The Effects of Hematocrit, Amplifier Input Impedance and Magnet Excitation Frequency on the Accuracy of Electromagnetic Flowmeters

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Abstract

Since the introduction of electromagnetic flowmeters, clinical users have found it necessary to contend with several problems in the accuracy of the flow signal. The cumulative results of these inaccuracies has commonly been referred to as the "hematocrit effect."

Blood was pumped through an in vitro circuit containing a segment of canine femoral artery. The hematocrit of the blood was varied from 10% to 70%. Flow through the artery segment was measured with two clinically popular electromagnetic flowmeters employing perivascular probes. Measured flow was compared to actual flow to quantitate the "hematocrit effect."

Both flowmeters increasingly overindicated flow as the hematocrit was decreased ($r = .85$, $p < .01$, $m = -1.51$). The overindication of flow was a result of entering a manufacturer's precalibration constant that inaccurately corrects for voltage assumed lost to erythrocyte impedance.

It is recommended that electromagnetic flowmeters not be used to evaluate coronary artery graft flow unless adequate compensation for hemodilution is made.

The amplifier input impedance and magnet excitation frequency were found to be great enough to prevent detraction from the flowmeter's accuracy at all hematocrits studied ($r > .90$, $p < .01$).

In an ancillary study, the Carolina Medical Electronics, Inc. model 701-D Cliniflow II™ flowmeter was found to be independent of the "hematocrit effect" (all $rs > .98$, all $ps < .01$). The Cliniflow II™ has a "user dictated" microprocessor that accurately compensates for the hematocrit effect.

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Introduction

Since the introduction of electromagnetic blood flowmeters with perivascular probes, clinical users have been aware of the potential inaccuracy of these instruments due to variation in hematocrit of the blood. Nevertheless, electromagnetic flowmeters remain the instrument of choice in assessing the patency of vascular grafts immediately after implantation and prior to the closing of the operative site.

Electromagnetic flowmeters produce a voltage by passing electrically conductive blood through an electromagnetic field.[2] The flowmeter probe contains an externally excited electromagnet and voltage detecting electrodes. The probe is placed around the vessel with the probe's electrodes securely in contact with the vessel wall. An electromagnetic field is generated across the probe with its direction perpendicular to that of blood flow. A resultant voltage that is directly proportional in magnitude and perpendicular in direction to the velocity of the flowing blood is generated by the flow of ion-bearing blood.[3] The voltage generates a current which flows through the detecting electrodes to the amplifier of the device where the voltage is dropped across a large resistor. Since the dimensions of the vessel are known and are held constant by the constraints of the probe, multiplication by the cross sectional area yields flow.

The accuracy of the flow measurement is dependent upon the establishment of the entire flow generated voltage at the amplifier of the flowmeter. There are several sources of impedance in the current path prior to the flowmeter's amplifier, across each of which is dropped a certain proportion of the flow generated voltage. The magnitude of the voltage drop is directly proportional to the ratio of the magnitude of the encountered impedance

to the total impedance of the current path[4] and is expressed mathematically:

$$Vd = Vf\,(Zd/Zt)$$

where:

Vd = voltage dropped
Vf = original voltage generated by flow
Zd = impedance at point of voltage drop
Zt = summation of all impedances in current path

One of the most influential and variable of the current path impedances is the erythrocyte concentration. Because erythrocytes are not as conductive as plasma, the magnitude of the voltage drop between the point of origin and the vessel wall is proportional to the concentration of erythrocytes.[5] The hematocrit induced impedance has traditionally been referred to as the "hematocrit effect."[6] As the hematocrit increases, the voltage drop across the cells en masse increases as well, causing a reduction in the magnitude of the voltage established at the flowmeter's amplifier. The subsequent result of this chain of events is artificial reduction in the flow indication. Manufacturers have attempted to correct for the hematocrit effect by determining a calibration constant that is to be entered into the flowmeter's circuitry by the user for each probe.

The purpose of this study was to evaluate the efficacy of the compensation technique for the hematocrit effect and to identify and quantitate the components of this effect.

The specific objectives of this study were:

1) To verify that the probe calibration technique employed by most of the currently available flowmeters accurately corrects for extremely low hematocrits.
2) To verify that the input impedance of the flowmeter amplifiers is of sufficient magnitude to render insignificant the summation of all other impedances in the current path as a function of hematocrit, and
3) To verify that the excitation frequency of the flow probe magnet is high enough to prevent capacitance from playing a significant role in reducing the voltage established at the input amplifier of the flowmeter as a function of hematocrit.

