# ACCURATE AND PRECISE MEASUREMENT OF BLOOD FLOW USING ULTRASOUND TIME DOMAIN CORRELATION

I. A. Hein, V. Suorsa, J. Zachary, R. Fish,
J. Chen, W. K. Jenkins, and W. D. O'Brien Jr.
Dept. of Electrical and Computer Engineering
University of Illinois, Urbana, IL

ABSTRACT

**The goal of this research is to produce an ultrasonic device to assist in the diagnosis of venous thrombosis in humans. The Ultrasound Time Domain Correlation technique can accurately and precisely estimate the volumetric fluid flow through a circular vessel without prior knowledge of the vessel diameter, flow velocity profile, or transducer measurement angle. This technique estimates the change in ultrasound arrival time (instead of frequency) of ultrasound reflected from scatterers. A system based on this technique has been constructed and the technique has been verified in a blood flow phantom system with both a blood mimicking substance and porcine blood. Under *in vitro* conditions, the measurement angle has been determined within 5%, and continuous and pulsatile volumetric flow has been measured to 150 beats/minute with an accuracy better than 18%. The effects of tissue attenuation have also been examined *in vitro* by surrounding the vessel with tissues. *In vivo* measurements with canine subjects indicate that blood flow velocity (the 1-D problem) measurements have an accuracy of better than 20%.**

## 1. INTRODUCTION

The quantitative knowledge of volumetric blood flow, blood velocity profile, as well as the vessel diameter are important quantities 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 [9]. These methods are inherently dangerous because of their known potential for harm. They also do not have the means to estimate flow velocity at a given distance. The primary noninvasive blood flow measurement method is Doppler ultrasound which have the advantages of being noninvasive and safe, as well as the ability to measure flow velocity *vs* range [1]. Unfortunately, Doppler ultrasound has theoretical and practical problems which limit it to being only a qualitative clinical tool [5] [3]. 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 [4], and previous research has shown that the UTDC technique can measure laminar flow in a circular vessel with an accuracy of 15% [4]. This current research examines the performance of this technique under *in vitro* conditions which more closely resemble flow in the human body. The *in vitro* experiments were performed in a blood flow phantom with occluded vessels, with various types of animal tissue interposed between the transducer and the vessel to examine the effects of tissue attenuation, and with pulsatile flow over the range of 0 to 150 beats per minute. *In vivo* experiments were also performed in canine subjects by interfacing the UTDC system to a commercial diagnostic ultrasound machine.

## 2. THEORY:

Figure 1 illustrates the UTDC flowmeter concept. In this figure an ultrasonic transducer is oriented at an angle $\Theta$ with respect to the blood vessel axis. At time t=0 a scatterer is in position 1. If an ultrasonic burst is transmitted at this time, then it will take a round trip time $t_1$ for the ultrasound signal to leave the transducer, be reflected from the scatterer, and return. If the next burst is fired at t=T, the scatterer will have moved to position 2, and the round trip transit time will be $t_2$. The distance d' the scatterer has moved in the direction of the ultrasonic beam is

$$d' = \frac{(t_1 - t_2)\, c}{2} \tag{1}$$

where c is the speed of sound. The distance d the scatterer has moved down the vessel is $\frac{d'}{\cos(\Theta)}$ and since velocity is distance/time, the scatterer velocity is

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

The actual ultrasonic echo will be due to all scatterers in the ultrasonic beam, illustrated in figure 2. In this figure, $E_1$ is the electrical signal from the echo due to volume 1, which has almost moved out of the ultrasonic beam due to motion of scatterers within the vessel. $E_2$ is the signal due to volume 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 scatterers remain common to both pulses (shaded areas of $V_1$ and $V_2$), then these common volume sections will produce similar sections of signals 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 signals, the signals are correlated with each other. This process is illustrated in figure 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, then the correlation can be pictured as shifting $E_1$ back in time by some

