A Newly Modified Electromagnetic Blood Flowmeter Capable of High Fidelity Flow Registration

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This paper describes a meter which, when inserted into an artery or vein, is capable of measuring the average flow, or the "instantaneous" flow throughout the heart cycle. Flow is recorded with a direct-writing instrument.

The general principle of the electromagnetic flowmeter was developed independently by Kolin in this country and by Wetterer in Germany. The system described by Kolin utilized a direct current electromagnet and a direct current system of recording using either a D'Arsonval or an Einthoven string galvanometer without amplification. In 1937, Kolin and Katz modified the flowmeter by interrupting the pickup potential with a tuning fork, and feeding the alternating potentials into an A.C. amplifying system to be observed on an oscillograph. Jochim modified Kolin's system by the use of a permanent magnet, closely fitting non-polarizing electrodes, and a direct current type direct-coupled amplifier. In 1941 and again in 1945, Kolin modified his instrument by substituting a 60 cycle alternating current magnet. This arrangement furnished a sinusoidal voltage in the input of the amplifier, which was modulated by the blood flow. A coil of wire around an arm of the magnet was used to buck out the voltage generated in the pickup at zero flow. To compensate for harmonics and phase shift, a filter was placed between the second and third stages of the amplifier. This meter, as previous ones, was designed to measure flow on the unopened blood vessel, and recording was accomplished by photographing a segment of the wave peak on an oscillograph.

In 1949, in an attempt to adapt a reproduction of the Kolin flowmeter to physiologic measurement, Richardson, Randall and Hines found it insufficiently stable and practical. This group developed a method of potential pickup that employed a cannula with imbedded electrodes which they used with the more adaptable alternating current system. The system featured an amplifier with sufficient gain to use a 5 milliamper ink-writing recorder. This flowmeter was found to have negligible drift and to be accurate to less than 5 per cent error with forward flow, but was not capable of a linear reproduction of backflow and was not adaptable to be used with high-speed pen recorders of greater internal resistance.

In view of the new potentialities of this method of blood flow measurement, it was thought to be of value to modify further the system of Richardson, Randall and Hines attempting to preserve its desirable features while altering the less desirable characteristics. This newly modified instrument has been found extremely practical in use. It possesses negligible instability, records flow linearly both forward and backward with an error of less than ±5 per cent and can be adapted to a wide range of pen recorders of various speeds and internal resistances.

Principle

When an electric conductor such as blood moves across the lines of force of a magnetic field, a potential difference is created in the conductor. If the field is uniform, and the conductor moves in an axis at right angles to the axis of the magnetic field, the electromotive force generated will be directly proportional to field strength, the speed of the conductor,
and the length of the conductor across the field and will be directed at right angles to the direction of movement and to the axis of the magnetic lines of force.

The potential \( E \) generated in the conductor will then be:

\[
E = B \cdot l \cdot \bar{v} \cdot 10^{-4}
\]

Where \( E \) is the potential difference in volts; \( B \), field strength in gauss, \( l \), length of the conductor across the field in centimeters (between the electrodes); and \( \bar{v} \), speed of the conductor in centimeters per second. In a blood flow system, \( \bar{v} \) is approximately the average velocity of flow across \( l \) in the cannula, and \( l \) is approximately the internal diameter of the cannula.

Therefore,

\[
E = \bar{v} \cdot K
\]

where \( K = B \cdot l \cdot 10^{-4} \), and \( \bar{v} \) = the average velocity of flow across \( l \). By use of a 60 cycle A. C. system, including a 60 cycle A. C. magnet, an additional constant is to be taken into account because the electrodes and their leads act as a one-turn transformer in which an additional \( A \) voltage is generated. Therefore, the total potential \( E' \) in the amplifier input leads is

\[
E' = E + A
\]

The \( A \) voltage is proportional to \( B \), the field strength, and is about 90 degrees out of phase with the \( E \) voltage generated by the flow. In order to cancel out the \( A \) voltage, a single turn of wire is wound about one arm of the magnet and led into the instrument to supply a bucking voltage. This bucking voltage, which is about 180 degrees out of phase with the \( A \) voltage, is passed through a variable resistance to control its magnitude and is balanced at the input of the second stage of the amplifier against the \( A \) voltage from the leads. Under this condition, with the exception of possible harmonics in the system, the output will read zero when flow is zero. However, if the phase of the bucking voltage is adjusted by additional capacitance, a controlled forcing potential which is in phase with the flow (90 degrees from \( A \) voltage), may be applied to the second stage of the amplifier. Back flow then may be measured in this system up to a value not to exceed this controlled forcing potential. If backflow should exceed this value it will be distorted, but since this controlled forcing potential may be increased to the full scale of the system, backflow equal to the full value of forward flow can be recorded as a linear function of flow.