Methods and Materials

The materials used in this study are listed below.

Device	Manufacturer
Statham SP 2202 electromagnetic flowmeter with 2-4 mm. diameter perivascular probes	Gould, Inc., Statham Instruments Oxnard, CA 93030
Narco RT-500 electromagnetic flowmeter with 2-4 mm. diameter perivascular probes	Narco Biosystems, Inc. Houston, TX 77017
Wavetek voltage controlled sinusoidal wave generator (Model III)	Wavetek, Inc. Beech Grove, IN 46107
Kray Breadboard	Edward Kray Ohio State University Columbus, OH 43210
Switchcraft ASF-4 and ASM-4 electrical connectors	Switchcraft, Inc. Chicago, IL 60630
B and K 10 MHZ. oscilloscope	B and K Instruments, Inc. Chicago, IL 60635
Keithley Multimeter	Keithley Instruments Cleveland, OH 44139
Introcath femoral artery catheter introducers	Travenol Laboratories, Inc. Deerfield, IL 60015
Travenol low flow roller pump	
Travenol miniprime heat exchanger	
Bentley BCR-3500 cardiotomy reservoir	American Bentley Laboratories Irvine, CA 92714

In Vitro Circuit

The in vitro circuit (Figure 1) was assembled and primed with isotonic saline. The femoral artery was kept moist with saline and the probe sites were surgically cleaned of all adventitia. The temperature of the prime was maintained at 28 ° C. The fluid in the circuit was first pumped from a volume reservoir into an elevated cardiotomy reservoir and allowed to drain by gravity through a segment of artery to eliminate any pulsatility inherently caused by a roller pump. The height of the fluid level was maintained at 165 cm. above the artery. The catheter introducers were used to cannulate the femoral artery at both ends and were secured with umbilical tape. The introducer-femoral artery assembly was then inserted into the circuit as shown in Figure 1. The flow probes were prepared and attached to the artery according to the manufacturer's instructions. Each probe was thoroughly cleaned with pumice between measurements and operating instructions were adhered to carefully.

PUMP CIRCUIT USED TO DEMONSTRATE THE HEMATOCRIT EFFECT

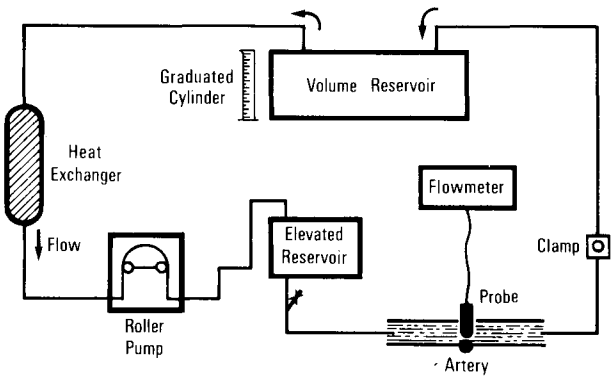

Figure 1

Hematocrit Effect

The hematocrit effect was studied by recirculating a solution of isotonic saline and packed human red blood cells through the circuit and measuring the true flow with a graduated cylinder and a timing device while simultaneously measuring the mean flow with one of the flowmeters. Four measurements were taken with each flowmeter at eight hematocrits, alternating flowmeters between each measurement. The percent deviation of the flowmeter's indications from true flow was calculated and plotted as a function of hematocrit. Percent deviation was calculated with the equation:

$$\% \text{ deviation} = \frac{(\text{meter}-\text{actual flow}) \times 100}{\text{actual flow}}$$

The line of Figure 4 was constructed by performing linear regression upon the set of data points containing hematocrits within the normal non-diluted range.

Hematocrit was varied over a range of 0%-68% by adding packed red blood cells to the isotonic saline. The actual hematocrit was measured. The in vitro system was allowed to recirculate until three consecutive hematocrit tests, each three minutes apart, returned similar results.