0090-5607/89/0000-0881 $1.00 © 1989 IEEE

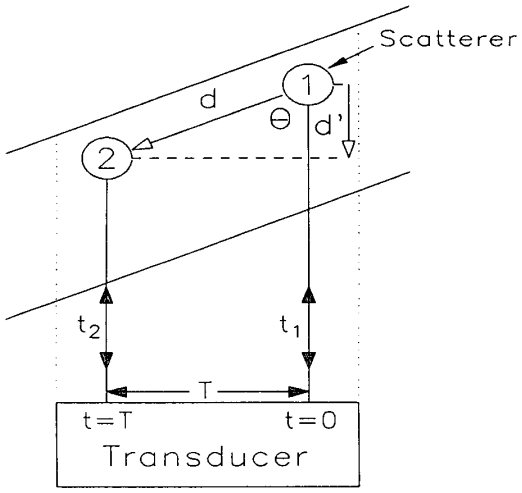



Figure 1: Ultrasonic Time Domain Correlation (UTDC) Flowmeter Concept

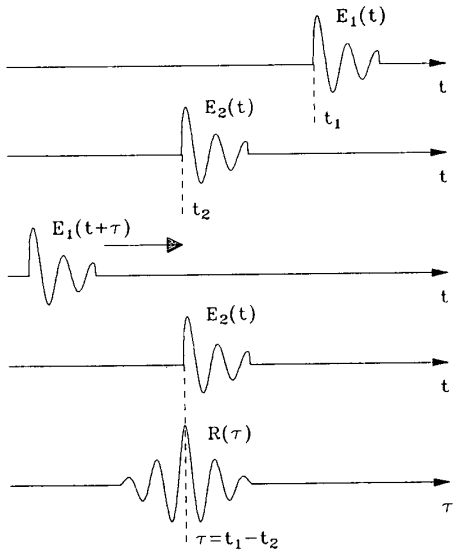
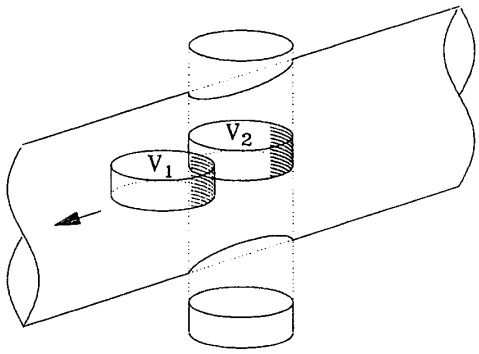



Figure 3: Correlation of Signals from Two Echoes



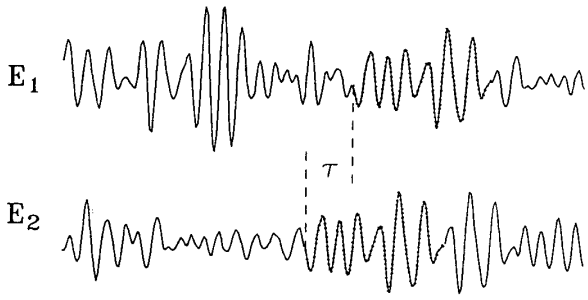




Figure 2: Volumes Sampled by Two Ultrasonic Pulses and their Echoes

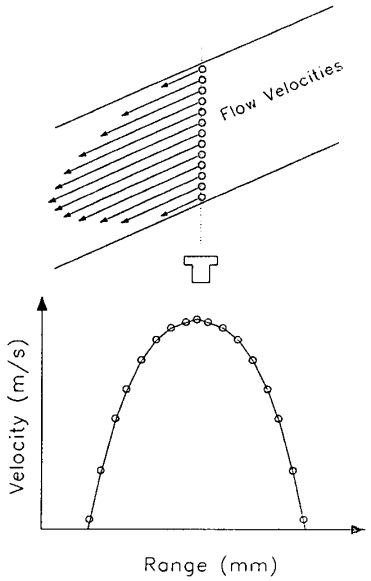



Figure 4: One Dimensional Velocity Scan

value of $\tau$ and multiplying by $E_2$ to produce the correlation coefficient $R(\tau)$. Mathematically, this can be expressed as

