AN ULTRASOUND TRANSDUCER FOR BLOOD FLOW MEASUREMENT WITH DOPPLER ANGLE CORRECTION

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Abstract

The Doppler velocimeter presented here allows determining the angle between the ultrasonic beam and the velocity vector of the flow, which is used to calculate the fluid (blood) flow in a tube (vessel), instead of estimating this angle. The practical limits of the current technique allow obtaining only an estimate of the blood flow value under investigation. We have constructed the Doppler velocimeter with four piezoelectric transducers: one of the three transducers transmitted the ultrasound beam into the fluid flow; two others received the echoes; and the forth was used to determine the diameter of the vessel and to monitor the inclination angle. The tests were accomplished in a phantom where well known flows of a blood mimicking fluid traversed a piece of silicon rubber tube. The results showed that this technique is able to accomplish precise measurement of a fluid flow reducing the subjectivity, since the Doppler angle is measured and not estimated.

Introduction

This work presents the construction and evaluation of a velocimeter designed to increase the accuracy of measurable speeds of the ultrasonic pulsed emission and coherent detection Doppler velocimeter [1] [2] [3]. The actual pulsed ultrasonic Doppler velocimeter needs to be positioned in such a way that the angle formed between the ultrasonic beam and the velocity vector of the blood flow has a well-known value. The practical limits of the current technique allow the user of the equipment to obtain an estimated value of the blood flow under investigation.

The transducer developed in this work, that we named Velocimeter, was constructed with four piezoelectric transducers arranged in a set up as shown in Figure 1. This set up allows the transducers Tr#1 to Tr#3 to be moved simultaneously. When the faces of transducers Tr#1, Tr#2 and Tr#3 move away, the distance between the other extremities of these transducers decreases and vice-versa. The focus, defined by the confluence of the three ultrasonic beams, moves away or gets closer to the transducers faces depending on the aperture of the mechanism.

The angles formed between each one of the ultrasonic beams and the velocity vector of the blood flow are equal ($\phi_1 = \phi_2 = \phi_3$), due to the transducers positioning (Figure 2). If we use transducer Tr#1 to transmit an ultrasound beam and perform two different Doppler measurements, with transducers Tr#2 and Tr#3, at the same point of a vessel, the measured frequencies shifts will be the same ($f_{D2} = f_{D3}$). With the values of f_{D2} and f_{D3} (measured) it is possible to calculate the value of the blood flow (V).

To determine the Velocimeter position relative to the blood vessel, we used a fourth transducer (Tr#4, single element also shown in Figure 1) which works in Doppler mode to localize the vessel; once the depth of the vessel is determined, then Tr#4 works as an A-mode scanner to determine the vessel diameter and to check if the initial positioning of the Velocimeter has changed. Monitoring the value of the vessel diameter, which increases when the Velocimeter inclines, allows compensating the transducer position, and to correct the value of the Doppler angle, before calculating the flow.

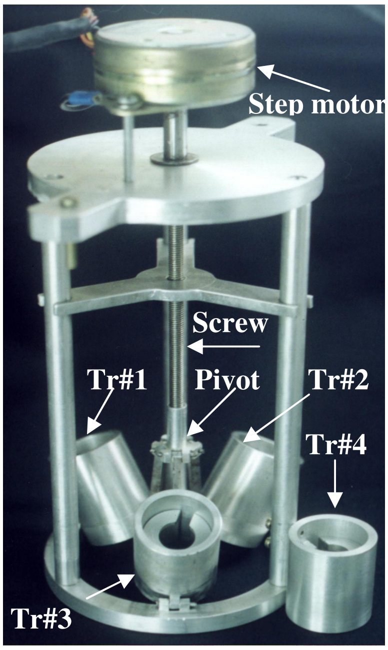


Figure 1: Picture showing the lateral view of the displacement system of the velocimeter.

