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Volumetric Measurement of Pulsatile Flow *Via* Ultrasound Time–Domain Correlation

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ABSTRACT

Previous research has shown that the application of ultrasound time-domain correlation (UTDC) can be used to measure accurately and precisely volumetric flow under continuous flow conditions without previous knowledge of the vessel size, flow velocity profile, or transducer measurement angle. This paper presents the results of applying the UTDC technique to estimate volumetric flow under pulsatile flow conditions and shows that pulsatile flow can be measured with similar accuracy as continuous flow.

INTRODUCTION

THE QUANTITATIVE KNOWLEDGE of volumetric blood flow, blood flow velocity profile, as well as the vessel diameter are important parameters in the diagnosis of vascular disease. Current clinical blood flow measurement techniques include invasive methods such as dye dilution, the Fick technique, angiography, and the electromagnetic flowmeter.[1] Because of their invasive nature, these methods exhibit a small but definite risk of physical harm. They also do not have the means to detect flow velocity as a function of range. The primary noninvasive method of blood flow measurement is the use of Doppler ultrasound which has the advantage of being noninvasive, as well as the ability to measure flow velocity *vs.* range.[2] Unfortunately, Doppler ultrasound has theoretical and practical problems that limit it to being only a qualitative clinical tool.[3–5] For these reasons, an ultrasonic technique using time-domain correlation has been developed as a quantitative alternative to Doppler ultrasound. The ultrasound time-domain correlation (UTDC) technique has a theoretical precision of 5% as opposed to 85% for Doppler ultrasound,[6] and previous research has shown this technique to measure accurately and precisely continuous flow in a circular vessel.[7] The purpose of this research is to validate that the time-domain correlation technique can be used to measure accurately and precisely pulsatile volumetric flow.

BACKGROUND

Figure 1 illustrates the UTDC flowmeter concept in which an ultrasonic transducer is oriented at an angle θ with respect to the blood vessel axis. At time t_0 an ultrasonic pulse is transmitted. It will take a round trip time t_1 for the pulse to travel between the transducer and scatterer at position 1. If the next pulse is initiated at $t = t_0 + T$, the scatterer will have moved to position 2, and the round-trip transit time will be t_2. The axial distance d_A the scatterer has moved in the direction of the ultrasonic beam is

$$d_A = (t_1 - t_2)c/2 \tag{1}$$

where c is the speed of sound in the medium. The distance d the scatterer has moved down the vessel is $d_A/\cos(\theta)$, where θ is the measurement angle (also called the Doppler angle), and therefore, the scatterer velocity is (assuming $V_s \cos(\theta) << c$)

$$V_s = \frac{(t_1 - t_2)\, c}{2T\cos(\theta)} \tag{2}$$

The actual ultrasonic echo is affected by all scatterers in the ultrasonic beam, as illustrated in Fig. 2. In this figure, E_1 is the echo due to volume 1 (V_1), which has almost moved out of the ultrasonic beam due to motion of scatterers within the vessel. E_2 is the echo due to volume 2 (V_2), which is shown totally within the beam. Conceptually, if the time between the initiation of pulse transmissions is chosen such that some of the original

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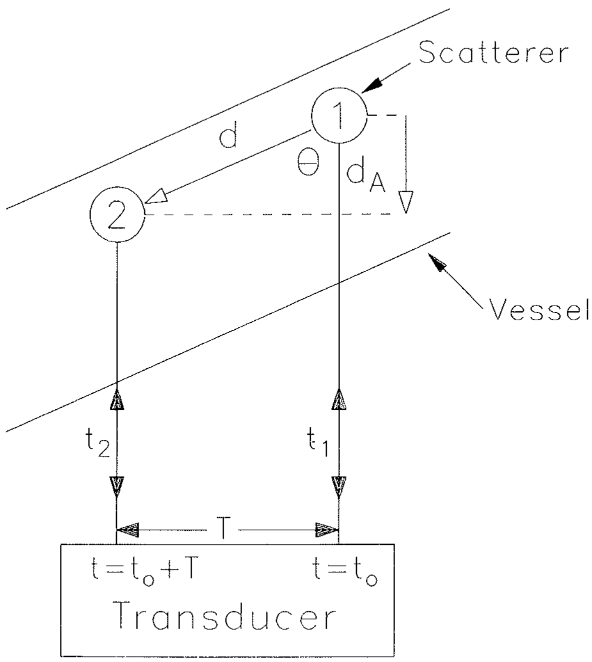

FIG. 1. Ultrasound time–domain flowmeter concept. The velocity of a scatterer can be calculated from the transit times of two ultrasonic pulses reflected from the scatterer at two positions along the vessel.

scatterers remain common to both pulses (shaded areas of V_1 and V_2), then these common volume sections will produce similar sections of echoes in E_1 and E_2 (emphasized sections of E_1 and E_2).

To calculate the time shift between these two similar sections of echoes, the echoes are correlated with each other. This process is illustrated in Fig. 3 assuming a point scatterer. If $E_1(t)$ and $E_2(t)$ represent the signals from two echoes received at different times from a moving scatterer, the correlation can be pictured as shifting E_1 back in time by some value of τ and multiplying by E_2 to produce the correlation coefficient $R(\tau)$. Mathematically, this can be expressed as

$$R(\tau) = \sum_t E_1[t + \tau]E_2[t] \tag{3}$$

The value of τ which produces a maximum in the correlation function $R(\tau)$ corresponds to the time shift $t_1 - t_2$, and Eq. 2 can be used to calculate the scatterer velocity. The background is more thoroughly presented in Refs. 4 and 6.