$$R(\tau) = \sum_t E_1(t+\tau)\, E_2(t) \qquad (3)$$

The value of $\tau$ which produces a maximum in the correlation function $R(\tau)$ corresponds to the time shift $t_1 - t_2$, and equation 2 can be used to calculate the scatterer velocity. Using the same range gating techniques as Doppler ultrasound, the velocity *vs* distance can be measured along a one dimensional scan line as shown in figure 4. The volumetric flow can be measured by sampling flow velocities over the entire vessel cross section with a number of one dimensional scans as shown in figure 5.

### 3. EXPERIMENTAL RESULTS

Figure 6 illustrates the blood flow phantom system used in the experiments. The phantom is capable of producing both continuous flow [2] and pulsatile flow [6]. 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. The resting inside diameter of the dialysis tubing is 6.5 mm. The volumetric flow was also estimated by a Zepeda Instruments SWF-5RD electromagnetic flowmeter with an accuracy of ±3% [10]. The output of the flowmeter was digitized and stored on a personal computer. The maximum and minimum flow peaks from a pulsatile experiment were calibrated from the stored traces by determining how long it took a known volume to be filled at that trace level. This was done for each experiment to ensure accuracy of the calibration. The volumetric flow determined by the UTDC technique was then compared to the volumetric flow measured by the electromagnetic flowmeter for evaluation. The fluid used in the blood flow phantom system is distilled water mixed with Sephadex. This mixture has been determined to reflect ultrasound in a similar manner as flowing blood [2]. Ultrasonic pulses were generated with a 5 MHz transducer and echoes were digitized and stored at 50 MHz by a custom designed ultrasonic data acquisition system [2] controlled by a COMPAQ 386/20 microcomputer. The calculation and plotting of velocity, flow rates, etc. were all done with the COMPAQ 386/20.

### 4. OCCLUSION

An application of the UTDC technique is to diagnose deep vein thrombosis, hence it is important to determine whether this technique can locate obstructions in vessels. Figure 7 shows the actual 3-dimensional perspective flow profile measured by performing a two dimensional velocity measurement across the dialysis tubing for unobstructed flow and figure 8 with a two millimeter obstruction on one side of the vessel. In these plots the horizontal plane represents location and the vertical direction represents velocity magnitude. In both of these cases the volumetric flow remained constant but the flow velocities changed. In the case of the obstruction, the area of the vessel was decreased by one third and the maximum measured velocity increased accordingly.

### 5. PUSLATILE FLOW

A total of 25 pulsatile flow experiments ranging from 50 beats/minute to 150 beats/minute were made with flow rates ranging from approximately 50 to 1100 milliliters/minute. The pulsatile volumetric flow was calculated by performing one-dimensional scans through the center of the vessel. One-dimensional scan results for a 120 beats/minute experiment are shown in figure 9. This figure shows that the velocity profile at the maximum and minimum flow peaks is laminar, 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. Figures 10 and 11 show flow *vs* time for 86, 100, 120, and 150 beats/minute as measured by the electromagnetic flowmeter and as measured by UTDC. The electromagnetic flowmeter is only capable of measuring volumetric flow through the vessel, hence the total volume flow *vs* time is plotted in figure 10, while the velocity at the center of the vessel (width of 0.8 mm) *vs* time is plotted in 11. The volumetric flow rates have also been shown at the maximum and minimum flow peaks. A number of important observations can be made from the flow *vs* time plots in figures 10 and 11. One is that the shape of the waveforms as measured by UTDC match those as measured by the electromagnetic flowmeter very well. At first glance, the UTDC 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 (0.5 mm wide), while the 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 changes from a nice sinusoid at 86 beats/minute to a ramp wave at 150 beats/minute. At low frequencies, the displacement of fluid by the syringe in the pulsatile pump can be described as

$$d = A \sin(\omega t) \qquad (4)$$

where d is displacement, $\omega$ is the fundamental frequency, and A is the maximum syringe displacement. The flow velocities will be proportional to the derivative of the displacement, or

$$v \propto A\, \omega \cos(\omega t) \qquad (5)$$

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 [7]. This has the effect of generating higher amplitude harmonics, which changes the flow *vs* time waveform from sinusoidal to ramp-like in nature.

