THE ACCURATE ULTRASONIC MEASUREMENT OF THE VOLUME FLOW OF BLOOD BY TIME DOMAIN CORRELATION

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ABSTRACT

A new ultrasonic flow measurement method employing time domain correlation of consecutive pairs of echoes has been developed. The time shift between a pair of range gated echoes is determined by searching for the shift with the maximum correlation. This shift indicates the distance a group of scatterers has moved between pulses. The high precision and good resolution of the velocity estimate indicate that quantitative flow mapping is possible. Total flow through the vessel is calculated and compared to accurate hydrodynamic flow measurements in order to determine the overall experimental accuracy of the time domain method.

The measurement of blood flow by ultrasonic means has proved to be a valuable tool for clinical diagnosis of vascular disease. Unfortunatly, current Doppler based measurement techniques are plagued with practical as well as theoretical difficulties which result in inaccurate flow measurement.

Most successful, current, clinical techniques are based on qualitative comparisons of measurements from the same patient [1] primarily because vascular system variation from patient to patient can be significant. Variations in the thickness and the frequency dependent attenuation [2] of the intervening tissue will affect the accuracy of mean Doppler estimate.

Another problem with Doppler flow measurement techniques is that volume flow is estimated, not measured. The typical Doppler flowmeter measures the average flow along the beam direction at a particular distance from the transducer. Both the vessel size and the measurement angle are unknown. Some have suggested using two or more different measurement positions and determining the Doppler angle by using a number of peak flow estimates [3]. Since the vessel wall is constantly moving (due to the pulsatile flow of blood), it is difficult to determine the position of the vessel at a given time. Also, since the tissue paths for each measurement are different, the two measurements could have different biases. Since each patient has different size vessels and it is difficult to measure the Doppler angle, quanitative comparisons between normal and abnormal flow are nearly impossible.

The recently developed time domain flow measurement technique has the potential to overcome many of the aforementioned difficulties [4]. Briefly, this technique correlates two successive echoes at a particular range distance from the transducer. The place where the maximum correlation occurs is used to determine the distance a section of blood scatterers has moved between the two echoes. Since the technique compares two successive echoes which have both passed through the same intervening tissue, frequency dependent attenuation of the tissue path will not effect the mean flow measurement.

The time domain technique requires a sufficiently small time (T) between echoes so that most of the scatterers stay within the beam and the correlation between the two echoes remains high. Figure 1 shows a schematic section of an ultrasonic beam intercepting through a vessel. A first echo results from the scatters inside the cylinder represented with the solid line. At a latter time, T, the scatterers (represented by the dashed lines) have moved across the stationary beam. As long as the time T is small enough so that the dashed cylinder overlaps the solid cylinder, the flow velocity (V) can be estimated from the echo time shift (τ) and the speed of sound in blood.

Figure 2 illustrates the technique. The three consecutive echoes, sampled at 50 MHz (8 bit), had a PRF of 2604 Hz. A 5 MHz transducer (Panametrics V307) with a beam width (BW) of 0.8 mm at the focus was used to measure the flow of Sephadex^R particles in a 6 mm dialysis tube. For illustration purposes, three 0.8 μs range gates are shown (A, B, and C). Range gates A and C are near the front and back walls, respectively. Range gate B is near the center of the tube where the flow is greatest. The correlation coefficient of each pair of range gated sections versus time shift is shown in the lower portion of Fig. 2. The time shift, τ , for range gate B is greater than that for either range gates A or C. Also, the time shift indicated between echoes 1 and 3 is twice as great as that between echoes 1 and 2 or 2 and 3. Since the measurement of flow velocity versus range can be estimated from the average time shift between consecutive range gated echoes, the midstream velocity is estimated to be greater then that near the walls.

The previous work [4] considered the one dimensional measurement of flow from which volume flow was estimated by aligning the ultrasonic beam so that it passed directly through the center of the vessel. The flow profile was assummed to be parabolic in shape and axially symmetric. Considerable difficulty was encountered in determing the measurement angle and the position where the beam intersected the vessel, both of which resulted in quite large experimental errors in the volume flow measurement. The purpose of the current research is to measure flow in a plane passing through the vessel and then determine the measurement angle and volume flow from the 2-D flow velocity field.

