Ultrasonic Doppler blood flowmeter for extracorporeal circulation

Ricardo G. Dantas[*a]; Eduardo T. Costa[b]; Joaquim M. Maia[c]; Vera L. S. N. Button[d]

[a,b,c,d]Departamento de Engenharia Biomédica da Faculdade de Engenharia Elétrica e de Computação (DEB/FEEC) e Centro de Engenharia Biomédica (CEB) da Universidade Estadual de Campinas (UNICAMP – SP – BRASIL)

ABSTRACT

In cardiac surgeries it is frequently necessary to carry out interventions in internal heart structures, and where the blood circulation and oxygenation are made by artificial ways, out of the patient's body, in a procedure known as extracorporeal circulation (EC). During this procedure, one of the most important parameters, and that demands constant monitoring, is the blood flow. In this work, an ultrasonic pulsed Doppler blood flowmeter, to be used in an extracorporeal circulation system, was developed. It was used a 2MHz ultrasonic transducer, measuring flows from 0 to 5 liters/min, coupled externally to the EC arterial line destined to adults perfusion (diameter of 9.53mm). The experimental results using the developed flowmeter indicated a maximum deviation of 3.5% of full scale, whilst the blood flow estimator based in the rotation speed of the peristaltic pump presented deviations greater than 20% of full scale. This ultrasonic flowmeter supplies the results in a continuous and trustworthy way, and it does not present the limitations found in those flowmeters based in other transduction methods. Moreover, due to the fact of not being in contact with the blood, it is not disposable and it does not need sterilization, reducing operational costs and facilitating its use.

Keywords: ultrasound, Doppler, flowmeter, extracorporeal circulation

1. INTRODUCTION

In cardiac surgeries it is frequently necessary to carry out interventions in internal heart structures, as valves substitutions, wall surgeries and others. This is only possible when the heart is disconnected from the circulation system, making the blood circulation and oxygenation by artificial ways, out of the patient's body, in a procedure known as extracorporeal circulation (EC) or heart-lung bypass.

In an EC procedure the heart pump function is substituted by an external mechanical pump, and the lungs oxygenation functions by an external oxygenator. Figure 1 shows a simplified scheme of the EC system. The venous blood, that comes from the SSC (superior systemic circulation) and the ISC (inferior systemic circulation), instead of going into the right atrium, is deviated to the oxygenator, through PVC flexible tubes. The oxygenator is an external patient device that changes the venous to arterial blood. This arterial blood is pumped back to the patient, going to the SSC and ISC, restarting the cycle[1]. One of the most important parameters, and that demands constant monitoring, is the blood flow. Quite often, blood flow estimators based in the pump rotation speed (for peristaltic pumps) or those using the electromagnetic principle (for peristaltic or centrifugal pumps) are used. The technology available for these methods is relatively well known, but not very reliable for EC systems due to their intrinsic characteristics. In this work, an ultrasonic pulsed Doppler blood flowmeter was developed. It was used a 2MHz ultrasonic transducer, measuring flows from 0 to 5 liters/min, coupled externally to the EC arterial line destined to adults perfusion. This flowmeter is also showed in figure 1, placed in the arterial line, just after the pump.

There are two major kinds of mechanical pumps used in EC systems: the centrifugal and the roller pump. The roller pump is the older model, where an U shape flexible tube is pressed by two rollers, pumping the blood in a peristaltic manner. It generates a negative pressure in the tube input and a positive pressure in its output. In this kind of pump, it is common to find a flow estimator based on the pump speed rotation. This flow estimator, depending on the flow rate and the characteristics of the hydraulic circuit, can lead to wrong results, as it will be shown ahead. The centrifugal pump pumps the blood by

[*] Correspondence: E-mail: [a]grossi@ceb.unicamp.br, [b]educosta@ceb.unicamp.br, [c]joaquim@ceb.unicamp.br, [d]vera@ceb.unicamp.br; Address: Caixa Postal 6040 – Campinas – SP – CEP: 13083-970 – Brazil; Telephone: +55-19-7887895; Fax: +55-19-2893346.

