularization procedures, in man at the time of surgery. Flow has been measured in the human carotid<sup>11</sup> hepatic,<sup>12</sup> pulmonary,<sup>13</sup> femoral<sup>8, 14</sup> arteries, as well as in saphenous vein bypass grafts placed distal to obstructed coronary arteries.<sup>15</sup>

The saphenous vein graft flow measurement is presently being done at many centers engaged in open heart surgery. The flowprobe is calibrated and used as previously described, and will determine the flow down the graft in ml/min. Flow patterns in saphenous vein bypass grafts to coronary arteries are usually comparable to the flow patterns obtained in the coronary arteries themselves. Figure 7 shows the flow pattern and the mean flow in ml/min obtained from five saphenous vein

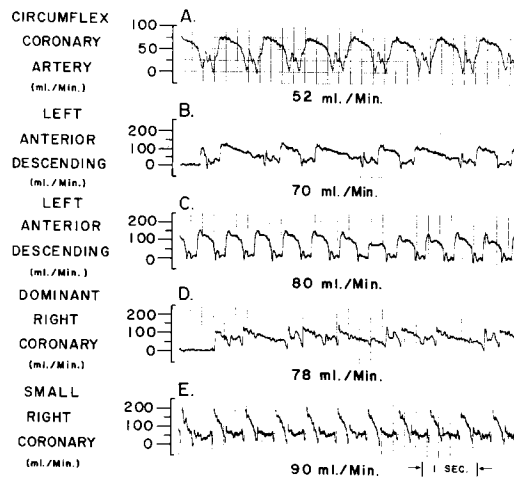


Figure 7—Phasic Flow Patterns in Aorto-Coronary Saphenous Vein Bypass Grafts

Phasic blood flow measured in five human saphenous vein bypass grafts at the time of surgery. The graft was placed from the aorta to the coronary artery indicated on the left of the figure.

Panels A, B, and C show a characteristic flow pattern normally seen in vein grafts sutured to the left coronary artery branches. Panel D shows the phasic flow pattern seen in a large right coronary artery which supplies a significant portion of the left ventricular wall. Panel E shows a phasic flow pattern often seen in saphenous vein grafts to small right coronary arteries, which do not supply significant portions of the left ventricle.

bypass grafts in man studied at the time of surgery. The coronary artery branch which received the saphenous vein graft is indicated on the left of Figure 7 for each of the five grafts. Panels A, B, and C in Figure 7 show flow patterns which are similar to flow in the main branches of the left coronary artery in animals and man. Flow is high during diastole and low during systole.

Blood flow patterns in the right coronary artery in animals have been shown to be more like blood flow elsewhere in the body.<sup>16</sup> That is, with high flow during systole and lower flow during diastole. The branches of the right coronary artery in dogs normally supply only the right ventricular wall, where the intraventricular pressure is approximately 1/6 as much as that in the left ventricle. Therefore the transmural pressure in the right ventricular wall will be 1/6 as much as in the left. This means that the coronary arteries in the right ventricle will not be pinched off nearly as much as those in the left, and will therefore not have a high resistance to flow during systole. In man however, the right coronary artery often provides blood



flow to significant portions of the left ventricle. The flow pattern seen in a human right coronary artery, or in a saphenous vein graft to a right coronary artery, will then depend on whether the right coronary artery feeds significant amounts of the left ventricle or not. Panel E in Figure 7 shows the phasic flow pattern in a vein graft to a small right coronary artery that did not appear to supply much of the left ventricle. The phasic pattern looks like that described in dogs, in which systolic flow is greater than diastolic.<sup>16</sup> Panel D however shows flow in a vein graft to a large dominant right coronary artery that supplies a significant portion of the left ventricle. Therefore this phasic pattern looks like that in a left coronary artery.

All the panels in Figure 7 show characteristic coronary flow patterns which are significantly different, even though the average flow in ml/min was between 52 and 90 ml/min. When one has calibrated the probe as previously described and established the calibration scale plotted on the y axis, then any phasic flow pattern can be mechanically planimeted or electronically integrated and the average value compared to the calibration scale.

There are several advantages to obtaining the instantaneous flow record on a direct writing recorder rather than just using the flowmeter readout. First a permanent record with a known calibration scale is obtained which can be filed with the other patient data. Secondly, the phasic flow pattern to be expected in many vessels is known and should conform to previously obtained records. If the record obtained looks quite different, or has random noise, one can suspect that the flowmeter is not operating properly. Finally, the phasic or instantaneous flow changes recorded can be compared to other events in the cardiac cycle such as opening and closing of the valves, or the beginning and end of systole.

## Summary

The electromagnetic flowmeter has become widely used for measuring blood flow in animals and man at the time of surgery. Flowprobes can be placed on surgically exposed intact vessels, and will measure blood flow in ml/min with an accuracy of  $\pm 5\%$ . This device measures blood flow linearly in both directions and clearly differentiates between forward and backward flow. Electromagnetic flowmeters have sufficient frequency response to reproduce faithfully the rapid changes in blood flow velocity that occur throughout the cardiac cycle. Blood flow has been measured in human carotid, hepatic, pulmonary, femoral, renal, arteries as well as the ascending aorta. In addition blood flow through aorto-coronary saphenous vein bypass grafts is routinely being measured at many centers.

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