**Materials and Methods**

*Description of Apparatus.* The complete flowmeter consists of a specially constructed plastic cannula which possesses relatively nonwettable properties, an A. C. magnet, a newly designed A. C. amplifier, and an Esterline-Angus 5 milliampere recorder or a Brush magnetic recorder.

![Photograph of plastic cannula used with electromagnetic flowmeter, showing the elements of construction.](image1)

**Fig. 1.** Photograph of plastic cannula used with electromagnetic flowmeter, showing the elements of construction.

![Schematic diagram of plastic cannula showing the positioning of the gold electrodes.](image2)

**Fig. 2.** Schematic diagram of plastic cannula showing the positioning of the gold electrodes.

*The Cannula.* The cannula structure consists of a Polystyrene or Plexiglas tube with an internal diameter equal to or slightly greater than the lumen of the blood vessel to be cannulated. While smaller sizes are adaptable to the instrument, they would increase unduly the frictional resistance to flow in the fluid system, thereby introducing an undesired error. A cannula such as found in figure 1, which has a lumen 3 mm. in diameter, is quite satisfactory for use in the femoral artery of a dog. This particular model is 5 cm. long with a 3 cm. plastic sleeve fitted over the middle section in such a manner that the leads from both the pickup electrodes and the ground traverse between the two pieces of tubing. The detailed construction is revealed better in figure 2. In the middle of the cannula are two gold...
wire tips, shown at the top and the bottom diametrically opposed to each other, which serve to pick up the $E$ potential generated in the magnetic field by the blood flow. These tips of noncorrosive and highly conductive metal just touch the periphery of the lumen. Onto these tips just outside the inner tubing are soldered the two pickup leads which are then tightly twisted and passed down the cannula in a precut groove, into a shielded cable which runs to the amplifier input connection. In addition to these leads, two gold tips are imbedded in the inner cannula tubing, bilaterally and equidistant from the magnet, and these are soldered to a single fine silver or tinned copper wire which in turn is brought down a groove to the end of the cannula where it is joined to the shielding.

When the above connections are complete, the outer and inner surfaces of the inner and outer respective plastic tubes are coated with solvent, and the outer sleeve is slipped over the smaller inner one so that the two encompass the connections and hold them rigidly and permanently in position. When dried, a flat groove may be filed on each side of the outer tube to fit the jaws of the magnet, and the cannula is ready to use. In cannulating a vessel, a 3 mm. nonwettable flexible plastic tube may be stretched to fit over each end of the cannula and bent to go into the appropriate vessel. Operationally, this is more adequate than a rigid system of cannulation, because movements of the part do not affect the potential pickup.

The cannula and pickup incorporate the following desirable features: (a) an electrical pickup system well isolated electrically from the inconstant surrounding tissue conditions; (b) a lumen of uniform size to match the vessel size with negligible loss due to frictional resistance to flow; (c) a minimum of nonwettable surface with which the blood is in contact; (d) a rigid, nonvarying position of the pickup leads which prevents extraneous voltage variation from appearing on the recorder; (e) flexible cannula tips to allow work with moving tissues such as are encountered in recording coronary artery blood flow; and (f) a newly designed grounding system which further aids in eliminating extraneous potentials from the immediate vicinity of the cannula during measurement.

The Magnet. The A. C. magnet used with this meter is made by recutting the stacked laminations from a 4 by 3 inch transformer, the laminations being $\frac{1}{2}$ inch wide and $\frac{3}{8}$ inch thick. Eighteen laminations make the total magnet $\frac{1}{2}$ inch thick. The jaws of the magnet are tapered to $\frac{1}{4}$ inch width making the magnet tips $\frac{1}{4}$ by $\frac{1}{4}$ inch with an air space $\frac{1}{2}$ inch wide. The coil is constructed of 1400 turns of No. 22 wire excited with a 110 volt A. C. 60 cycles per second source. This gives a field of better than 1000 gauss across the poles. This magnet has been used with the meter successfully with or without a constant voltage regulator, although a regulator has obvious theoretic advantages, if its voltage wave form has a minimum of harmonics. However, the regulating transformer may produce enough second harmonic distortion to nullify the benefit obtained from its voltage stabilization.

The Amplifier. A diagram of the amplifier is shown in figure 3. It features a balanced push-pull circuit with the plate supply circuit +150 volts and the cathode supply −150 volts to achieve maximum stability. In the present form it is adaptable for 200 cycles per second or 60 cycles per second carrier frequency but the availability of 60 cycles per second voltage source makes it more practical. On the other hand, the use of 200 cycles carrier frequency allows optimal gain with minimum recording of hum and allows recording of higher speed transients.

