

**Original Article**

## ***Validation of Two Flow Probes Using Bovine, Porcine, Ovine and Human Blood***

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### **ABSTRACT**

In-line electromagnetic and doppler flow probes employed in extracorporeal circuits are calibrated for use with human blood. This study was performed to compare the accuracy of the Sarns Delphin II Doppler and the Medtronic Bio-Medicus electromagnetic flow probes to actual flow using bovine, porcine, ovine and human blood. The flow probes were incorporated into an *in vitro* extracorporeal circuit. Hematocrit, temperature and flow were randomized over ranges of 15-45% (increment 10%), 22-37°C (increment 5°C) and 1-5 L/min (interval 1 L/min), respectively. Probe flow readings were compared to the measured flow.

Flow probe readings in all species significantly correlated with actual flow ( $p < 0.05$ ). Doppler and electromagnetic probe flow readings significantly differed within species ( $p < 0.001$ ). The doppler percent error positively correlated with hematocrit ( $p < 0.001$ ) in all species except human. The electromagnetic percent error did not consistently correlate with hematocrit or temperature. Neither of the flow probe percent errors correlated with erythrocyte diameter or mean corpuscular volume utilizing the average population measurement. Regression equations were developed to derive actual flow from the doppler probe readings in ruminants. These data will allow investigators to select a flow probe appropriate for the experimental conditions and animal model.

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## INTRODUCTION

Electromagnetic and doppler flow probes are used routinely for both clinical and research applications. Clinically these probes have proven to be extremely accurate in determining blood flow through extracorporeal circuits (1). In the domain of research, their accuracy has been assumed. However, these flow probes are calibrated using human rather than animal blood. The purpose of this study is to determine the accuracy of the Sarns Delphin II doppler and the Bio-Medicus electromagnetic flow probes using bovine, porcine and ovine blood. This data will allow investigators to select a flow probe appropriate for the experimental conditions and animal model.

## MATERIALS AND METHODS

An *in vitro* extracorporeal circuit was constructed using 3/8 inch internal diameter tubing, a roller pump<sup>a</sup>, cardiotomy<sup>b</sup>, membrane oxygenator<sup>c</sup>, hemoconcentrator<sup>d</sup>, Bio-Medicus electromagnetic flow probe<sup>e</sup>, Sarns Delphin II doppler flow probe<sup>e</sup>, pressure monitor<sup>f</sup>, Hemotherm heater/cooler<sup>g</sup> and a modified 1000 ml graduated cylinder. The circuit was primed with normal saline and heparinized. Bovine, ovine, human or porcine blood was added. Activated clotting time was maintained at greater than 480 seconds.

The circuit was designed with two loops (Figure 1). The primary flow pathway was through the probes, which were positioned according to the manufacturers' specifications as discussed below (2-3), and into a graduated cylinder connected to a volume reservoir by a gravity drain line. The secondary loop was utilized as a recirculation loop. Incorporated into the recirculation loop were an oxygenator, heat exchanger and hemoconcentrator to maintain appropriate  $pO_2$  levels, and to vary temperature and hematocrit, respectively. A pressure monitor was placed proximal to the Y-connector and distal to the flow probes in order to maintain a constant pressure seen by the two probes.

To adjust the blood flow, hematocrit or blood temperature, the primary loop was clamped and blood was circulated through the secondary loop until the specific parameter reached the desired test point. The hematocrit tested ranged from 15% to 45% in increments of 10%. Temperature was varied from 22°C to 37°C in increments of 5°C at each hematocrit. Flows were adjusted from 1.0 to 5.0 L/min and altered in one liter increments at each temperature. All parameters were modified in a randomly selected order. Col-

lectively, 855 data points were compiled and analyzed.

