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IN VIVO MEASUREMENT OF BLOOD FLOW USING ULTRASOUND TIME-DOMAIN CORRELATION

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Introduction

The use of Doppler ultrasound as a non-invasive measurement of blood flow has become a standard clinical practice. Unfortunately, Doppler ultrasound has theoretical and practical problems which limit it to being only a qualitative clinical tool [1] [2]. 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 [3], and previous research has shown that the UTDC technique can measure constant and pulsatile flow in a blood flow phantom with an accuracy of 20% [4] [5]. *In vivo* measurements on canine subjects have also been performed; however, previous UTDC measurement systems were not capable of running in real time which made *in vivo* measurements difficult. Recently, a real-time system using ultrasound time domain correlation has been constructed which can produce velocity vs range information every 0.7 seconds. Previous versions of the system required 45 seconds for the same measurements.

Theory

Figure 1 illustrates the UTDC flowmeter concept. In this figure an ultrasonic transducer is oriented at an angle θ 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 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. Since velocity is distance/time, the axial velocity of the scatterer is

$$v_A = \frac{(t_1 - t_2)c}{2T} \tag{2}$$

If the transducer measurement angle θ is known, the distance d the scatterer has moved down the vessel is $d_A/\cos(\theta)$ and the velocity of the scatterer

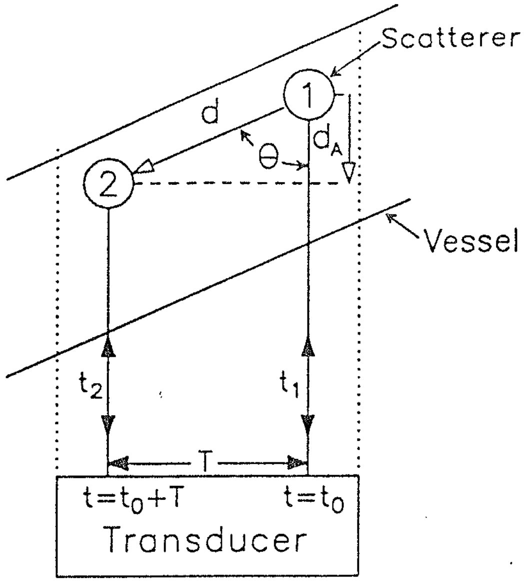

Figure 1: UTDC flowmeter concept.

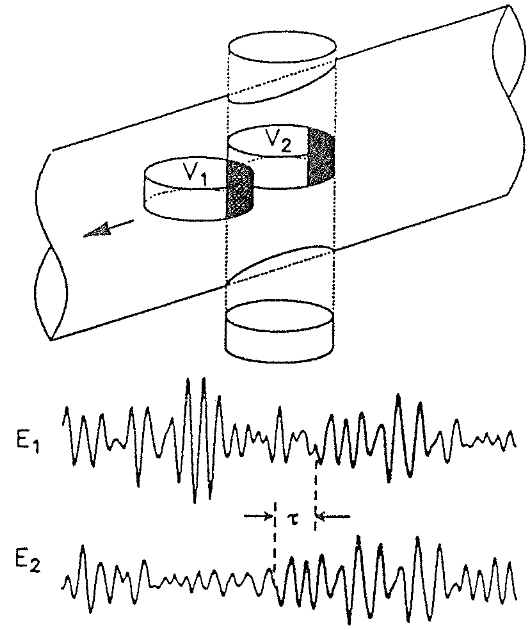

Figure 2: Volumes sampled by two ultrasonic pulses and their echoes.