Methods

Four commercial transducers (Tr#1, Tr#2, Tr#3 and Tr#4), all of them 19mm diameter and 1.6MHz center frequency, were used in the Velocimeter construction. Three of those transducers were placed in a displacement system that allowed that the center of the transducers faces coincided with the vertexes of an equilateral triangle (Figure 2). The purpose of this system is to regulate the focus of the velocimeter (Figures 2 and 3).

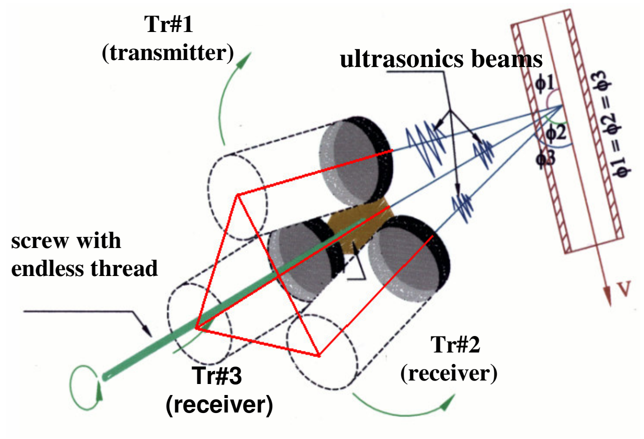
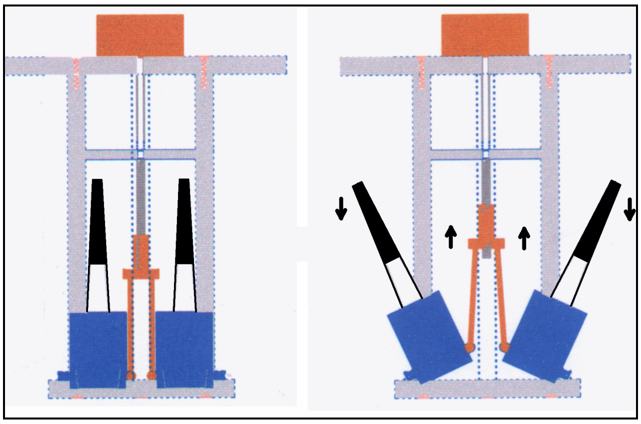


Figure 2: Schematic diagram of the transducers displacement mechanism of the Doppler Velocimeter.



(a) (b)

Figure 3: Schematic representation of the Velocimeter focalization: (a) in this position there is no inclination and the focus is at the infinite; (b) when the central pivot moves upward, the ultrasound transducers incline and the focus occurs near the transducers faces; otherwise, the focus moves away from the transducers faces.

The mechanism of movement of the transducers Tr#1 to Tr#3 was provided by a step motor which rotates a screw with endless thread, positioned among the transducers; as the screw rotates, a pivot tied at the extremities of the transducers by hinges, moves upward or downward, depending on the direction of the rotation of the motor, what brings closer or moves away the transducers faces, which allows to adjust the distance at which the ultrasonic beams meet (focus), according to the depth of the blood vessel under study (Figure 3). The transducers always move simultaneously, which means that the three transducers have the same inclination angles relative to the moving target: $\phi_1 = \phi_2 = \phi_3$.

The transducer Tr#1 emits the ultrasonic pulses, while Tr#2 and Tr#3 receive the echoes from the vessel under investigation. So, it is possible to accomplish two Doppler deviation measurements at the same point of the vessel. We have used bursts with 4 sinusoidal pulses at 1.6MHz to pulse Tr#1. The fourth transducer, Tr#4 (Figure 2), is used to localize the blood vessel: while the user moves the Velocimeter over the flow site, the software calculates the Doppler frequency shift until a null shift is obtained, meaning that Tr#4 and also the Velocimeter are perpendicularly aligned to the blood flow. Then Tr#4 works as an A scanner to determine the vessel diameter. From this moment on, Tr#4 monitors the value of vessel diameter: if the diameter increases, the angle between the transducer beam and the velocity vector of the flow has changed, meaning that the manipulator is no longer perpendicular to the blood vessel. The software uses this new value of the diameter to determine the new position of the Velocimeter (and the new value of ϕ_i) to correct the blood flow velocity calculation, without the intervention of the user.