MATERIALS AND METHODS

Pulsatile flow was generated in a blood flow phantom system over the range of 0 to 150 beats/min. The flow velocity profile

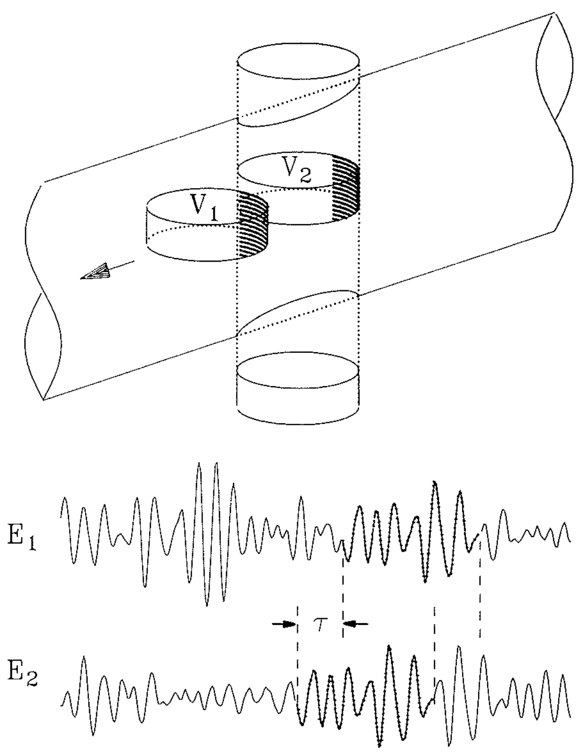

FIG. 2. The actual ultrasonic echoes are due to all of the scatterers within the ultrasonic beam. E_1 is the echo due to volume V_1, which has almost moved out of the beam. E_2 is the echo due to volume V_2, still within the beam. The common sections of V_1 amd V_2 will produce similar sections of echo in E_1 and E_2.

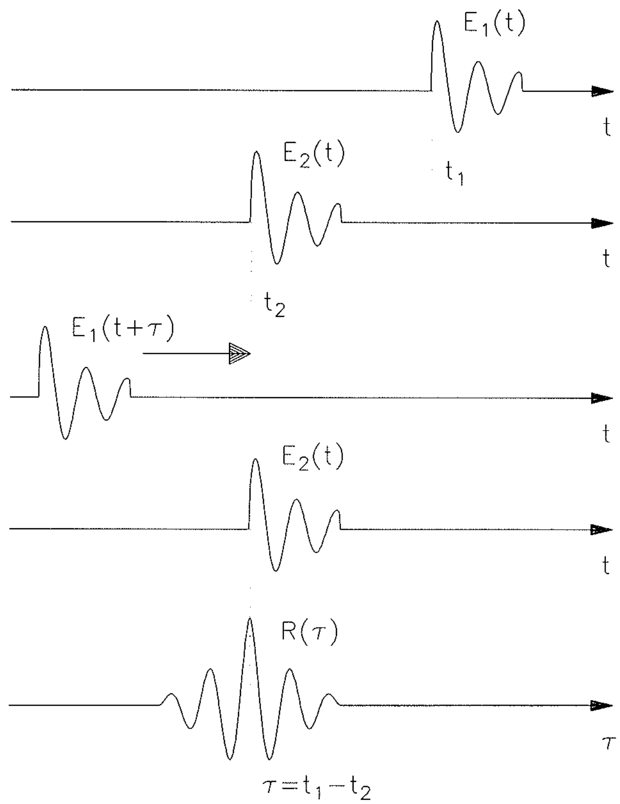

FIG. 3. The correlation of two echoes consists of shifting one echo back in time by τ and multiplying it by the other to produce the correlation value $R(\tau)$. The value of τ which produces the maximum $R(\tau)$ corresponds to the time shift $t_1 = t_2$.

was measured across the vessel using the UTDC technique. The transducer measurement angle, the vessel wall diameter, and the total volumetric flow rate were calculated from the flow velocity profile. The volumetric flow through the vessel was also measured with a calibrated electromagnetic flowmeter, which was used as the reference.

Blood flow phantom

Figure 4 illustrates the blood flow phantom system used to generate pulsatile flow. The phantom is capable of producing both continuous flow and pulsatile flow. Continuous flow is set by adjusting the height difference H between the upper and lower reservoirs. A pulsatile pump, which consists of a syringe moved in and out by a motor, is in series between the upper and lower reservoirs. When the pulsatile pump is off, only constant, non-time varying flow is present. When the pulsatile pump is on, a peak-to-peak flow component oscillates around an average flow component. The fluid passes through a minimum entrance length E of straight dialysis tubing before the transducer measurement point to insure that fully developed laminar flow exists for all flow rates (both pulsatile and continuous) used in our experiments.[8] The resting inside diameter of the dialysis tubing is 6.5 mm. The phantom was calibrated by measuring the time required for the lower reservoir to be filled with a given volume of liquid. This hydrodynamic flow rate, the reference volumetric flow rate, has an accuracy of ±0.7%.

The fluid used in the blood flow phantom system is distilled water mixed with Sephadex (G-50; 20–80 μm diameter, Pharmacia Fine Chemicals, Uppsala, Sweden). This mixture has been determined to reflect ultrasound in a similar manner as flowing blood.[7]

Data acquisition

Ultrasonic pulses were generated with a 5-MHz transducer and echo signals were digitized and stored at 50 MHz by a custom-designed ultrasonic data acquisition system[6,7] con-