The amplifier consists of a series of A. C. stages followed by a tuned circuit resonant at the carrier frequency, a rectifier, and a D. C. current amplifier. The major modification of the basic circuit is the control of phase in the initial bucking potential stage. Here, a critical R-C circuit adjusts the bucking voltage phase to interact at the input to the second stage with the potentials originating in the cannula pickup so that backflow may be accurately reproduced as described. Another useful modification in this circuit is the balancing circuit in the rectifier stage which serves to cancel the zero flow forcing voltage, thereby allowing one to adjust the recording pen to a desired zero point when no flow is present, and to change the “D. C. gain” sensitivity without altering this zero. The bank of capacitance shunts just preceding the first D. C. stage aids in damping out pulsatile transients, making possible mean flow recording or critical damping when different recorders are employed. The series resistors at the output allow recorders of different internal resistance and different current or voltage sensitivity to be used.

It has been a practice to use this amplifier with a standard power supply using gaseous voltage regulating tubes, and to supply the filaments of the first three stages with 6 volt D. C. voltage to avoid 60 cycle A. C. voltages in these stages. This latter precaution is not necessary except at very high gain settings.

Adjustment of the instrument is accomplished most conveniently by use of an oscilloscope attached between a plate of the 6SN7 and ground, with the sweep synchronized with the supply frequency. A voltage is applied in phase with the flow-induced voltage until the pen is moved up to about one-half scale on the recorder. This will permit recording an equal amount of backflow if desired. The proper output resistance is selected, the zero line adjusted, the blood flow released, and the meter is in operation.

Calibration of the Instrument. The instrument may be calibrated by measuring the flow of blood out of the distal end of the cannula to which plastic
tubing is attached and run into a graduate; a clamp varies the diameter to achieve the desired range of flow rates. Since a point on the record will corre-

Fig. 4. Flow calibration of the flowmeter with the use of a Brush magnetic high speed recorder.

spond to each flow rate, a curve of best fit may be drawn transecting these points and extrapolated to zero when plotted on graph paper.

**Linearity.** Figures 4 and 5 reveal the linear calibration curves as measured on the two recorders previously mentioned. It may be observed that backflow on these curves is in a linear relationship with forward flow. Measurement error, including observers' reading error, has been found to be less than ±5 per cent up to full scale deflection of the instrument.

**Sensitivity.** The maximum sensitivity which has been attained with this system, while at the same time maintaining the stability indicated below, is 3 milliamperes deflection from zero on a 5 milliam-

**FIG. 3.** Diagram of amplifier, complete, with the exception of the power supply.

**FIG. 4.** Flow calibration of the flowmeter with the use of an Esterline-Angus 70 ohm, 5 milliampere, slow speed recorder.

**FIG. 5.** Flow calibration of the flowmeter with the use of an Esterline-Angus recorder and 12 mm. on a Brush pen motor for a flow of 30 ml. per minute.

**Constancy of Calibration.** Base line deviation over a four hour period under constant test conditions is less than ±2 per cent as determined on the 5 milli-

ampere recorder; and the deflection for a 60 ml. per minute flow remained within ±5 per cent for the same period. The flowmeter has been tested over the past 12 months on 95 experimental animals, using the same cannula for potential pickup. The system has maintained its sensitivity and base line
stability within ±2 per cent during this period of time.

Flow Records

Mean Flow Records. This flowmeter as described is adaptable to be used with a 5 milliampere Esterline-Angus recorder, a Brush magnetic recorder, or others with similar characteristics. We have found the Esterline-Angus more practical for mean blood flow measurements where both the cardiac rate and true mean flow measurement are desired. A typical record showing a flow of 72 ml. per minute in the femoral artery of a dog and obtained by use of the Esterline-Angus recorder is found in figure 6; this record demonstrates typical contours due to cardiac pulse and respirations as reflected in arterial flow, and then the altered contour when the rapid changes are integrated by damping electronically for mean flow measurement.

Instantaneous Flow Records. Fast recorders such as the Brush pen motor and the Sanborn direct writer may be used where it is desired to record high speed transients. Figure 7 shows a femoral artery flow of 62 ml. per minute as recorded on the Brush instrument revealing the detailed flow pattern with time. Fine lines on the abscissa equal one second. Figure 8 is a sample record of the output of a hydraulic square wave generator. The sharpness of the deflections, and the absence of lag and overshoot demonstrate the fidelity of reproduction of rapidly fluctuating forward and backward flow.

Pressure Loss. The loss in lateral pressure due to resistance to flow in this instrument amounts to less than 1 mm. Hg for a blood flow of 30 ml. per minute through the cannula alone. The pressure drop for the cannula plus connecting tubes, etc., is less than 3 mm. Hg for a flow of 30 ml. per minute.