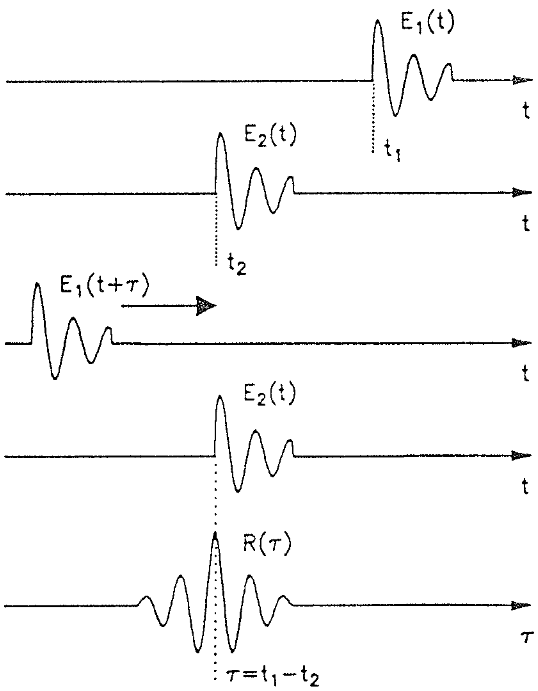

Figure 3: Correlation of signals from two echoes.

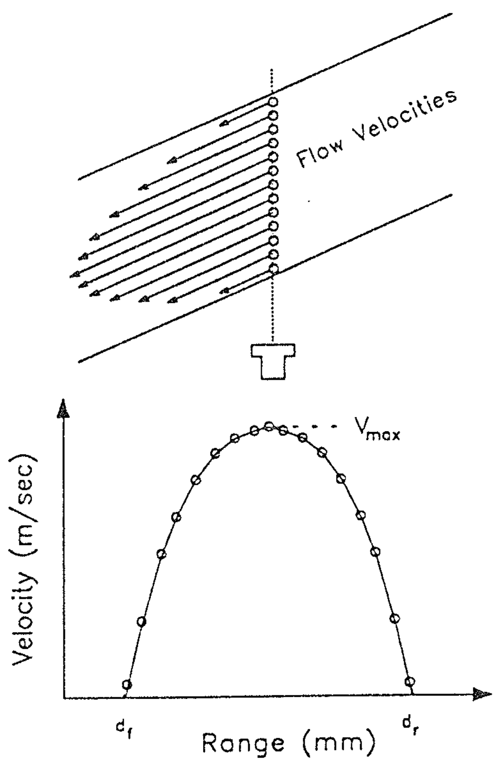

Figure 4: One-dimensional velocity scan.

down the vessel is $v_A/\cos(\theta)$. 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 V1 and V2), 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 value of τ and multiplying by E_2 to produce the correlation coefficient $R[\tau]$. Mathematically, this can be expressed as

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

The value of τ which produces a maximum in the correlation function $R(\tau)$ corresponds to the time shift $t_1 - t_2$, and equation 2 can be used to calculate the velocity. Using the same range gating techniques as Doppler, the velocity vs. distance can be measured along a one dimensional scan line as shown in figure 4, and is the real-time output of the current UTDC blood flowmeter.

Real-Time Data Acquisition Setup

Figure 5 shows the setup of the real-time system, which consists of an ATL MK500 imager, a COMPAQ computer, and a custom-built ultrasound data acquisition and residue number correlator (UDA-RNC) system. The UDA-RNC consists of a TRW 50 MHz A/D and bus expander interfaced to a residue number system (RNS) correlator unit. The high-speed hardware RNS correlator provides the real-time capability for UTDC measurements [5]. The RF signal and the cursor position are tapped from the MK500 and the RF signal is digitized at a physical location corresponding to the cursor position in the image display. The digitized echoes are placed in the RNS correlator memory and the correlator produces time shift values, which are sent to the COMPAQ.

Procedure

The carotid artery of a normal human subject was imaged with the help of sonographer and the axial velocity within the artery was calculated and plotted by the real-time system. Long axis measurements were made and the measurement angle θ was estimated from the ultrasound image. Measurements were later made in the same subject with a commercial Doppler device for comparison. Figure 6 shows the long-axis ultrasound image of the artery. The cursor was placed at a location just before the front wall. The angle of the measurement is very close to 90 degrees. This high angle is necessary due to the unchangeable pulse repetition frequency of the MK500, which is set at 1 KHz. The 1 KHz PRF rate limits the maximum axial velocities measurable to less than 5 cm/sec. Since the velocities in the carotid artery are typically 100 cm/sec and higher, the measurement angle must be high to insure that the axial velocities are under 5 cm/sec.