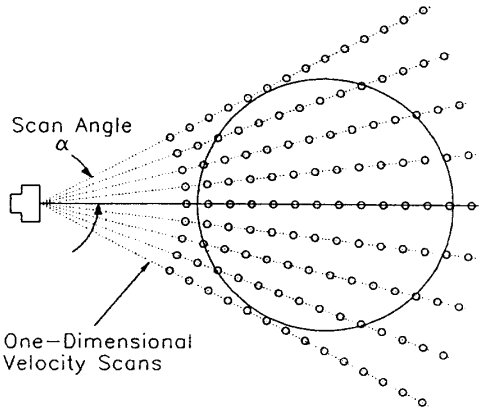



Figure 5: Two Dimensional Velocity Measurement

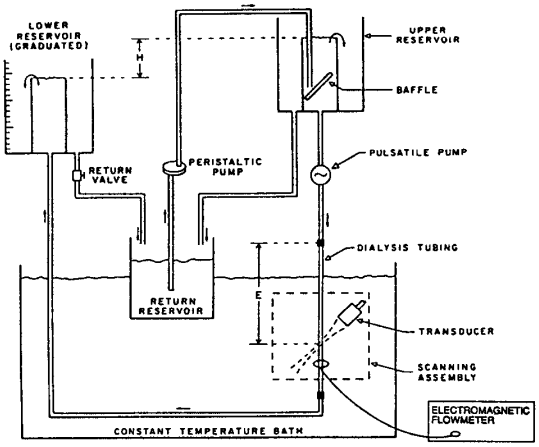



Figure 6: Blood Flow Phantom

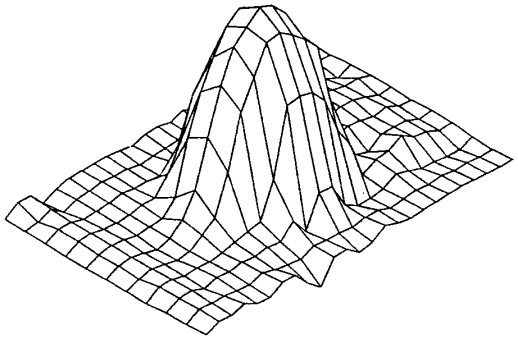


Figure 7: Three Dimensional Velocity Profile of Flow Through a Normal Vessel

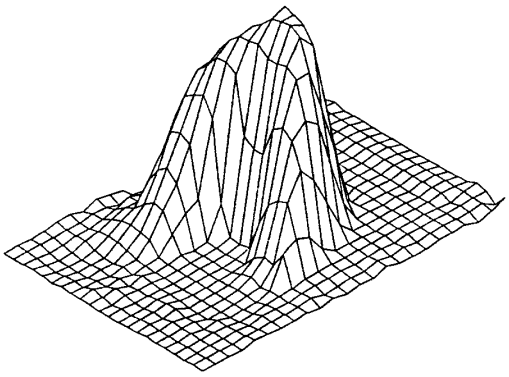


Figure 8: Three Dimensional Velocity Profile of Flow Through an Occluded Vessel

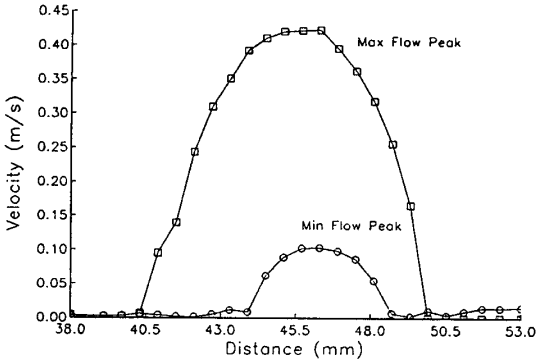



Figure 9: One Dimensional Velocity Profiles of Maximum and Minimum Flow Peaks at 120 Beats/Minute