Changes in the conductivity of the vessel wall as a result of passage of time was controlled for by clamping the tubing between the "Y" port and the cardiotomy

SCHEMATIC OF THE CIRCUIT USED TO TEST THE EFFECT OF AMPLIFIER INPUT IMPEDENCE ON FLOW SIGNALS

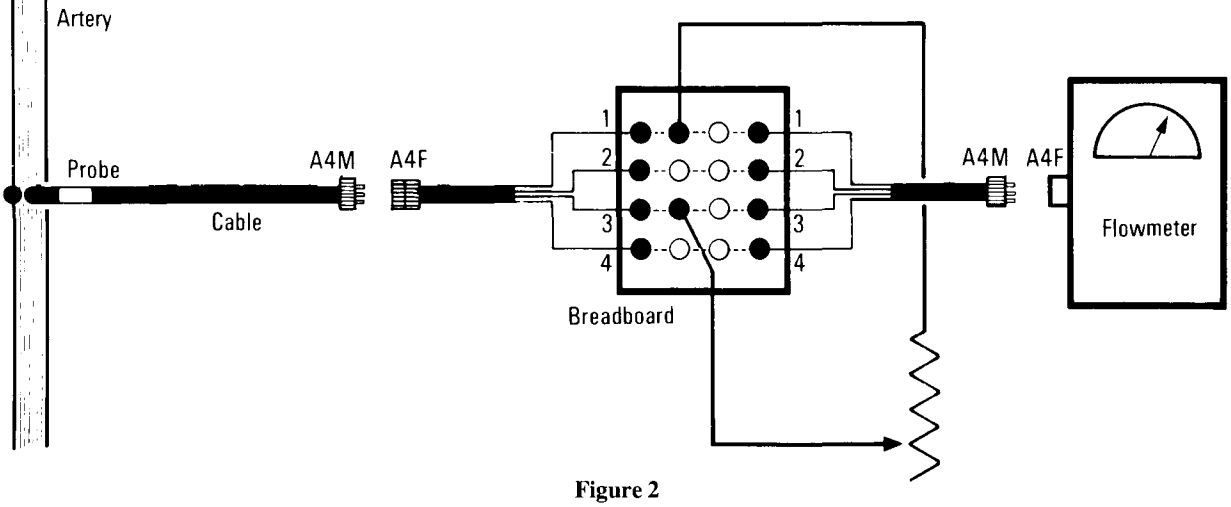

Figure 2

reservoir and flushing the system distal to the "Y" with saline while performing flow measurements and comparing their results to earlier saline measurements. This procedure was carried out between each change in hematocrit.

Input Impedance Effect

The effect of various amplifier input impedances was studied using the same pump circuit (Figure 1), but with an addition to the flowmeter's probe cable that was designed to make it possible to alter the effective amplifier input impedance of the flowmeter without actually altering its internal circuitry. The electrical circuit employed to study the amplifer input impedance consisted of a Kray breadboard and two Switchcraft A4M and two A4F cable connectors as is illustrated in Figure 2. The electrical circuit reduced the effective input impedance of the amplifier by the quantitative relationship:

$$Z_3 = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2}}$$

where:

Z_1 = input impedance of amplifier (2 M Ω)
Z_2 = impedance of resistor inserted in parallel
Z_3 = effective impedance of amplifier

In this portion of the study, as well as the next, it was only possible to use the Statham flowmeter because of the Narco flowmeter's extreme sensitivity to capacitance resulting in baseline drift.

The investigation was conducted by varying the effective input impedance over a range of 2 megaohms (M Ω) — 114 kiliohms (K Ω) while holding flow and hematocrit constant. This procedure was repeated at five hematocrits and the results were graphed as percent deviation of measured flow from actual flow as a function of the log of impedance.

Magnet Excitation Frequency Effect

The potential for erythrocytes to significantly reduce the delivered voltage due to capacitance was tested via another electrical circuit (Figure 3). This circuit was independent of the flowmeter's internal circuitry. The probe's magnet was driven by a variable frequency voltage source and the flow signal's amplitude was measured with an oscilloscope. The excitation signal's amplitude was held constant at 22 millivolts (mV.) as the frequency was reduced. Frequency was varied from limits of 10,000 Hz to 250 Hz. These limits far exceed the Statham flowmeter's normal excitation frequency of 2500 Hz.[7]

Results

The demonstration of the hematocrit effect using commercially precalibrated probes is illustrated in Figure 4 in which the percent deviation of the flowmeter's indications from the actual flow is plotted as a function of hematocrit. The ± 25 percent limits encompassed the majority of the points taken at "normal" non-hemodiluted hematocrits.