Experimental results

Figure 7 shows a typical axial velocity vs range plot of flow within the carotid artery. The measurement was made near systole, where the velocities are maximum. The vessel wall diameter as estimated from the plot agrees well with the vessel width in the ultrasound image. The shape of the plot is

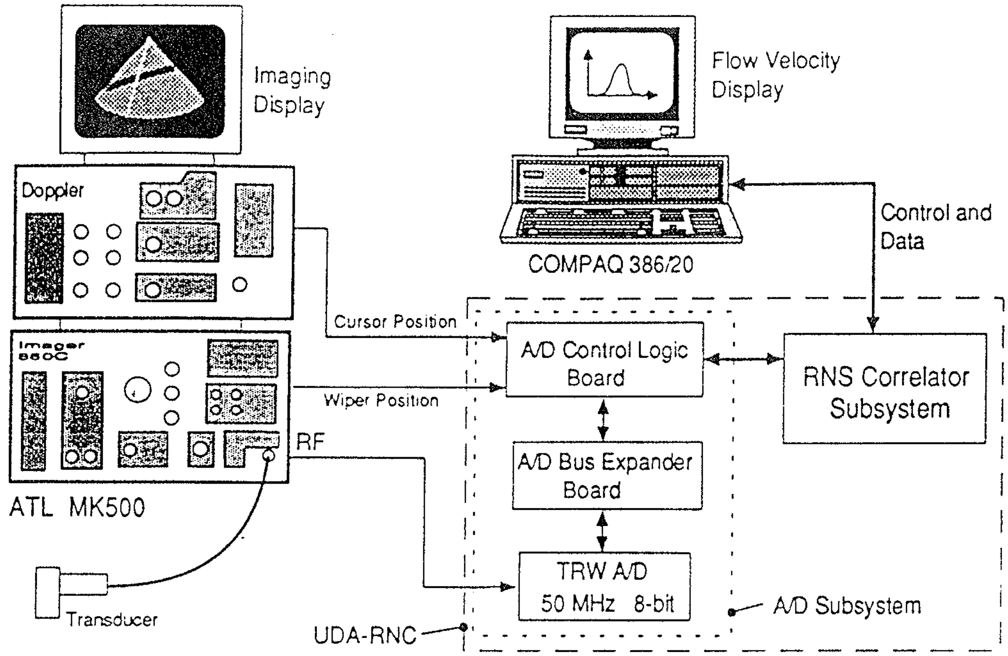

Figure 5: Real-time UTDC blood flow measurement system.