Many of the sources of error in the measurement of the scatterers' speed can be associated with the finite ultrasonic beam. As more scatterers enter the beam between echoes, the maximum correlation decreases. For a given scatterer speed, as the time between echoes increases and the accuracy of the flow velocity estimate decreases. On the other hand, if the time between echoes is too small, the position of maximum correlation and the corresponding flow velocity estimate will vary randomly due to the random noise in the backscattered signal.

Figure 3 shows the precision of the time domain flow method measured near the center of a 6 mm tube where velocity gradients are small. Precision is defined as the ratio of the standard deviation of the flow estimate to the mean, expressed in percent. The precision versus time shift curve for the three measurement angles depends on the transducer beam width, bandwidth, and signal to noise ratio. The results were obtained at 5 MHz (bandwidth of about 2 MHz) and a 20 dB signal to noise ratio. The mean and standard deviation estimates where derived from 6144 echoes.

To obtain an accurate estimate of the flow velocity, a large number of echoes are used. Each flow velocity estimate has the form,

$$V = \frac{c\, S(i,j)}{2\,(j-i)\, T \cos(\theta)}$$

where:

- V = Magnitude of the velocity of the scatterer at a particular range.
- S(i,j) = Time shift between the ith and jth echo (j>i).
- T = Time interval between the transmitted pulses.
- c = Speed of sound in the fluid.
- θ = Angle between sound beam and velocity (measurement angle).

Since each echo is an independent measurement, all pairs of echoes can be used to determine a shift value and corresponding flow velocity value at each range position. Since there are N echoes separated by T, N-1 echoes separated by 2T, N-2 echoes separated by 3T and so on, a total of N(N+1)/2 velocity values can be determined at each range position. A minimum variance velocity estimate can be obtained by weighting the velocity estimates with the known variance of the estimate. Shifts with a small variance are weighted more heavily than those with a large variance. This weighted velocity estimate is used in all of the volume flow measurements.

Two dimensional flow measurements of continuous constant laminar flow have been obtained by using the experimental setup shown in Fig. 4. The transducer is rotated about the scan axis by hand and a laser beam is used to measure the angular position of the transducer with an uncertanity of $\pm$ 0.03°. The measurement angle (θ) can be changed by sliding the transducer along a specially machined circular track (Fig. 5). The focus of the transducer remains near the center of the tube independent of the measurement.

Figure 6 shows the results of a flow measurement of a continuous non-pulsatile flow of Porcine blood through a tube with a diameter of about 6 mm at $\theta = 60^{\circ}$. Fourteen different tranducer scan angles were used. Each scan line measurement was obtained from 384 echoes, each of 1024 samples. The flow velocity measurements versus range along the transducer beam are used to determine the range positions where the velocity is a given value. Ten equally spaced flow velocity values along each scan line are used to develop a set of constant velocity points. The polar coordinates (range along scan line and scan angle) are then converted to rectangular coordinate values by using the known distance from the rotational axis to the transducer. When the positions of ten constant velocity values for all angular positions are plotted on a rectangular grid, a result similar to Fig. 6 is obtained.

For the round tube used in this experiment with constant laminar flow, the constant velocity curves form a set of concentric ellipses (for a nonzero measurement angle). The data points of constant velocities represent only a portion of each ellipse. The portion of the ellipses which are nearly parallel to the beam is not visible. An elliptical curve is fit to the data points. Although this is somewhat difficult to accomplish in the general optimum sense, the data can be fitted by least square curve fitting. The result of the elliptic fitting program are depicted in Fig. 6 by the solid lines. The largest ellipse represents the tube wall and each smaller ellipse indicates where the velocity is greater by 10% of the peak flow.

The estimation of volume flow from the elliptical curve fitted data is now relatively simple. The center, angle of rotation, major and minor axis of each constant velocity ellipse is determined by the curve fitting program. The average measurement angle is given by,

$$\theta = \frac{1}{M} \sum_{n=0}^{M-1} \sin^{-1}\left[\frac{a_n}{b_n}\right]$$

where a_n is the minor axis length and b_n is the major axis length of the n^{th} constant velocity ellipse. A total of M ellipses are determined with the first and largest ellipse having n=0. The volume flow is determined by numeric integration of the flow profile.