In *Medical Imaging 2000: Physiology and Function from Multidimensional Images*, Chin-Tu Chen, Anne V. Clough, Editors, Proceedings of SPIE Vol. 3978 (2000) • 1605-7422/00/$15.00

increasing its kinetic energy, through a high speed moving group of palettes[1,2]. The flow estimator based on the pump speed rotation can no longer be used in centrifugal pumps, and there is the need of a real blood flowmeter. It is common to find an electromagnetic flowmeter coupled to this kind of pump, but, in our opinion, this is not the better choice, due to its characteristics, such as its hematocrit dependency[3,4,5].

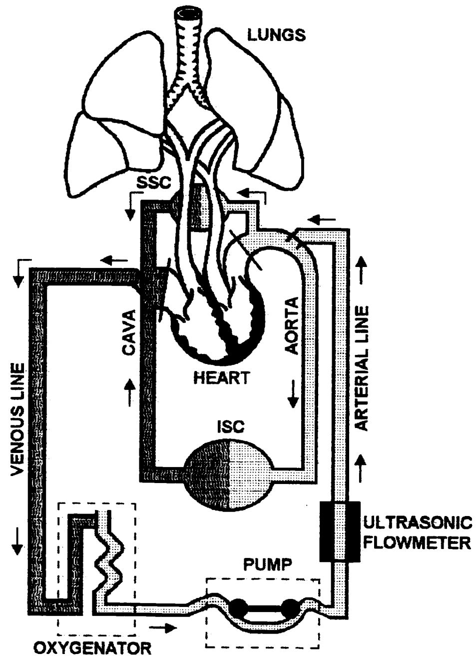

Figure 1. The extracorporeal circulation scheme.

The choice of using the ultrasonic method is justified due to the fact that the ultrasound is considered harmless to the patient's health and because there is no contact between the transducer and the blood, resulting that it is not disposable and it does not need sterilization, reducing operational costs and facilitating its use[6,7,8,9].

The ultrasonic flowmeter was developed using conventional pulsed Doppler techniques (see figure 2). The ultrasonic transducer emits acoustical pulses that are scattered by the red blood cells and detected by the same transducer, working as a receiver. According to the Doppler effect, as the red blood cells are travelling through the tube in a velocity V, there is a frequency shift between the transmitted (f_T) and the received frequency (f_R) known as the Doppler shift ($f_D = f_T - f_R$).

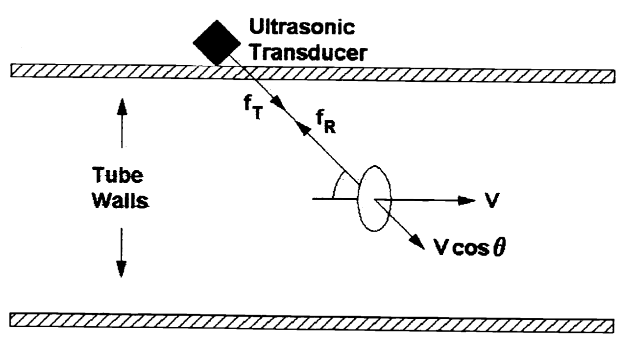

Figure 2. The ultrasonic pulsed Doppler technique.

The Doppler shift is related to the blood velocity according to the following equation[10]:

$$f_D = \pm \frac{2Vf_T \cos\theta}{c}, \tag{1}$$

where c is the sound velocity in the blood (approximated 1540m/s) and the ± signal means that f_T can be greater or smaller than f_R, depending on the direction of the blood flow.

2. MATERIAL AND METHODS

In this work, the ultrasonic pulsed Doppler blood flowmeter, to be used in an extracorporeal circulation system, was developed using a 2MHz ultrasonic transducer, measuring flows from 0 to 5 liters/min, coupled externally to the EC arterial line destined to adults perfusion (diameter of 9.53mm). The transducer (KB-Aerotech) is represented in figure 3. Figure 4 shows how the transducer is coupled to the EC tube. As it can be seen, the EC tube does not need to be cut.