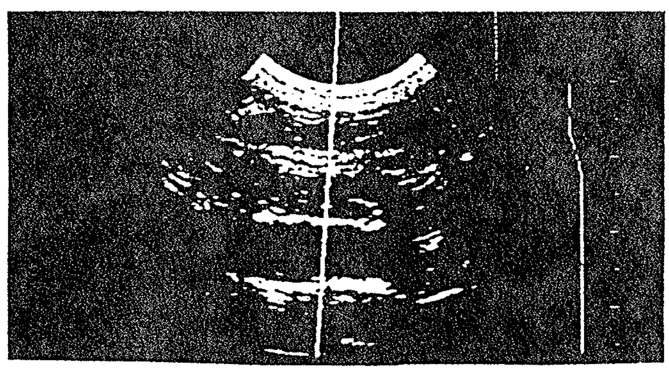

FIgure 6: Long-axis ultrasound image of a human carotid artery

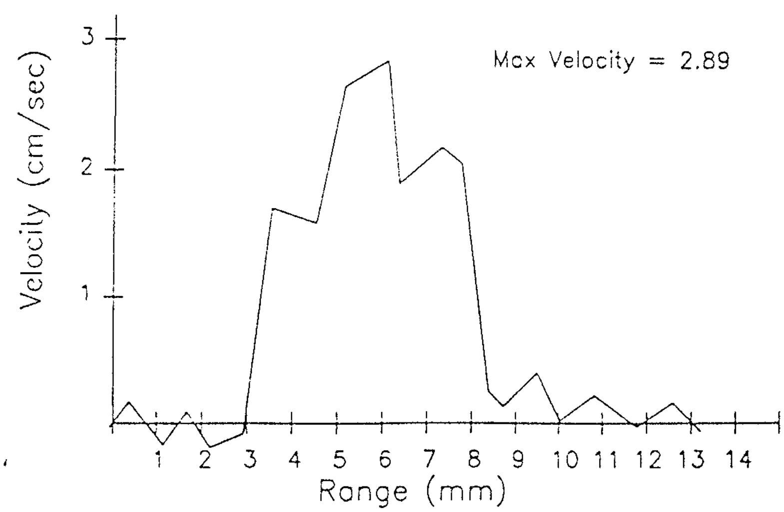

Figure 7: Axial velocity vs. range in a normal human carotid artery.

somewhat parabolic, except that it has a number of dips in it which most likely are not due to the actual flow. There are a number of causes for these dips. One is that stationary echo cancellation has not been incorporated into the system. The presence of echoes reflected from stationary tissues can corrupt the signal reflected from the moving blood and will negatively bias velocity measurements. Another is the limitation of the MK500's pulse repetition frequency. If the angle is not adjusted correctly and the axial velocity goes beyond the 5 cm/sec maximum, then the echoes will decorrelate and produce negatively biased estimates. In practice the adjustment of the angle was difficult since a small change in the angle produces large changes in the axial velocity at angles near 90 degrees.

The measurement angle is difficult to estimate precisely form the image in figure 6. Assuming that it is between 85 and 90 degrees, the 2.89 cm/sec peak axial velocity in figure 7 translates to approximately 66 cm/sec. The measurement in figure 6 was taken somewhere between systole and diastole, and the real-time display varied between zero and 5 cm/sec in time with the cardiac cycle. The 5 cm/sec maximum translates to a peak systolic velocity of approximately 100 cm/sec. Doppler measurements were also made on the same subject with a state-of-the-art ATL Ultramark 9 for comparison. The Ultramark 9 displayed a peak systolic velocity of 110 cm/sec, which agrees well with the UTDC measurements.

Concusions

This prototype ultrasound time-domain correlation blood flowmeter demonstrates that real time *in vivo* measurements in humans can be made. The next version of this system will utilize an ultrasound imager capable of higher PRF rates and will also incorporate stationary echo cancellation.

One disadvantage of the current system, as with all current Doppler systems, is that no good method of measuring the measurement angle θ exists. This angle can in theory be extracted from the statistics of the ultrasound echoes by the UTDC technique. The possibility of extracting the angle information from the echoes is currently under investigation and will be incorporated in future versions of the UTDC blood flowmeter.

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References

[1] P.M. Embree and W.D. O'Brien, Jr., "Pulsed Doppler accuracy assessment due to frequency-dependent attenuation and Rayleigh scattering error sources," *IEEE Trans. Biomed. Engineering*, vol. 37, no. 3, March 1990.

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

[3] P.M. Embree, "Volumetric bood flow via time-domain correlation: experimental verification," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 37, no. 4, May 1990.

[4] I.A. Hein and W.D. O'Brien Jr., "Volumetric measurement of pulsatile flow via ultrasound time-domain correlation," *Journal of Cardiovascular Technology*, vol. 8, no. 4, pp. 339-348, 1989.

[5] J.T. Chen, "Design and implementation of a high-speed residue number system correlator for ultrasonic time domain blood flow measurement," M.S. thesis, Dept. of Electrical Engineering, University of Illinois, Urbana, IL, 1990.