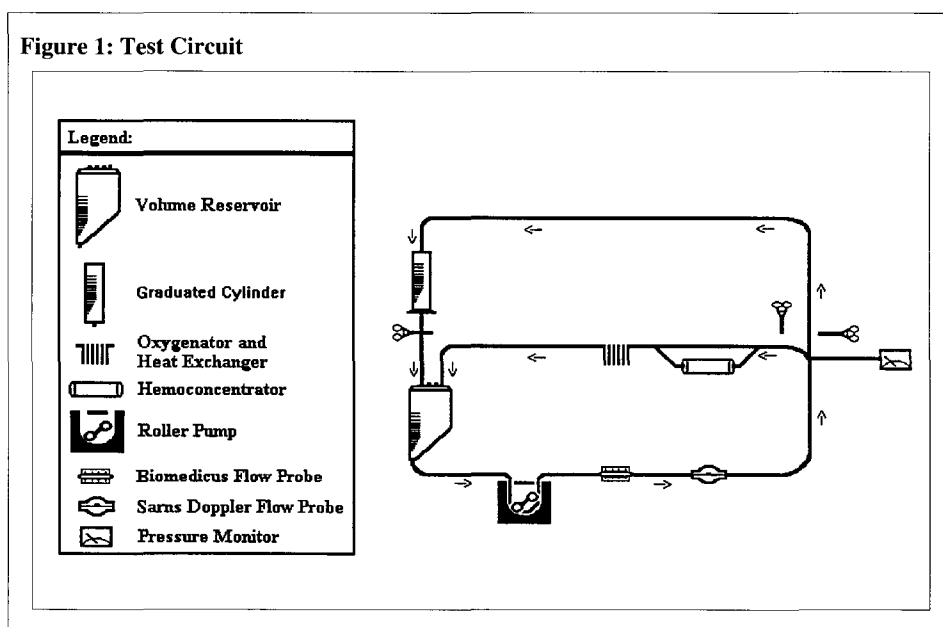
The Bio-Medicus flow probe is a disposable in line sensor which fits into a housing factory calibrated for a specific tubing size. The gain number found on the probe housing is entered into the pump console to obtain an accurate reading. The Sarns doppler flow probe is a clamp-on sensor with a calibration number which is entered into the message display on its pump console. The flow probes were thus calibrated per manufacturers' instructions. The roller pump was set just non-occlusive: 1 cm/min fluid drop at a height of 30 inches (4). These settings were not changed during the study.

When measuring flow the secondary loop and the gravity drain line from the graduated cylinder to the reservoir were clamped and blood was allowed to move from the volume reservoir to the graduated cylinder for 15 seconds. The amount transferred in that time period was multiplied by four to obtain a rate in milliliters per minute (ml/min). This procedure was performed three times at each flow rate for each temperature and hematocrit. The average of these three measurements became the final actual flow in ml/min delivered by the roller pump. If there was a difference of greater than 5% in one of the three measurements at a given flow rate, that measurement was repeated.

The mean percent error from actual blood flow, standard deviation of the percent error and correlation coefficient for

- a Sorin Bomedical, Inc. Irvine, CA 92714
- b BCR 3538 Cardiotomy; Baxter Healthcare Corp., Bentley Division, Irvine CA 92714
- c SMO Membrane Oxygenator; Sarns 3M Health Care, Ann Arbor, MI 48103
- d Bard Cardiopulmonary Division, Tewksbury, MA 01876
- e Medtronic, Inc., Anaheim, CA 92807
- f DLP, Grand Rapids, MI 49501
- g Cincinnati Sub Zero, Cincinnati, OH 45241

Figure 1: Test Circuit



each of the flow probes were calculated. The plasma free hemoglobin, mean corpuscular volume and red blood cell diameter were compared with the mean percent error for each species and flow probe. The flow reported by each of the probes was compared to actual flow. Statistical comparison of percent error for each probe versus hematocrit and temperature by species was made using Student's t-tests, correlation, regression, and ANOVA.