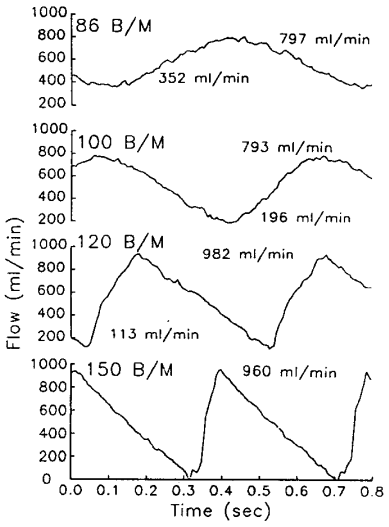



Figure 10: Pulsatile Flow Measured by Electromagnetic Flowmeter

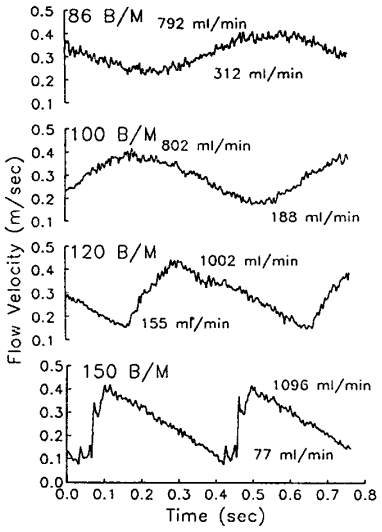



Figure 11: Pulsatile Flow Measured by UTDC

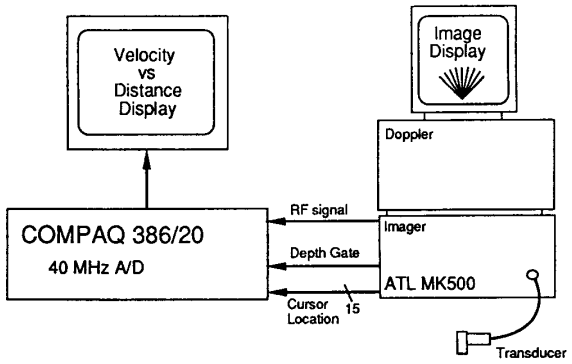



Figure 12: In Vivo UTDC Measurement Setup

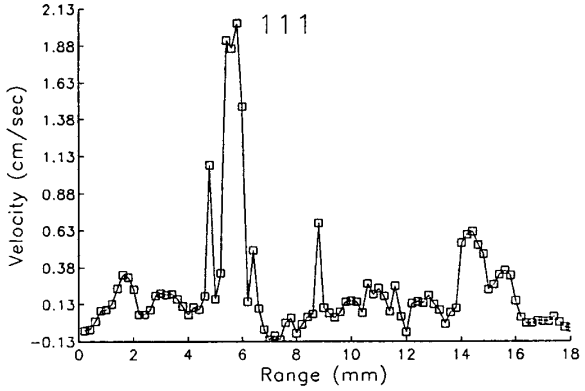



Figure 13: One Dimensional Velocity Profile of Canine Femoral Artery

The last observation is that at 150 beats/minute, the electromagnetic flowmeter indicates a minimum flow rate of 0 ml/minute, while the UTDC measurement indicates a minimum flow of 77 ml/minute. This is due to the fact that the vessel walls have lost contact with the electromagnetic flowmeter probe, which translates to a zero flow rate. Of the pulsatile experiments made, the error between the measured flow by UTDC and that of the electromagnetic flowmeter agreed to within 18% except where the electromagnetic flowmeter probe lost contact with the vessel walls.