The phantom used to simulate the blood flow was constructed in agreement with IEC standards [8, 9]. A silicon tube (length 30cm, outer diameter 16mm and inner diameter 11mm) was used as the substitute for the vessel and the fluid test was composed by 70% of distilled water and 30% of alumina, mimicking the blood components.

The experiments were accomplished to calculate the Doppler shift when the Velocimeter was positioned at distances 2cm and 3cm from the center of the silicon tube. The Velocimeter was positioned initially perpendicular to the silicon tube. After the control program had determined the vessel depth it calculates the diameter of the tube. Then, the tube was inclined sequentially 10°, 15° and 20° from the initial position, and three reference flows were used to verify the Velocimeter performance.

The reference "blood" flows used were 1.4l/min, 1.8l/min and 2.29l/min, and the sound velocity value was c = 1.540m/s. Fast Fourier Transform (FFT) was used to calculate the Doppler shift (frequency components between 0 and 3.8 kHz) [4].

The data acquisition was made through a digital oscilloscope (100Mega samples/sec and 40MHz bandwidth) that allowed the simultaneous acquisition of two signals (channel 1 and channel 2). As the Velocimeter sends three RF signals from Tr#1, Tr#2 and Tr#3 to be processed, a multiplexer was used to acquire the RF signal from Trans#2 or Trans#3, and to send it to channel 1 of the oscilloscope. The control software was developed in C language.

Results

Figure 4 shows the results of the experiments obtained correcting the Doppler angle (B), and considering 45° angle as default (A), without correcting the true angle between the velocity vector of the flow and the ultrasonic beam.

The results showed that there were significant differences between the velocity measurements done with the true inclination angle and with a 45° default angle to the three flows tested.

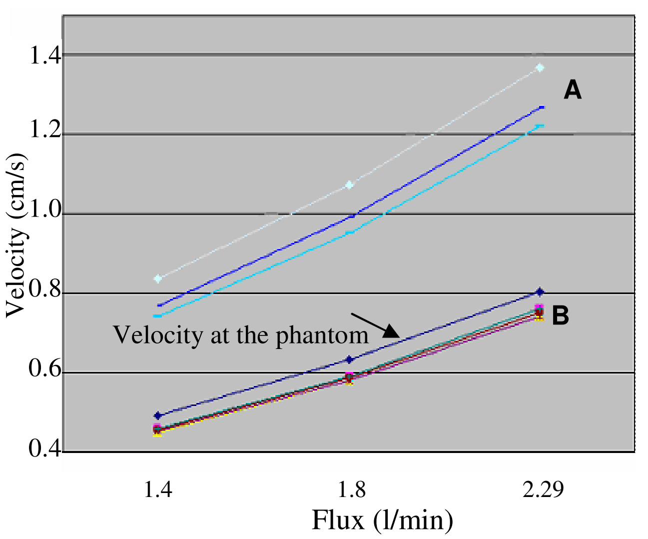


Figure 4: Velocity measurements of three reference flows (1.4, 1.8 and 2.29 l/min) at three inclination angles, 0°, 10° and 15°, using the Doppler angle correction technique presented in this work (B) and considering 45° as the default Doppler angle (A), independent of the velocimeter inclination.

The 1.4l/min flow measurements results at 2cm depth are shown in Figure 5 separated in two groups of curves: A and B, each one with ten measurements for the same flow. The silicon tube was stretched in the "U" support of the phantom in order to avoid a catenary, but this transformed the circular section of the tube into an ellipsoidal section. Besides monitoring the external diameter of the silicon tube with Tr#4, we have also utilized an ultrasonic scanner to get the image of the tube and to read its internal and external diameters. These diameter values were used to correct the vessel section area calculation. The flow measurements made with and without correcting the cross section area were compared.