## RESULTS

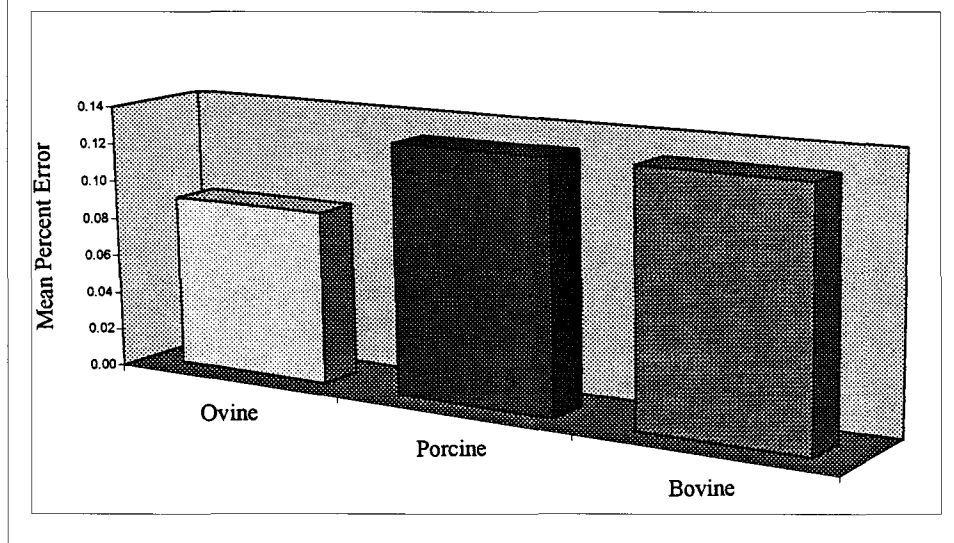
All probe flow readings within each species significantly correlated with actual flow ( $p < 0.01$ ). Doppler and electromagnetic flow probe readings significantly differed within species ( $p < 0.001$ ). Electromagnetic flow probe mean percent error was substantially lower than the doppler flow probe mean percent error in the bovine, porcine and ovine models (Table 1). In all species studied the doppler probe percent error was significantly higher than zero ( $p < 0.01$ ) (Figure 2) and positively correlated with hematocrit ( $p < 0.001$ ) (Figure 3). Conversely, the electromagnetic percent error did not vary consistently with hematocrit or temperature changes. Neither of the flow probe

**Table 1: Mean % error**

	Human	Bovine	Porcine	Ovine
Electromagnetic	-3.6*	-3.25*	-0.07 <sup>∇</sup>	0.05 <sup>∇</sup>
Doppler	4.04	11.94 <sup>^</sup>	12.61 <sup>^</sup>	8.13
Roller	-4.88	-4.75	-2.74	-3.62

\*, ^, <sup>∇</sup> = no significant differences between groups

**Figure 2: Sarns Delphin II doppler flow probe mean percent error**



percent errors correlated with species erythrocyte diameter or mean corpuscular volume. Plasma free hemoglobin measured at regular intervals was found not to correlate with either the electromagnetic or doppler flow probe readings (Table 2).

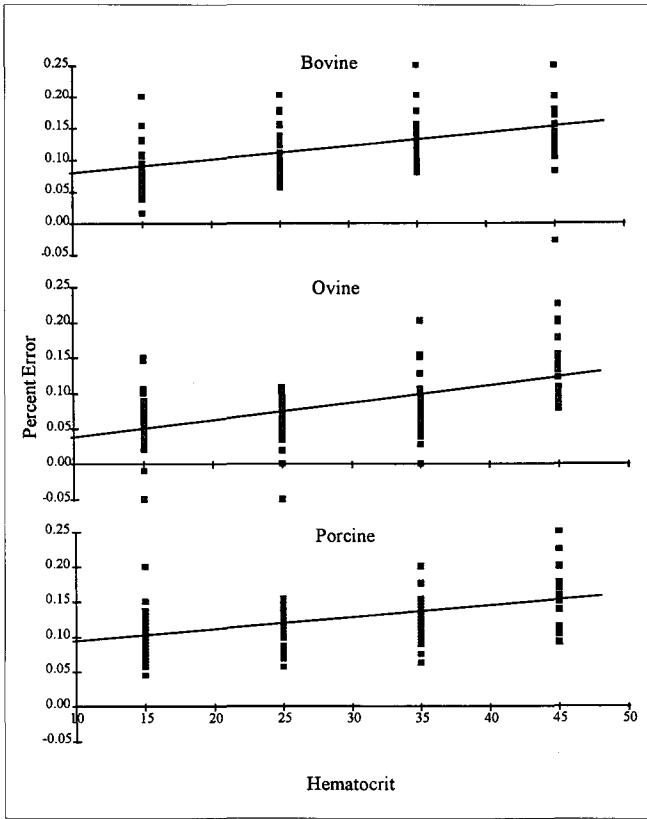
A linear relationship between actual flow and measured flow allowed regression equations to be derived. These regression equations for the Sarns Delphin II doppler flow probe at all hematocrits and temperatures (15% to 45% and 22°C to 37°C, respectively) have been derived for each of the three animal models used in this study (Table 3).