For the blood flow measurement shown in Fig. 6 the flow rate was determined to be 103.1 ml/min. This agrees with the reference flow measurement of 109.5 ml/min determined by the time to fill the 253 ml volume of the lower resevior. Thus, the total flow may be measured without prior knowledge of the vessel size or transducer orientation.

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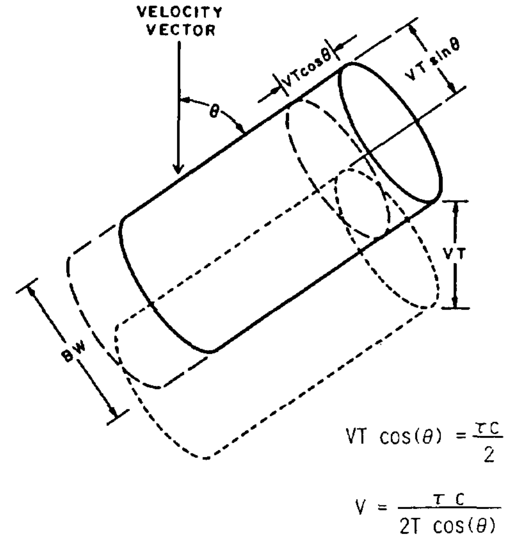

Figure 1. Ultrasonic beam (BW:beam width) intercepting a vessel at angle Θ.

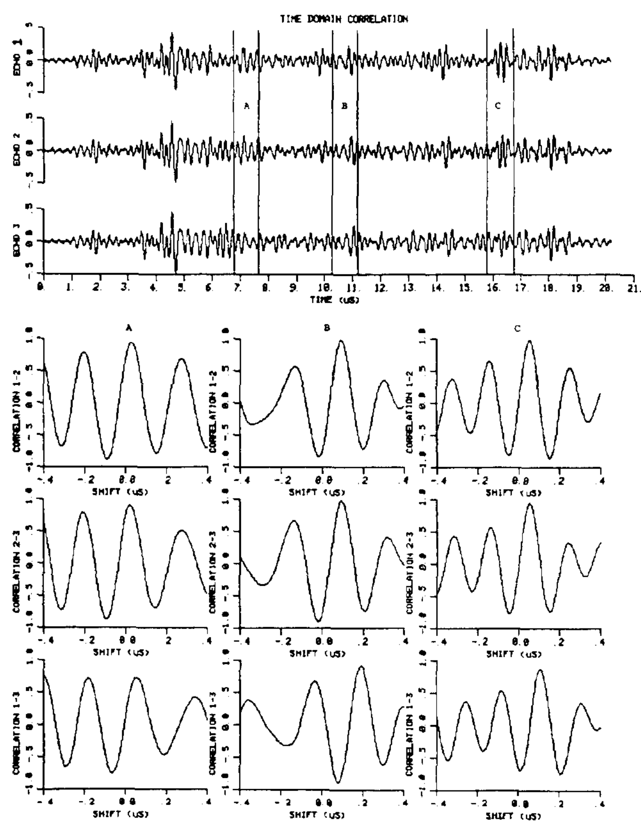

Figure 2. Time domain correlation method.

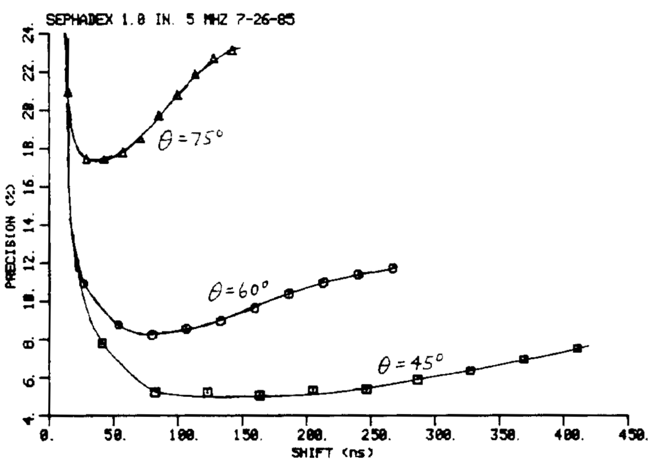

Figure 3. Precision of time domain flow measurement method.