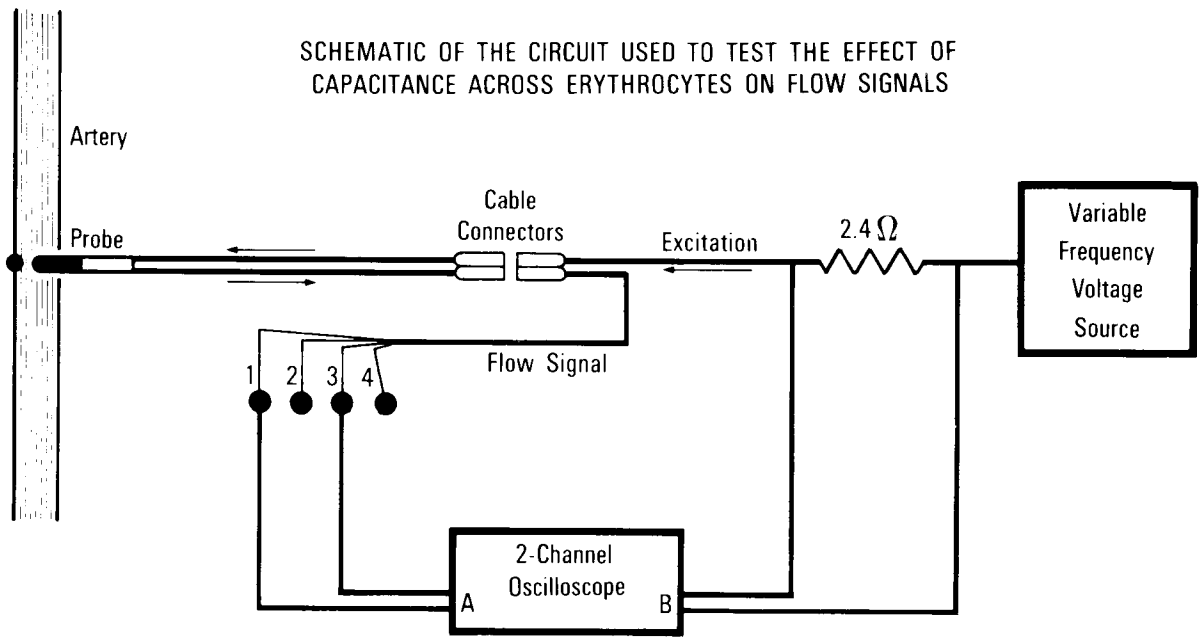

Figure 3

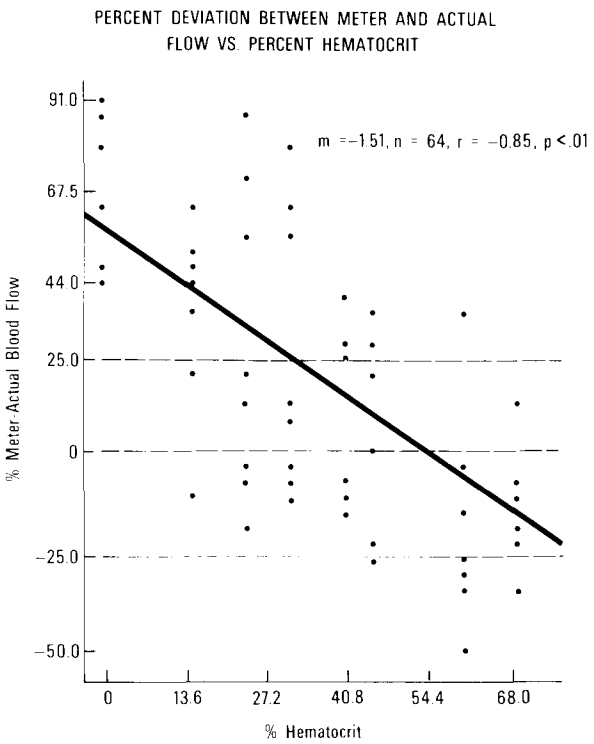

Figure 4

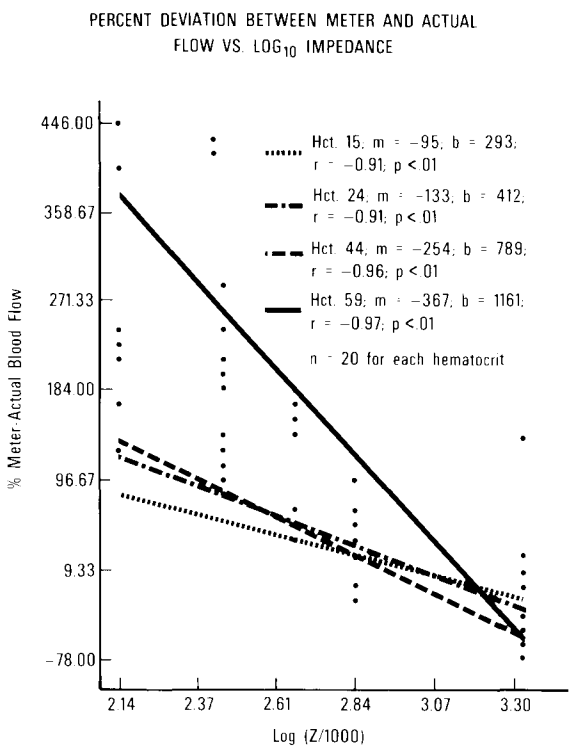

Figure 5

Figure 4 reveals that as the erythrocyte concentration declined, the flowmeters consistently and increasingly indicated a higher than actual flow. Furthermore, Figure 4 illustrates that the flowmeters tended toward over-indicating flows by margins increasingly greater than 25 percent at hematocrits below 32 percent.

Figure 5 illustrates the accuracy of the electromagnetic flowmeter as a function of its effective amplifier input impedance. The inaccuracy of the flowmeter increased as the input impedance was diminished at all hematocrits. In addition, as hematocrit was increased, the magnitude of the inaccuracy tended to increase. The "spread" of the points at each impedance tended to increase as the input impedance declined. The reproducibility of the flow indications lessened as input impedance fell.

The results of the study of the capacitive component of the hematocrit effect are presented in Table 1. Frequency, and therefore capacitance, played no significant role in determining the magnitude of the incoming flow signal at the lower hematocrits. However, as hematocrit was increased, the excitation frequency began to play a significant role in determining the amplitude of the flow-generated voltage. This is especially evident at a hematocrit = 59 percent. The flow-generated voltage that reached the monitoring site was reduced as the excitation frequency was decreased.

Discussion

Methodology

In varying the hematocrit of the in vitro circuit fluid, packed human red blood cells were utilized rather than concentrated canine blood. The use of human RBCs helped assure that appropriate cell size, configuration and conductivity were maintained to aid in supporting the study's external validity.