In B group results shown in Figure 5, the cross-section area of the vessel was determined utilizing the value of the inner diameter of the silicon tube obtained with Tr#4; this value was applied in the circle area equation to obtain the cross-section area of the tube. As the tube was squeezed, and the real shape of its cross-section area was elliptical rather than circular, this led us to obtain significant errors during the measurements of fluid flow (between -24.6% and -26.4%) due to the underestimation of the vessel area [7].

The A group measurements (Figure 5) were accomplished with an ultrasonic scanner operating in B mode in order to obtain both diameters of the elliptical cross-section area of the vessel. This procedure allowed reducing the error of fluid flow measurement to approximately -9% because the measurement of the vessel area was precise.

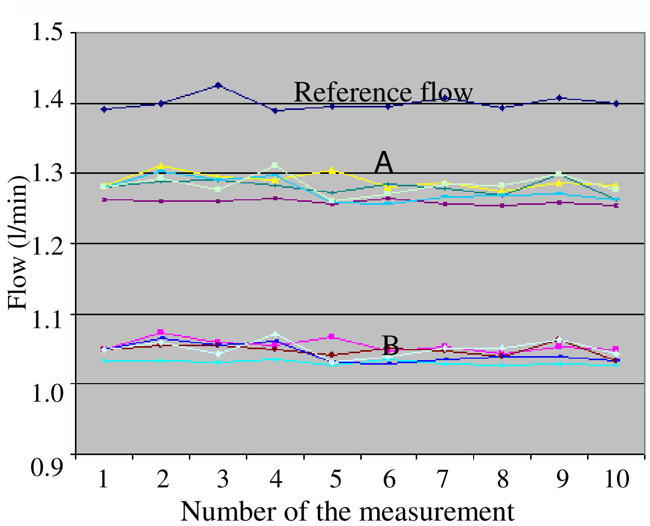


Figure 5: Comparison of measured flows and the reference flow (1.40l/min at 2cm depth). The A group results showed errors from -7.9% to -10.1%, and the B group showed errors from -24.6% to -26.4% (without correction of the cross-section area of the tube).

Discussion and Conclusion

The Velocimeter is an ultrasound transducer designed to measure fluid (blood) flow velocity, which automatically calculates the depth of the tube or blood vessel under study and the Doppler inclination angle between the ultrasound beam and the fluid flow. The Doppler shift calculated from the returning echoes from transducers Tr#2 and Tr#3 are the same, once the angular distance between these transducers is constant (adjusted according to the vessel depth); Tr#4 allows the software to compensate any change in the Velocimeter inclination relative to the fluid flow.

As the Velocimeter uses the vessel position (depth) and its physical dimensions (internal and external diameters) to adjust the focus and to correct the Velocimeter positioning, it allows minimizing the errors due to the estimative of the value of the ultrasound beam incidence angle [4]. This is true provided the initial work condition of the Velocimeter is respected: to localize the Velocimeter in a perpendicular position (reference) relative to the fluid flow. This can be an application restriction if we want to use the Velocimeter to measure blood flow on a vessel localized in turbulent surroundings (as can be the example of the fetus umbilical cord) [5] [6] [11].

Our experimental results showed good agreement between calculated and measured values of Doppler angles and flow velocities. The system was able to identify the change in the inclination of the silicon tube relative to the central axis of the velocimeter and to correct the value of the Doppler angle; this allowed obtaining flow measurements with errors around 10%. The results showed that with this technique it is possible to accomplish measurement of blood flow reducing Doppler measurements subjectivity, once the true cross-section area of the vessel can be determined precisely.

The experimental results confirmed that not only the estimation of Doppler angle is responsible for errors in the measurement of blood flow; errors in the measurement of the vessel cross-section area showed to have an important influence in the flow calculation. In some cases, they are more significant then the errors caused by inappropriate determination of the Doppler angle, especially if the Doppler shift measurement are accomplished at angles close to 0°, due to the little variation of the cosine values.

Acknowledgment

The authors acknowledge the financial support of FAPESP, CAPES and FINEP (RECOPE).

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