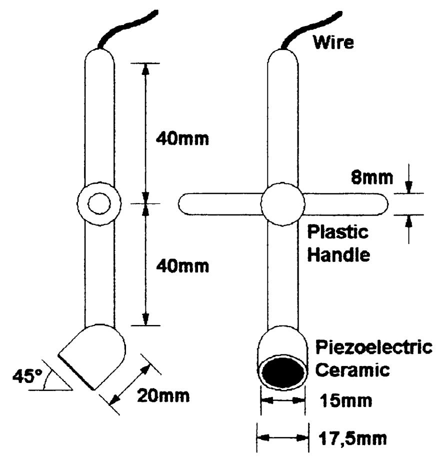

Figure 3. The ultrasonic transducer.

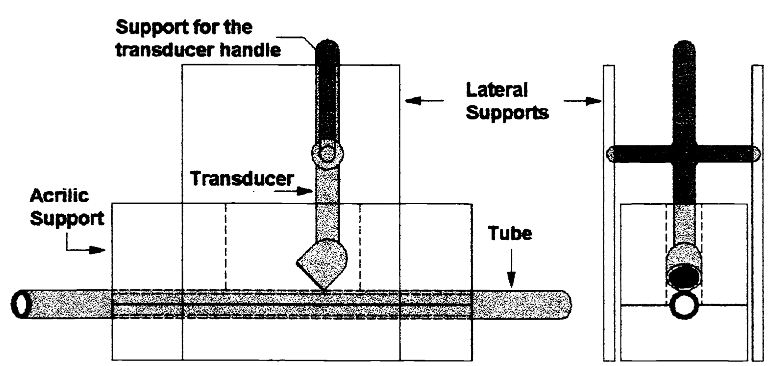

Figure 4. The ultrasonic transducer coupled to the EC tube.

Figure 5 shows the block diagram of the ultrasonic flowmeter. As there is only one ultrasonic transducer, it is used as a transmitter and a receiver. During a brief period of time, the transducer acts as a transmitter, sending a burst of 10 pulses in a 2MHz frequency. These pulses are scattered by the red blood cells, going back to the transducer, that now acts as a receiver. The burst generation circuit generates a 10-pulse 2MHz burst with a 15.625kHz (64μs) rate. These pulses are amplified till 12V by the transmitter circuit, using an IGBT transistor, and applied to the ultrasonic transducer.

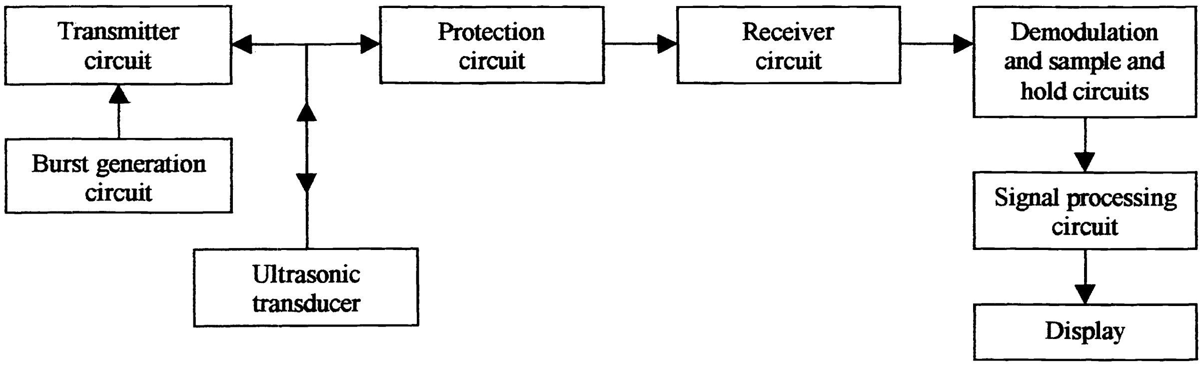

Figure 5. The ultrasonic flowmeter block diagram.