In preserving the harvested canine femoral arteries, the cold heparinized lactated Ringers flush and 4 °C storage technique were chosen because it is similar to the technique that has been found adequate for the preservation of saphenous vein segments intended for coronary artery grafting.

In graphing the input impedance data (Figure 5) the log of impedance was used because it had the highest correlation coefficient relative to natural log or impedance alone.

In the study of the frequency dependent capacitive component of the hematocrit effect, the initial input signal was adjusted with the Wavetek attenuator until the flow signal was returned to its initial amplitude of 22 mV. at 10,000 Hz. This was carried out so that the resistance component of the hematocrit effect introduced by increasing the erythrocyte concentration was nullified. The assumption that the monitored return signal

Table 1

EFFECT OF MAGNET EXCITATION FREQUENCY

Hematocrit	Frequency (Hz.)	E in (Volts)	E out (mVolts)	Actual flow (ml/min)
0	10,000	3.2	22	56
	↓	↓	↓	
	200	3.2	22	
15	10,000	3.2	22	46
	↓	↓	↓	
	384	3.2	22	
24	10,000	3.5	22	36
	↓	↓	↓	
	300	3.5	22	
44	10,000	3.7	22	20
	↓		↓	
	1000		22	
	900		20	
	↓		↓	
	238	3.7	20	
59	10,000	3.9	22	14
	6000		22	
	4000		20	
	3000		19	
	1500		19	
	1000		18	
	500		18	
	270	3.9	17	

was actually the flow generated signal was verified threefold: 1) It was verified that the input and output signals were the same frequency, 2) that both signals responded simultaneously to the attenuator and frequency control, and 3) that the return signal was flow dependent. Flow dependency was verified by clamping the circuit distal to the artery and verifying that the return signal was severely diminished.