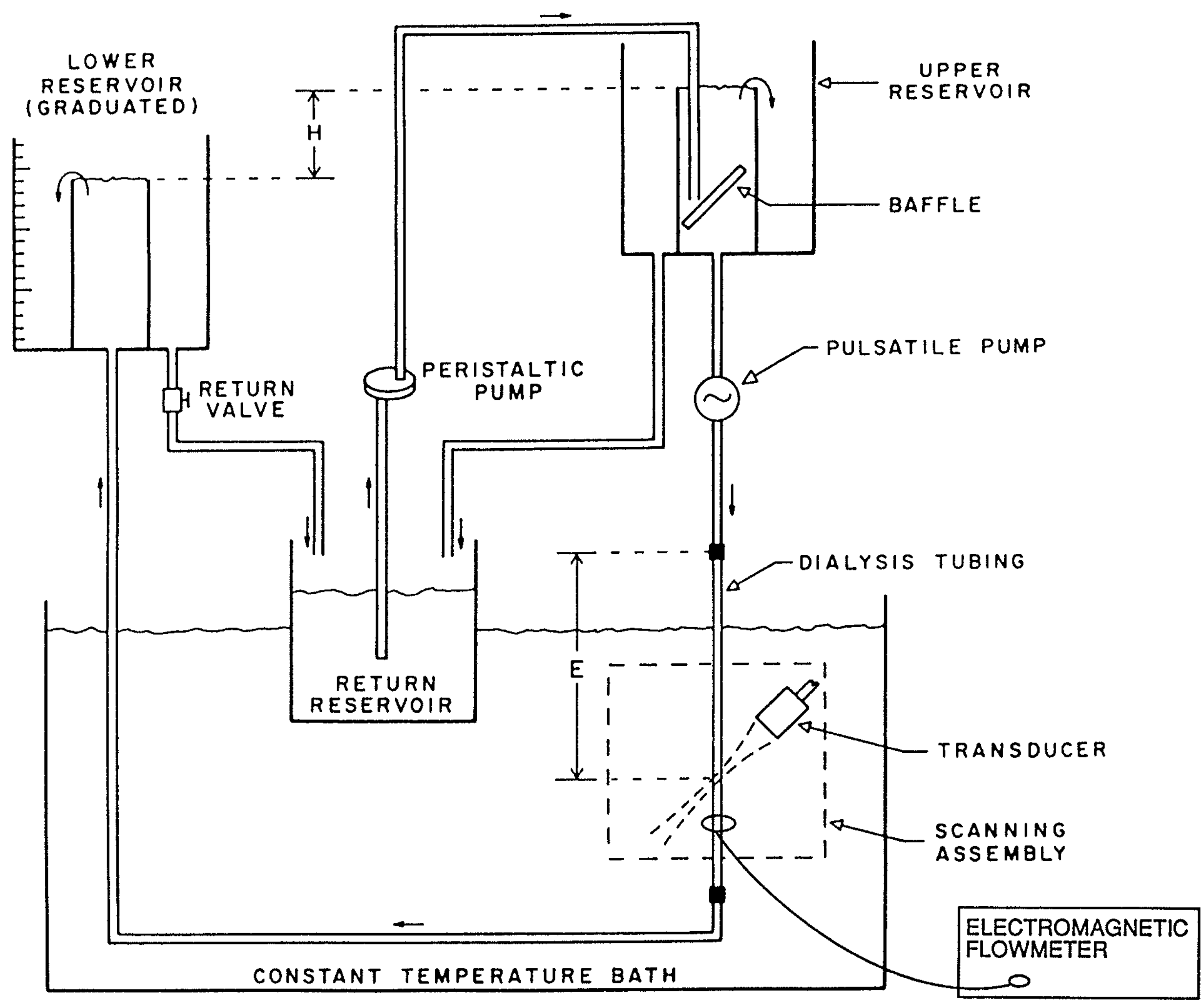

FIG. 4. Illustration of the blood flow phantom system used in pulsatile experiments. Continuous and pulsatile flow can be set independently, and the flow is also measured by an electromagnetic flowmeter.

trolled by a COMPAQ 386/20 microcomputer. The calculation and plotting of velocity, flow rates, *etc.*, were all done with the COMPAQ 386/20.

Flow determination

Figure 5 illustrates the transducer configuration as it is set up in the blood flow phantom system. A one-dimensional velocity scan consists of 25 equally spaced axial flow velocity estimates in the focal region (5 cm axially) of the transducer beam. A two-dimensional velocity scan consists of a number of one-dimensional scans such that the entire vessel cross section is sampled. From two-dimensional scan data, ellipses are curve-fit to M constant flow levels, which produces M ellipses, as shown in Fig. 6 for $M = 10$. The transducer measurement angle θ can be calculated from the ratio of ellipse minor axis to major axis by the equation:

$$\theta = \frac{1}{M} \sum_{n=0}^{M-1} \sin^{-1}\left[\frac{A_n}{B_n}\right] \qquad (4)$$

where $n = 0$ represents the outermost ellipse (position of vessel wall) and A_n and B_n are the minor and major axes, respectively, of the nth ellipse. Once the angle is known, the volumetric flow rate (Q) can be determined for fully developed laminar flow from the equation[9]

$$Q = 0.5\ V_{\max} A/\cos(\theta) \qquad (5)$$

where $V_{\max}$ is the maximum velocity at the center of the vessel and A is the cross-sectional area of the vessel $\pi(A_0/2)^2$. The current data acquisition system was originally designed to measure continuous, time-invariant flow, and is not fast enough to perform a two-dimensional scan for pulsatile flow.[7] Hence, the transducer measurement angle was determined from a two-dimensional scan for continuous flow only with the pulsatile pump off. Later, the pulsatile pump was turned on, and pulsatile flow was determined from one-dimensional scans through the center of the vessel, which provides $V_{\max}$ and the vessel diameter, A_0. The volumetric flow was determined using Eq. (5) at the maximum and minimum flow peaks of the pulsatile flow waveform. The peak-to-peak flow was calculated by subtracting the minimum flow from the maximum, and the average flow was calculated by adding the minimum and maximum and dividing by 2.

The volumetric flow was also measured by a Zepeda Instruments SWF-5RD electromagnetic flowmeter which has an accuracy of ±3%.[10] The output of the flowmeter was digitized and stored on a personal computer. The electromagnetic flowmeter was calibrated for each experiment by performing hydrodynamic flow measurements at the maximum and minimum flow peaks. The volumetric flow determined by the ultrasound time-domain correlation (UTDC) technique was then compared to the volumetric flow determined by the electromagnetic flowmeter for evaluation.