## DISCUSSION

The Sarns Delphin II flow sensor functions by emitting an ultrasonic signal from a transmitting mechanism. The signal is reflected by the red blood cells (RBC) and detected by a receiving transducer. The doppler shift of the ultrasonic echo is related to the flow velocity, and, therefore, the rate at which the blood is flowing can be determined (2). This principle assumes the fluid being used flows with pure laminar characteristics (5). Red blood cells within blood, however, flow with a number of non-laminar characteristics. Thus the number of RBC's per unit volume flowing through the probe may significantly affect the reading of the reflected ultrasonic signal. The RBC's in all species tested are 23% to 30% smaller in diameter than that of the human RBC, which has a mean diameter of 7.7 microns (6,7). There are consequently more RBC's per unit volume at a given hematocrit in bovine, porcine and ovine than in human blood. The greater number of RBC's per unit volume at a given hematocrit in the former groups will accentuate any non-laminar effects. With diverse signals reaching the doppler flow probe skewed readings may result.

Conversely, the percent error of the electromagnetic flow probe measurements were not hematocrit or temperature dependent. This finding also likely relates to the flow probe design. The Bio-Medicus probe operates by utilizing two electrodes located on opposite sides of the probe in a plane perpendicular to both the magnetic field and the direction of blood flow. An electrical current is used to energize the transducer's electromagnet. Blood flowing through the probe cuts through the magnetic lines of force at a right angle creating an electrical current. The resulting voltage is sensed by the electrodes and is directly proportional to the velocity of blood flow (3). Theoretically, this inductive current should be largely temperature and hematocrit independent. It has been previously shown that he-

**Figure 3: Sarns Delphin II doppler flow probe percent error vs. hematocrit**



matocrit will affect the electromagnetic flow probe reading (1). However, the present study was unable to document a consistent correlation between hematocrit and the electromagnetic flow probes' percent error in the animals tested.

**CONCLUSION**

In summary, the Sarns Delphin II doppler flow probe percent error was found to be hematocrit dependent in the bovine, ovine and porcine models. With this in mind, if a study using these animals requires flows to be more precise than the reported errors, we suggest using the appropriate regression equation to more accurately determine actual flow (Table 3). Since the Bio-Medicus electromagnetic flow probe percent error did not consistently correlate with hematocrit or temperature in these three animal models, a regression equation is unnecessary providing a small degree of random error is acceptable to the investigator. This data should allow investigators to select a flow probe appropriate for the experimental conditions and animal model, with a better appreciation of their accuracy limitations.

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**Table 2: Percent error, mean corpuscular volume, mean red blood cell diameter, and plasma free hemoglobin correlation table**

	Mean Corpuscular Volume	Mean RBC Diameter	Plasma Free Hemoglobin at 15% Hct.	Plasma Free Hemoglobin at 25% Hct.	Plasma Free Hemoglobin at 35% Hct.	Plasma Free Hemoglobin at 45% Hct.
% Error at 15% Hct.	-0.11936	-0.56938	-0.2072	-0.40126	-0.20676	-0.39878
% Error at 25% Hct.	-0.09687	-0.55966	-0.27492	-0.41301	-0.22867	-0.40742
% Error at 35% Hct.	-0.13509	-0.50435	0.1416	-0.2479	-0.0211	-0.25876
% Error at 45% Hct.	0.048326	-0.41013	-0.08033	-0.21655	-0.01357	-0.21458

Critical Value: .8783 (p<0.05)

**Table 3: Sarns Delphin II doppler flow probe regression equations**

	Bovine	Porcine	Ovine
Equation	0.932841D + 0.0510223	0.918350D + 0.0315621	0.941151D + 0.0583082

D = Sarns Delphin II doppler flow reading

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