As the transducer acts as a transmitter and as a receiver, the transmitter circuit is electrically connected to the receiver circuit. In other to avoid the receiver amplifier saturation, there is a protection circuit that cuts the voltage in ±0.7V. The receiver circuit amplifies the received signals with an AGC (automatic gain control) RF amplifier. This amplified signal is demodulated in frequency with a 2MHz carrier. This demodulated signal contains the Doppler shift of the reflections at different depths, including the tube walls. There is a 10μs sampling channel that enables the sample and hold circuit, allowing the signal processing of only the scattering of ultrasound waves from the tube central region. In the signal processing circuit unit, a zero crossing detector converts the Doppler shift to a pulsed signal, whose frequency is measured by a frequency-to-voltage converter. According to equation 1, the Doppler shift frequency is proportional to the blood flow velocity. A linearization circuit to correct small deviations from the measured to the expected (desired) values has been added. The linearization circuit converts the analog signal into an 8 bit resolution digital signal. We have used an EPROM as a look up table linearization circuit. The digital signal is used as the EPROM's address (table input), and the EPROM's data (table output) corresponds to the linearized digital signal. The linearized flow value is showed in a two digit numeric display.

Figure 6 illustrates the 10-pulse 2MHz burst and the sampling channel. As can be seen, the bursts are repeated at each 64μs, avoiding interferences between the actual transmitted pulse and the reflections caused by the last transmitted pulse. The sampling channel starts 17.5μs after the beginning of the burst transmission. During the flowmeter development, instead of using blood for the tests procedures, it was used a solution of water with corn starch. The solution was used with different concentrations in order to simulate the hematocrit variation caused by hemodilution.

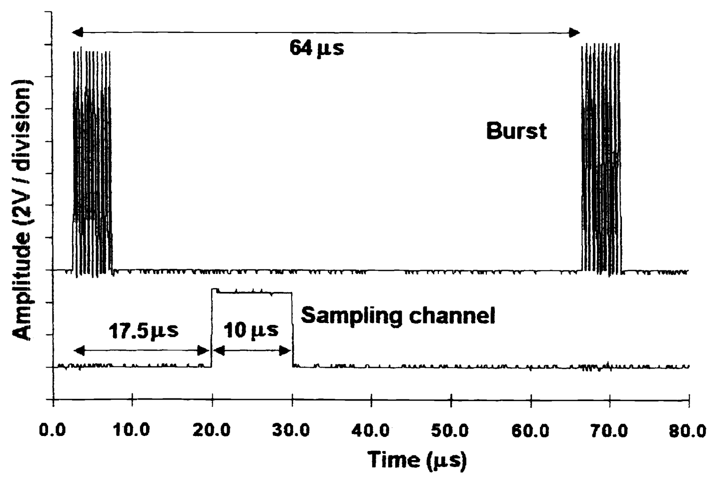

Figure 6. The transmitted burst and the sampling channel.

3. TESTS AND RESULTS

Most of the ultrasonic Doppler systems use sinusoidal transmitted pulses. In order to simplify the electronic circuit and reduce its cost, we decided to use an asymmetric square pulse. The transducer works as a filter for frequencies greater than its resonance frequency, attenuating the high order harmonics. In figure 7-a, it is shown a 12Vpp sinusoidal burst and its echo generated by reflections in a stainless steel flat disc. In figure 7-b, it is shown the same test, but with a 12Vp square burst.