Finally, in constructing Figure 4, only the hematocrits between 32 percent and 49 percent were used because these limits bound those of the bovine blood used by the manufacturers to derive the calibration constants assigned to the flowmeter probes. (Ronald Hileman, Carolina Medical Electronics, Inc., King, NC 27021)

Hematocrit Effect

As the hematocrit fell, the flowmeters increasingly over-indicated the flow (Figure 4). The circuitry of the meter is in effect amplifying the flow voltage by a large enough multiple to correct for voltage that the meter "assumes" was lost to normal range hematocrit erythrocyte impedance. However, as a result of hemodilution, the degree of compensation was unnecessary and the resulting voltage signal was far too large.

The primary goal of coronary artery bypass grafting (CABG) is to increase the blood delivery, hence, O_2 delivery to endangered ischemic regions of the myocardium. If the amount of blood flowing through a graft can be measured, the actual volume of oxygen delivered to each gram of myocardial tissue can be closely estimated. Since it is also possible to calculate the amount of oxygen required to perform a known amount of work, the adequacy of revascularization can be approximately determined. However, if the volume of blood delivered is incorrectly assumed to be higher than it actually is, a dangerous, perhaps lethal, ischemic condition may go unnoticed and uncorrected.[8] Since CABG necessarily involves cardiopulmonary bypass (CPB) which inherently causes radical hemodilution to hematocrits often as low as 18-25 percent, the danger of over-indication of flows by electromagnetic flowmeters cannot be dismissd following CABG. The potential for the incorrect conclusion that a graft is adequately patent is also a very real danger. Furthermore, should a surgical team use a "before and after" approach to evaluating the adequacy of redo revascularization by measuring flow through the old graft prior to CPB, and then measuring flow through the new graft following CPB, it should be apparent that the hemodilution would artificially increase the indicated flow following surgery. Therefore, the "before and after" method of flow analysis is not only suspect but it could mask a compromised graft that had actually further diminished the myocardial blood supply.

Based on this study's results and review of other clinical users' reports, this author must conclude that evaluation of graft patency and myocardial revascularization adequacy with electromagnetic flowmeters is contraindicated following a procedure involving CPB unless adequate hemodilution compensation techniques are employed. This is not to state that electromagnetic flowmeters are not useful in research or in some instances of vascular surgery in which hematocrit is held constant within the normal range and in which trending

is sufficient. Figure 4 indicates that a wide margin of error ($\pm$25 percent) exists at normal hematocrits.

Should a surgical team or team leader be insistent upon using a flowmeter, this author recommends that at least a calibration chart be developed to allow compensation for the falsely high flow indications with hemodilution. Such a chart should be developed by the manufacturer and supplied to the users.

Input Impedance

Roberts hypothesized that a large component of the hematocrit effect was due to insufficient input impedances.[9] Since Roberts' report, the input impedances of the newer flowmeters have been substantially increased. The purpose of the amplifier input impedance study was to determine if the increases had been sufficient and, if not, what portion of the hematocrit effect was still due to insufficient input impedance.

The increasing percent error as the amplifier input impedance decreases clearly illustrates the importance of high input impedance (Figure 5). However, it can also be seen that the lines of Figure 5 approach a convergant point near the 0 percent error margin at the unaltered input impedance of the Statham SP-2202 (2 M Ω)[7]. This leads to the conclusion that the input impedance for the Statham model is sufficient.

It was expected that as the input impedance fell and the hematocrit rose, the flow indication would have been decreased. This would be expected because as the ratio of hematocrit impedance: amplifier input impedance rose, a larger proportion of the voltage would be lost to the current path proximal to the amplifier. However, the opposite effect was observed and remains unexplained. It is difficult to accept coincidence in this case because of the high correlation coefficients ($r > .90$), therefore, a yet unidentified factor must be assumed to be playing a role. It is postulated that this may be a result of capacitive coupling in the breadboard.