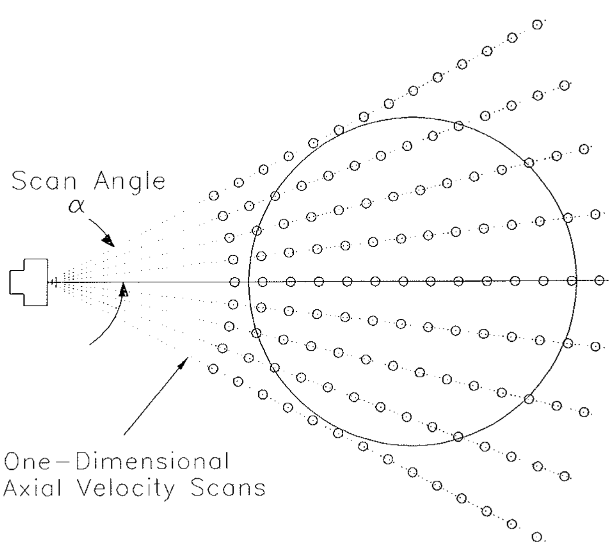

FIG. 5. A two-dimensional velocity measurement consists of performing a number of different one-dimensional axial velocity scans such that the velocities across the entire vessel are sampled.

RESULTS

A total of 25 experiments ranging from 50 to 150 beats/min (b/m) were made, with flow rates ranging from approximately 50 to 1100 ml/min. Constant flow experiments were also performed throughout the range of volumetric flows to ensure the flow was laminar. Figure 7 shows the measured three-dimensional velocity profile at 100 ml/min. The flow was shown to be fully developed and laminar to at least 1000 ml/min. Figure 8 shows the elliptic curve fit to data at a constant flow rate of 462 ml/min. The hydrodynamic flow measured to be 449 ml/min, a 3% error. The measurement angle θ was set at 45° and estimated from Fig. 8 to be 51.9°.

Pulsatile flow experiments

Volumetric Flow: The pulsatile volumetric flow was calculated by performing one-dimensional scans through the center of the vessel. Figure 9 shows that the velocity profile at the maximum and minimum flow peaks is approximately parabolic, and also shows the vessel wall diameter expands to 8 mm at the maximum flow peak and contracts to 4.5 mm at the minimum flow peak.

Table 1 shows the results of all of the pulsatile experiments made. The vessel wall diameter, the maximum and minimum flow peaks, the peak-to-peak and average flow calculated from the maximum and minimum peaks, and the error referenced to the electromagnetic flowmeter are shown.

Flow vs. *Time:* Figure 10, a and b, shows flow *vs.* time for 86, 100, 120, and 150 b/m as measured by the electromagnetic flowmeter and as measured by the UTDC technique, respectively. The electromagnetic flowmeter is only capable of measuring volumetric flow through the vessel, hence the total volume flow *vs.* time is plotted in Fig. 10a, while the velocity at the center of the vessel (beamwidth of 0.8 mm and cell length of 0.6 mm) *vs.* time is plotted in Fig. 10b. The volumetric flow

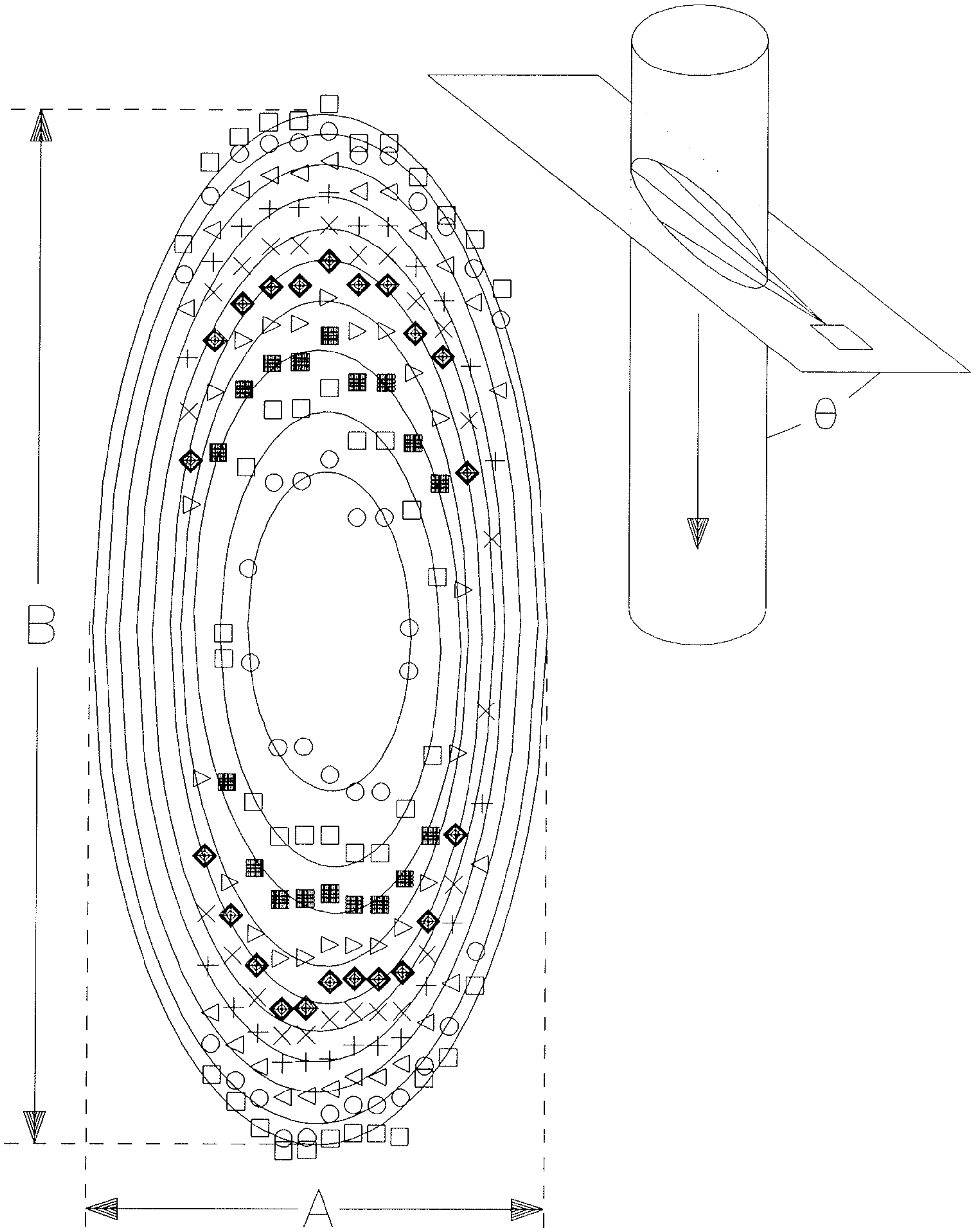

FIG. 6. The transducer measurement angle can be calculated from the major and minor axes of ellipses curve fit to velocity data.

rates have also been shown at the maximum and minimum flow peaks.