Physiologic Flow Measurement. Since this system accurately measures high speed transients with critical damping, studies have been carried out in the femoral artery of the dog to determine the flow pulse contour and to evaluate the possibilities of backflow in this vessel as reported by Shipley, Gregg, and Schroeder. Figure 7 is a sample of femoral artery flow of 62 ml. per minute as recorded on a high speed Brush magnetic recorder. It may be observed in this record that backflow typically was not present in the femoral artery, although the flow rate approached zero at two points during the cardiac cycle. However, when 1.0 µg. of epinephrine was injected intra-arterially, with consequent increase in peripheral resistance and diminution in femoral arterial flow, backflow was observed to occur for a short time during each cardiac cycle (fig. 9). Such backflow-containing contours have been
observed for over five minutes following a single injection of 1.0 µg of epinephrine.

Studies with other flowmeters in this laboratory which have been undamped or subdamped with a resultant characteristic of overshoot have shown that typical control blood flow in the femoral artery may be recorded so that there appear to be backflow when the flow rate approaches zero, due to distortion in the reproduced record. Critical damping, or even underdamping close to the critical point, of one of these systems (differential pressure flowmeter) eliminated this phenomenon of "backflow" and the contours closely resembled that shown in figure 7, recorded by the use of the electromagnetic flowmeter. In keeping with a conservative analysis, the system was slightly undamped at a near-critical level for this recording.

In order to demonstrate the fidelity of this system under these circumstances, a hydraulic square-wave generator was attached to the cannula. The reproduced contours are presented in figure 8, where five lines on the abscissa represent one second. It may be seen that the system adequately reproduces the flow both forward and backwards with fidelity including the gross and minute transients in the hydraulic movement. The near-critical damping used here was identical with that used in the femoral flow contours shown in figure 7.

The hydraulic square-wave generator consisted of a 10 cc syringe with the plunger attached to a dual set of metal racks in such a manner that a cog engaged each of the racks during 90 degrees of rotation alternately and was free before each alternate gear engagement. To facilitate this, the teeth were filed off three-fourths of the gear allowing it to engage during one-fourth of its rotation. Since one rack was situated above the gear and one rack was situated below, alternate engagements forced the syringe in opposite directions. With the syringe securely stabilized, this resulted in an abruptly generated forward and backward flow of fluid.

**Discussion**

While this instrument was built to be a pulsatile flowmeter, the electronic damping selector built into the device makes it adaptable to mean flow measurement as well. A criticism of this type of flowmeter is that general anesthesia and an anticoagulant must be used because the blood vessel is cannulated. The newly developed flexible cannula now makes it possible to cannulate by use of procaine as local anesthesia, thereby eliminating one of these objections, leaving only the anticoagulant and the cannulation itself as criticism of this method of flow measurement. In favor of the vessel cannulation method it may be said that attempts at measurement from a pickup surrounding the artery by members of this group and others have entailed the difficulty of drift and extraneous pickup and changes in calibration due to variation in vessel diameter with inconstant pressure. These factors result in measurement errors of considerable magnitude. The use of an A.C. system reduces these difficulties considerably, and further work in this field also may reduce errors of potential pickup from vessel surfaces to a minimum.

This meter as described has a negligible pressure drop due to resistance, at physiologic rates of flow. The cannula may be cleaned easily following each use by means of a detergent and distilled water. It is felt that the significant modifications over previous electromagnetic flowmeters include a flexible cannula pickup with an improved ground, an electronic damping selector for critical damping and for mean flow measurement, a phase-controlling discriminator which allows accurate measurements of backflow as well as forward flow, both being linear through zero, an electronic centering device to adjust the zero point for flow measurement with minimal drift from carrier harmonics.
or extraneous stray voltages, and an improved power gain enabling the system to be used with high speed recorders.

**Summary**

A newly modified electromagnetic blood flowmeter is described which produces a continuous permanent record of pulsatile and of mean blood flow. While the use of this meter entails some of the disadvantages inherent with cannulation, it possesses the advantages of direct flow measurement, a linear calibration both forward and backward with fidelity, accuracy, stability (drift less than 2 per cent in four hours), and ease of operation. It can measure flow in an organ where there is considerable movement of the blood vessels during flow registration, and the cannula has been found to exhibit negligible frictional resistance to fluid flow (less than 1 mm. Hg for a blood flow of 30 ml. per minute). The sensitivity is such that a flow of 30 ml. per minute will give 3 milliampere deflection from zero on a 5 milliampere Esterline-Angus Record, and a 12 mm. deflection from zero on a Brush penmotor.

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