Excitation Frequency

The results indicated that there was a capacitance component detected at the high hematocrits. This finding can probably be attributed to the fact that erythrocytes are less electrically conductive than is plasma and therefore, serve as many very small resistors.[9] The electromagnets in the probes are driven with an AC source and all resistors in an AC circuit have a capacitive component.[7,10] The magnitude of the capacitive component is inversely proportional to the excitation frequency.[4] These phenomena were a major impetus for this investigation. It may be concluded that reduction in the flow signal due to capacitance does occur in vitro, but it was not observed at the lower hematocrits and probably plays a nonsubstantial role in signal artifact.

Summary/Conclusions

- A protocol for the detection of error by electromagnetic flowmeters as a function of hematocrit using precalibrated probes was designed and carried out.
- Electromagnetic flowmeters should not be used in the evaluation of patency of a graft following cardiopulmonary bypass or any other cause of hemodilution unless steps are taken to correct for the low hematocrit error.
- A means of correcting flowmeter readings for hematocrit is essential. A chart that allows conversion of readings to actual flow would be the simplest method. This should be carried out by the manufacturers to help guarantee consistency.
- The input impedance of the flowmeter amplifier was studied to determine if its magnitude was sufficient to render insignificant its contribution to the hematocrit effect. While its magnitude was found to be large enough, more work is needed in determining the cause of the overindication of flow measurements as the input impedance of the amplifier was diminished.
- The relationship between resistors in AC drive circuits and capacitance was briefly discussed. A red cell capacitance component was found to exist at high hematocrits but was not detected to a significant extent at the lower hematocrits associated with post-CPB hemodilution that this study was concerned with.

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Addendum:

An Evaluation of the Carolina Medical Electronics Model 701D Cliniflow II™ Flowmeter

Introduction

Following the completion of the original study, "The Effects of Hematocrit, Amplifier Input Impedance and Magnet Excitation Frequency on the Accuracy of Electromagnetic Flowmeters," an additional flowmeter was made available for testing in May of 1984. (Carolina Medical Electronics Model 701-D Cliniflow II™).[a] The Cliniflow II™ features a microprocessor based component that allows the user to enter the hematocrit of the blood directly into the flowmeter's electronic calculation of blood flow.[1].

Methods

The method used for the evaluation of the Cliniflow II™ was similar to the method used to demonstrate the hematocrit effect in the original study. This method is described in the "Methods" section of the original paper.

Results

The results of the evaluation of the Cliniflow II™ are presented in Table 2. The flowmeter accurately indicated flow at all five hematocrits tested. The average error by the flowmeter was 1.2 percent with standard deviation = 11.9 percent. No significant inaccuracy in flow measurement was detected as a function of the changing hematocrit ($p < .01$).

Discussion

One of the key characteristics of the Cliniflow II™ 701-D is its variable hematocrit compensation feature as opposed to a constant hematocrit compensation fac-

Table 2

RESULTS OF THE EVALUATION OF THE CAROLINA CLINIFLOW II 701-D FLOWMETER

% Hematocrit	Actual flow (ml/min)	Measured flow (ml/min)	Statistics x = actual y = measured
59%	160	160	m = 0.99
	106	92	b = −6.8
	36	24	r = 0.997
	224	211	p < 0.01
	43	40	
	85	80	
43%	360	346	m = 0.959
	246	258	b = 13.2
	110	110	r = 0.997
	58	68	p < 0.01
	112	124	
	303	313	
31%	246	250	m = 1.008
	308	311	b = −1.67
	240	224	r = 0.997
	108	106	p < 0.01
	53	56	
	304	312	
28%	256	245	m = 0.998
	220	205	b = 0.049
	159	161	r = 0.996
	38	45	p < 0.01
	360	368	
	304	310	
11%	324	354	m = 1.08
	320	311	b = −6.08
	276	233	r = .987
	168	167	p < 0.01
	52	62	
	92	96	

[a]Carolina Medical Electronics, Inc., King, NC 27021

tor employed by other manufacturers. As indicated by Table 2, this feature served to correctly compensate for the hematocrit of the blood and virtually eliminated the hematocrit effect.

The hematocrit effect was demonstrated in the original study and was found to cause severe inaccuracy of the flow measurements at hematocrits below normal. It was recommended that electromagnetic flowmeters not be used to evaluate the patency of a vessel if the patient is hemodiluted unless adequate steps are taken to compensate for the inflated flow indications. It appears that Carolina Medical Electronics has incorporated the necessary correction features into the Cliniflow II™ 701-D and that this flowmeter can be relied upon to supply accurate data across a wide range of hematocrits.

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