## 6. EFFECTS OF ATTENUATION

In order to investigate the effects of ultrasonic attenuation on the accuracy of the UTDC method, a number of measurements were made with different types of tissues interposed between the transducer and the vessel and around the vessel. The types of tissues used were cow liver, pig liver, and pig spleen. The two-way attenuation of ultrasound due to the tissue varied from 6 to 19 dB. The results of tissue attenuation on the UTDC technique suggest as the attenuation increases, the volumetric flow estimate becomes more negatively biased. The greatest error measured was -45% with spleen tissue which is acoustically more inhomogeneous than liver. The reason for the negative bias may be due to multiple reflections from the surrounding tissue. This tissue is stationary; i.e., it has a velocity of zero. If the signal from these multiple reflections is on the same order of magnitude as the signal from the flow, then it would bias the flow estimate more towards zero.

## 7. IN VIVO EXPERIMENTS

A number of *in vivo* experiments were made with canine subjects. For these experiments, the COMPAQ 386/20 was equipped with a 40 MHz A/D and interfaced with an ATL MK500 commercial ultrasound imager as shown in figure 12. The MK500 was operated by registered professional sonographers who located the blood vessels. The dogs were anesthetized by a veterinarian and measurements were made at the femoral arteries and veins. The RF signal was taken from the MK500 and processed using UTDC. This temporary system is capable of performing only one-dimensional velocity scans, and takes about 45 seconds to process one scan. The results of a measurement of a canine femoral artery are shown in figure 13. It shows very clearly the vessel location and the flow velocity profile. The vessel diameter, flow velocity profile and magnitude are all within the range found in normal dogs. Currently no alternative noninvasive means of measuring flow (such as the electromagnetic flowmeter, which is invasive) were used so no quantitative comparisons could be made. At present, a new high speed UTDC system is under construction which will present one-dimensional flow data in real time.

*Acknowledgements* - The authors are grateful to Joyce Bender-Schmale and Roberta O'Connor for scanning the dogs; to Dr. Jan E. Novakofski for providing the tissue samples, and for support from the National Institutes of Health, National Heart, Lung, and Blood Institute (HL 39704) and the Academy of Finland.

## REFERENCES

[1] Baker, D. W. (1970), Pulsed Ultrasonic Doppler Blood Flow Sensing. IEEE Trans. Sonics-Ultrasonics SU-17, 170-185.

[2] Embree, P. M. and O'Brien, Jr., W. D. (submitted), Volumetric Blood Flow via Time Domain Correlation: Experimental Verification. IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control.

[3] Embree, P. M. and O'Brien, Jr., W. D. (in press), Assessment of Pulsed Doppler Accuracy due to frequency-dependent attenuation and Rayleigh scattering sources. IEEE Trans Biomed Engr.

[4] Embree, P. M. (1986), The accurate ultrasonic measurement of the volume flow of blood by time domain correlation. Ph.D. Thesis, Department of Electrical Engineering, University of Illinois, Urbana,Il.

[5] Gill, R. W. (1985), Measurement of blood flow by ultrasound: Accuracy and source of error. Ultrasound Med. Biol. 11, 625-641.

[6] Hein, I. A., Embree, P. M.., and O'Brien, Jr., W. D. (in progress), A Blood Flow Phantom Capable of Producing Continuous and Pulsatile Flow Waveforms.

[7] McDonald, D. A. (1960), Blood Flow in Arteries, Edward Arnold Publishers Ltd., London.

[8] Robeson, J. A. and Crowe, C. T. (1965), Engineering Fluid Mechanics, Houghton Mifflin, Boston.

[9] Webster, J. G. (1978), Medical Instrumentation: Application and Design, Houghton Mifflin, Boston.

[10] Zepeda Instruments, Operating Manual for SWF-5RD Electromagnetic Square Wave Flowmeter, Zepeda Instruments Co., Seattle, Washington.