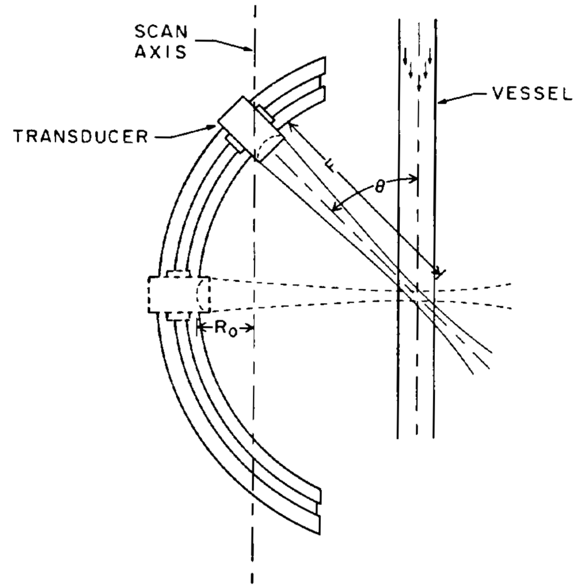

Figure 5. Scanning assembly and vessel.

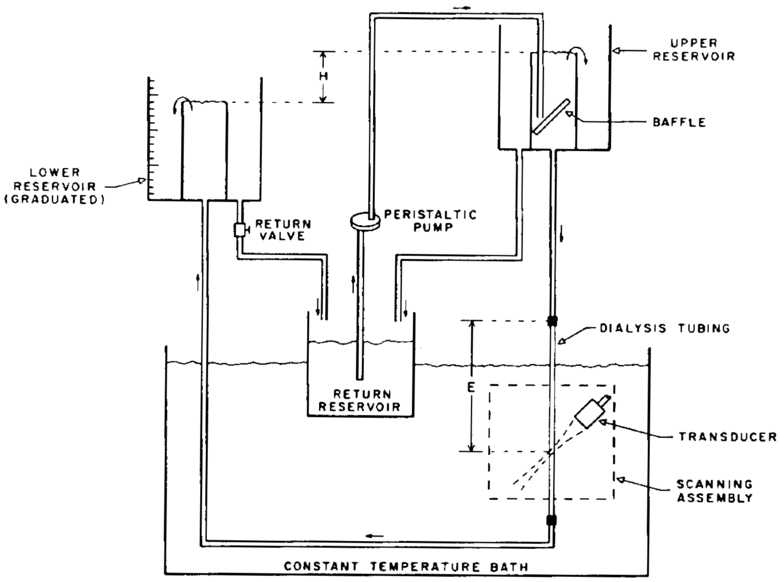

Figure 4. Experimental setup.

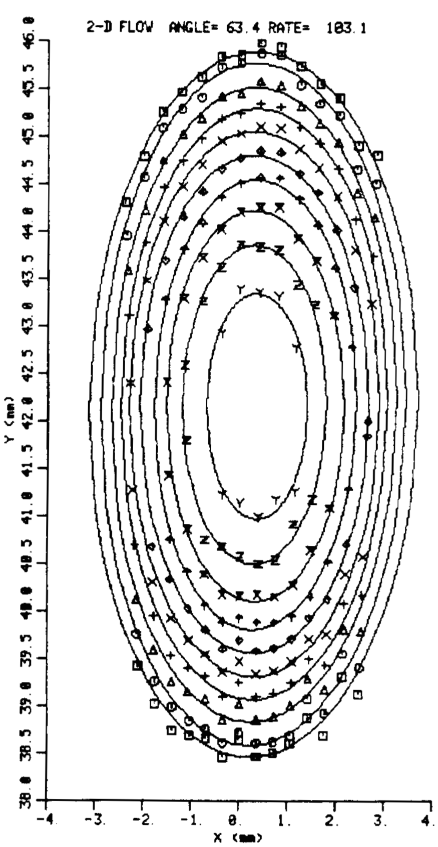

Figure 6. Porcine blood flow measurement.