DISCUSSION

Volumetric flow

A summary of the UTDC technique measurement errors as compared to the electromagnetic flowmeter measurement is plotted in Fig. 11. The errors between the ultrasonic and electromagnetic flowmeter measurements were within about 18% for both the peak-to-peak and average flow up to 125 b/m (see Table 1). The average flow error appears to increase to 24% at 150 beats/min. This is mainly due to the error in the measurement of the minimum flow peak, which has a much larger error than the maximum flow peak. The errors in the maximum flow measurements are within 15%; however, the minimum flow errors vary widely and are almost always positive. There are three possible sources of error to account for a greater error at minimum flow compared to maximum flow conditions.

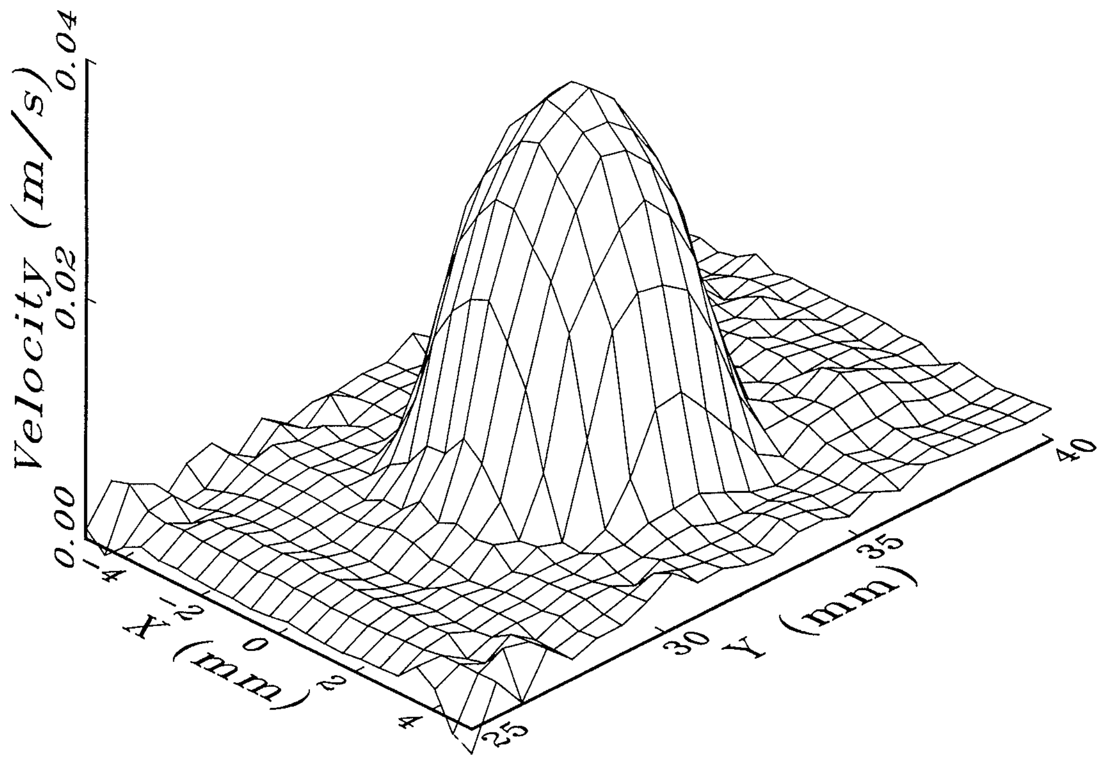

FIG. 7. Three-dimensional velocity perspective of flow within the vessel.

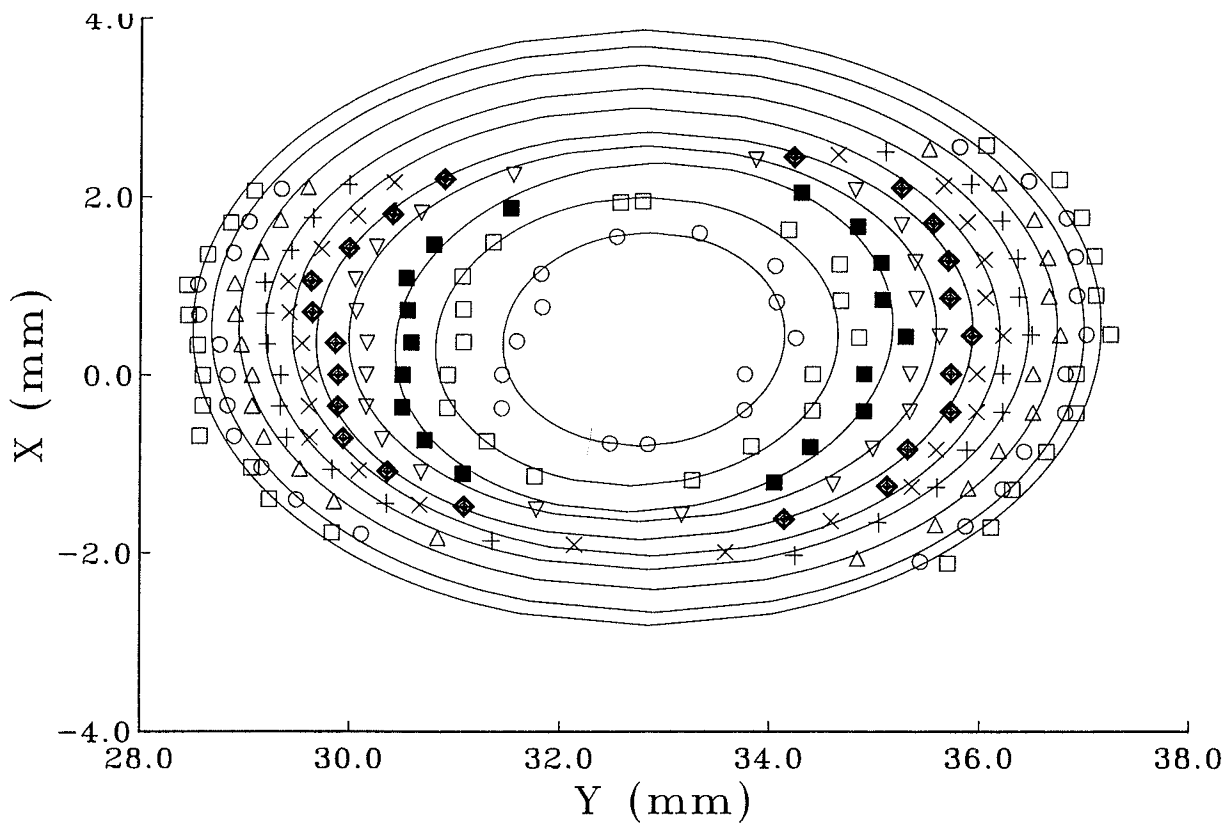

FIG. 8. Constant velocity ellipses used to calculate the transducer measurement angle for the pulsatile experiments. The angle was calculated to be 51.9°.

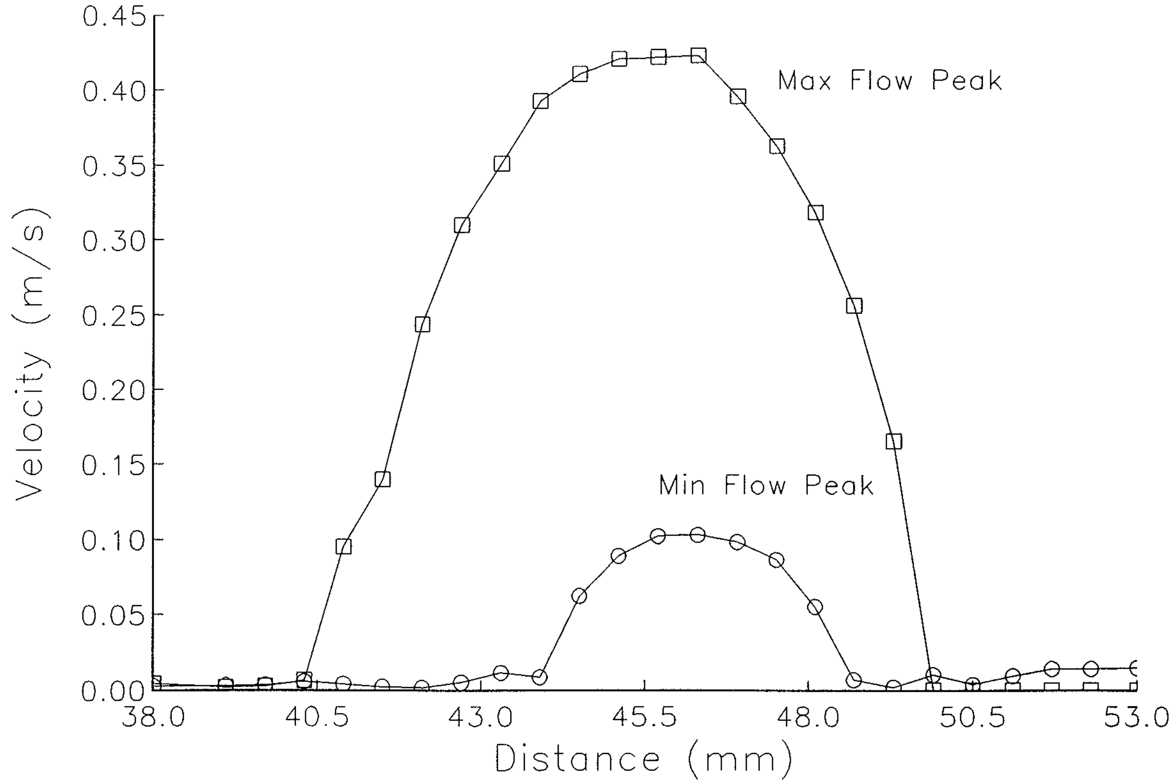

FIG. 9. Velocity profiles of the maximum and minimum flow peaks at 120 b/m. The profiles are approximately parabolic and illustrate how the vessel wall diameter changes.

A major source of error appears to be due to the electromagnetic flowmeter probe. The probe has an internal diameter of 6 mm; the normal diameter of the dialysis tubing is approximately 6.5 mm. Since the dialysis tubing is elastic, it changes diameter with the changing flow rate. It expands to a maximum diameter at the maximum flow peak and contracts to a minimum diameter at the minimum flow peak. From Table 1, it is apparent that for most of the experiments the minimum vessel wall diameter is under 6 mm, which causes the electromagnetic flowmeter measurement to be less reliable. In extreme cases the probe totally lost contact with the vessel, which causes zero measured flow rate by the electromagnetic flowmeter. This is demonstrated in Fig. 10a for 150 b/m where the electromagnetic flowmeter indicates a minimum flow rate of zero, while the UTDC technique measurement indicates a minimum flow of 77 ml/min. This is due to the fact that the vessel walls have lost contact with the electromagnetic flowmeter probe. This caused the large error of 24% in the average flow measurement of experiment I40.

A second source of error is that the minimum flow rates were near the lower limit of the dynamic range of the electromagnetic flowmeter. The maximum flow rates measured were 1100 ml/min; on this scale, measurements under 100 ml/min are less accurate.

This also may be true of the ultrasonic measurement. As a third source of error, the precision of the time–domain correlation technique is, in part, dependent on the pulse repetition period. For time-varying flow, faster flow velocities require a smaller period (higher PRF), while slower velocities require a larger period (lower PRF). The time–domain technique currently calculates the time shift from 10 consecutive echoes (45 echo pairs), which is an effective period range of T to $9T$. The fundamental period T was set such that the maximum flow velocities were most accurately measured; it is possible that the minimum flow velocities were slower than could be accurately measured at 9T. To remedy this, more than 10 echoes may need to be used to produce a larger dynamic range.

In general, the error in the minimum flow peak has a much smaller effect on the overall error than the error maximum flow peak, since its value is small compared with the value of the maximum flow peak. Hence, the overall error for the pulsatile flow experiments was within about 18% (except for experimental I40).

Flow vs. *time*

A number of important observations can be made from the flow *vs.* time plots in Fig. 10. One is that the shape of the waveforms as measured by the UTDC technique match those as measured by the electromagnetic flowmeter very well. At first glance, the UTDC technique measurements appear more "noisy" than the electromagnetic flowmeter measurements. One reason for this is that the ultrasonic measurement is estimated from a small range cell at the center of the vessel, while the

TABLE 1. RESULTS OF PULSATILE FLOW EXPERIMENTS

Data Set	Frequency		Walls (mm dia)		Max Peak (ml/min)		Error	Min Peak (ml/min)		Error	Pk-Pk Flow (ml/min)		Error	Average Flow (ml/min)		Error
	Hz	BPM	Max	Min	UTDC	EMF	(%)	UTDC	EMF	(%)	UTDC	EMF	(%)	UTDC	EMF	(%)
C120	.83	50	7.06	5.88	419	426	- 1.6	122	134	- 8.9	297	292	- 1.5	270	280	+ 3.5
W120			6.68	5.48	396	423	- 6.3	131	147	-10.8	264	275	+ 3.8	263	285	+ 7.6
P100	1.00	60	7.19	5.12	405	423	- 4.2	87	71	+22.5	318	352	+ 9.9	246	247	- 1.8
B100			7.18	5.76	423	427	- 0.9	91	63	+44.4	331	363	+ 8.8	256	245	- 4.5
C100			7.09	4.60	429	445	- 3.5	63	65	- 3.1	366	380	+ 3.4	246	254	+ 3.4
W100			6.76	5.22	384	444	-15.6	100	100	0.0	283	343	+17.3	272	241	+11.0
C90	1.11	67	7.31	4.97	428	445	- 3.8	36	28	+28.6	374	417	+10.0	236	240	- 1.8
B80	1.25	75	7.56	5.60	531	511	+ 3.9	67	0		462	510	+ 9.5	299	255	-17.0
D80			7.10	4.60	487	537	- 9.3	42	0		446	537	+16.8	268	265	+ 1.2
W80			6.65	5.22	425	478	-11.1	87	67	+40.3	338	415	+18.5	270	255	+ 5.3
F80			7.48	4.65	520	495	+ 5.5	98	62	+58.1	421	432	+ 2.4	278	309	-10.9
G80			7.06	4.50	449	460	- 2.3	73	53	+37.8	375	407	+ 7.7	260	256	- 1.5
I80			7.36	6.37	874	818	+ 6.8	450	433	+ 6.3	424	385	+10.1	662	625	+ 5.9
F70	1.43	86	7.65	4.52	576	505	+14.1	73	47	+55.3	503	457	- 9.9	324	276	-17.6
G70			7.68	4.67	599	556	+ 7.7	94	82	+14.6	505	474	- 6.6	346	319	- 8.6
I70			7.25	5.88	801	797	+ 0.5	321	352	- 8.8	480	445	- 7.9	560	574	+ 1.1
X70			7.30	5.22	907	902	+ 0.5	84	0		822	901	+ 8.7	495	450	- 9.9
F60	1.67	100	7.70	4.52	824	759	+ 8.5	100	47	+ 112	728	711	- 2.3	464	403	-15.2
G60			7.23	4.78	667	674	- 1.0	115	70	+64.8	551	604	+ 8.6	393	372	- 5.2
I60			7.48	5.18	817	793	+ 3.0	192	196	- 2.1	625	595	- 4.9	504	494	- 1.8
F50	2.00	120	8.41	4.51	1022	957	+ 6.7	77	0		946	956	+ 1.2	549	478	-14.8
G50			7.83	4.66	962	870	+10.4	133	97	+37.1	828	773	- 7.2	547	484	-13.1
I50			7.87	5.29	992	982	+ 1.0	194	113	+71.7	798	868	+ 8.1	593	547	- 8.3
H40	2.50	150	8.61	4.83	1047	901	+16.2	98	67	+46.3	949	832	-14.0	572	483	-18.3
I40			8.64	4.59	1095	959	+14.1	99	0		995	959	- 3.8	597	479	-24.4

electromagnetic flowmeter is measuring the average of the flow velocities across the entire vessel cross section. The averaged waveform will naturally look smoother than the non-averaged waveform.

Another interesting observation is that the flow *vs.* time waveform shape changes from a sinusoid at 86 b/m to a ramp wave at 150 b/m. At low frequencies, the displacement of fluid by the syringe in the pulsatile pump can be described as

$$d = D \sin(\omega t) \tag{6}$$

where d is displacement, ω is the fundamental frequency, and D is the maximum syringe displacement. The flow velocities will be proportional to the derivative of the displacement, or

$$v \propto D\, \omega \cos(\omega t) \tag{7}$$

which indicates the amplitude should increase linearly with frequency. For low frequencies, this model is valid. However, at higher frequencies, the effects of the elasticity and motion of the vessel walls as well as inertia and viscosity of the liquid become significant.[11] This has the effect of generating higher-amplitude harmonics, which changes the flow *vs.* time waveform from sinusoidal to ramp-like in nature.

CONCLUSION

Previous research[4,6,7] has shown that the UTDC technique can measure continuous volumetric flow in a circular vessel with an accuracy of about 15%. The work reported herein has shown that it can measure pulsatile volumetric flow in the frequency and flow ranges found in blood vessels with similar accuracy. These results indicate that the UTDC technique may be a quantitative alternative to Doppler ultrasound, and a blood flowmeter for validating the UTDC technique under *in vivo* conditions is currently under construction.

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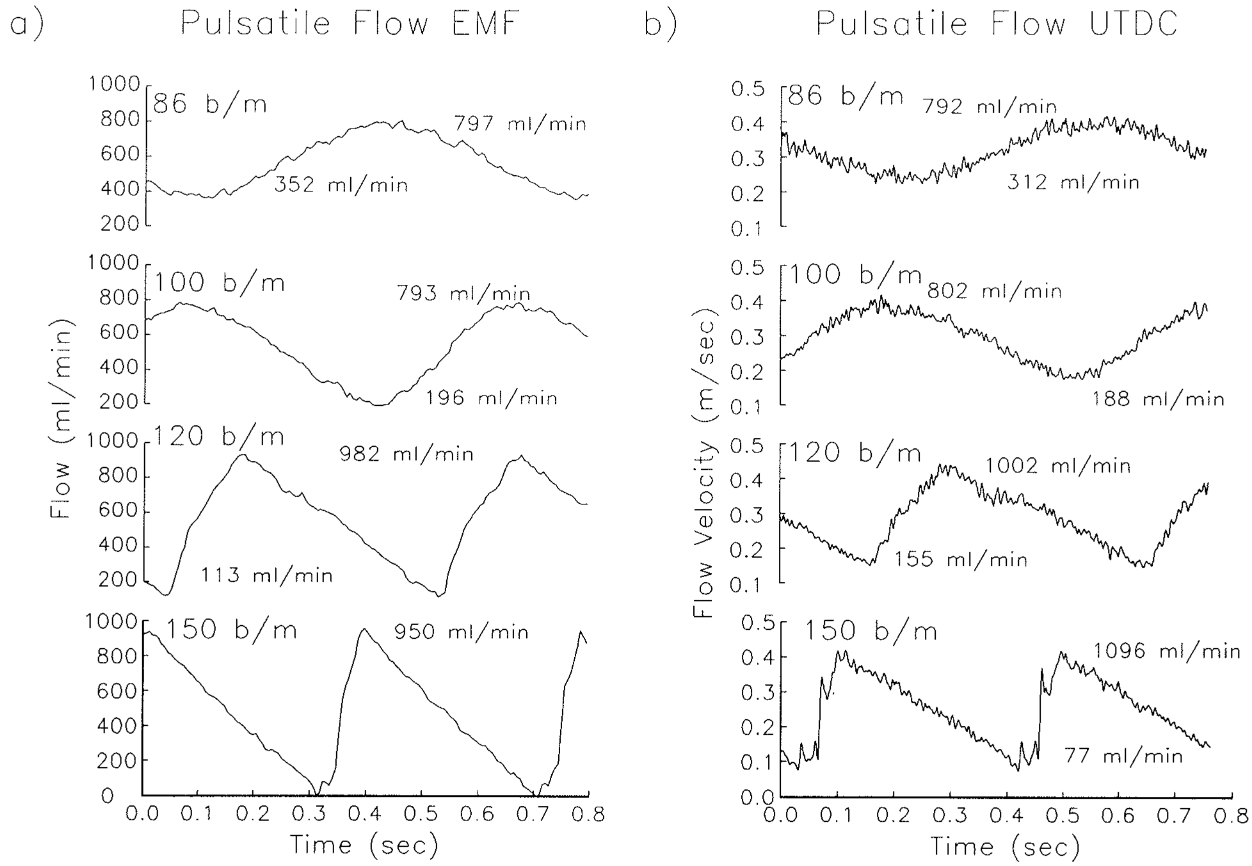

FIG. 10. a. Pulsatile flow measured by the electromagnetic flowmeter. The total volumetric flow in ml/min is plotted. b. Pulsatile flow measured by the UTDC technique. The velocity in m/sec of the range cell at the center of the vessel is plotted.

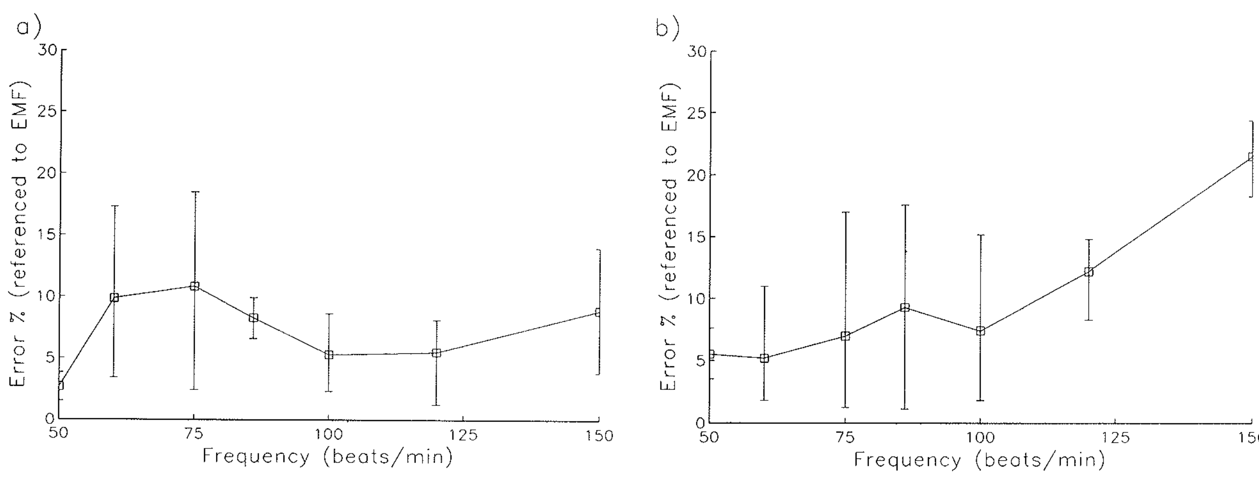

FIG. 11. a. Error of the UTDC peak-to-peak flow measurements as compared to the EMF. b. Error of the UTDC average flow measurements as compared to the EMF. These graphs represent a composite of all pulsatile experiments performed. A number of experiments were performed at each frequency (see Table 1) and the error bars show the maximum and minimum errors encountered for a given frequency.

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