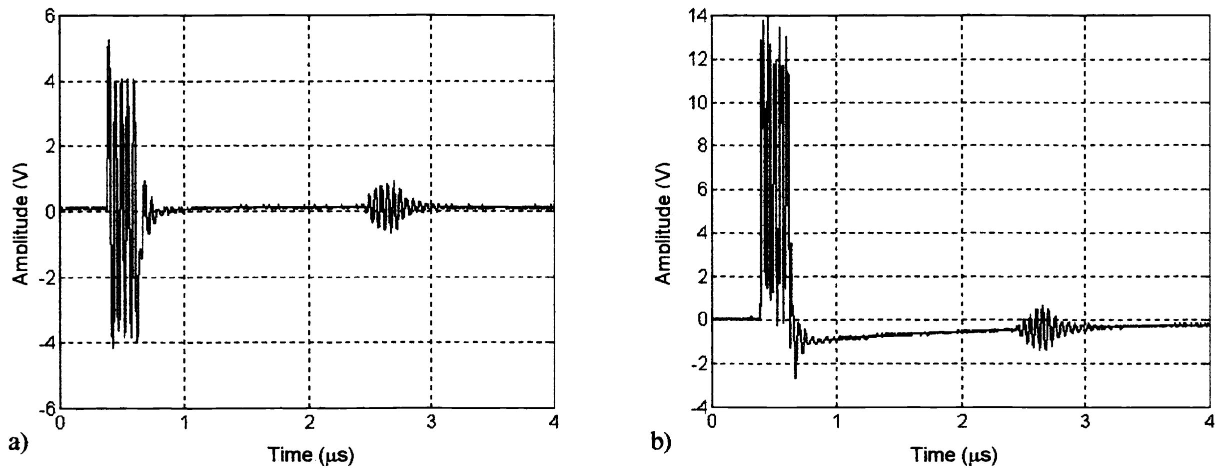

Figure 7. The sinusoidal (a) and the square (b) bursts used on tests.

In figure 8-a and 8-b, it is shown the Fast Fourier Transform (FFT) of the received echoes. The graph of figure 8-a corresponds to the echo of the sinusoidal burst, and the graph of figure 8-b to the echo of the square burst. It can be seen that the central frequencies are almost the same: 1.96MHz for the sinusoidal burst and 1.95MHz for the square burst. The bandwidth, measured at -3dB line, is 240kHz for both transmitted pulses.

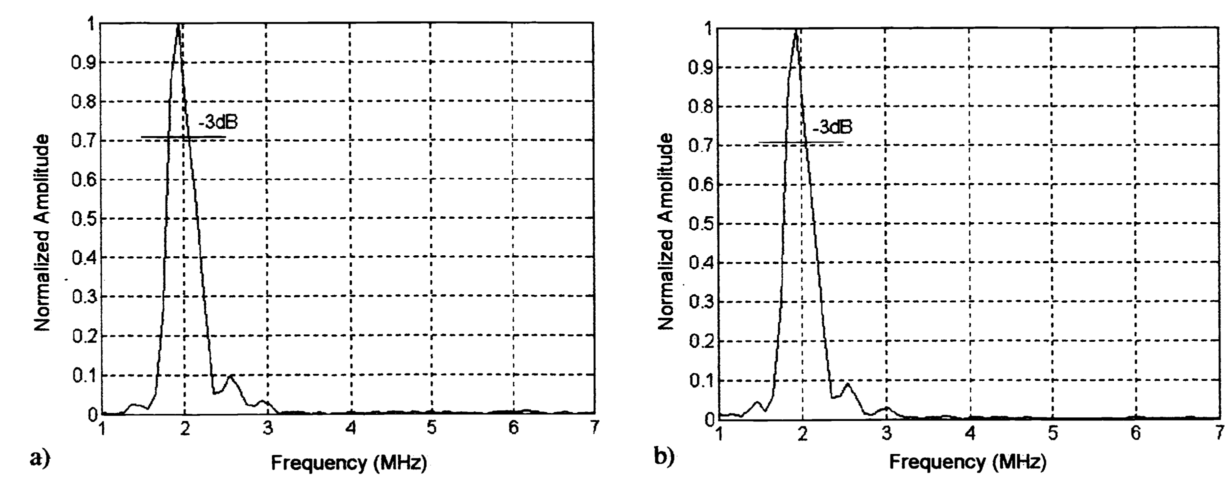

Figure 8. The Fast Fourier Transform of the received echoes generated by the sinusoidal pulse (a) and the square pulse (b).

In order to calibrate the developed ultrasonic flowmeter, it was used an hydraulic test circuit. Figure 9 shows this experimental setup. The tank #1 has two infra-red level sensors, a low and a high level sensor. During the tests, the pump speed rotation was set to a fixed value, and the test solution pumped from tank #2 to tank #1. When the test solution reaches the low level sensor, it triggers a timer, stopping it when the solution reaches the high level sensor. The flow value do not change during each test, and can be calculated knowing the volume between the level sensors and the time spent to fill this volume. This flow reference value was compared to the flow indicated by the ultrasonic flowmeter and by the roller pump flow estimator.

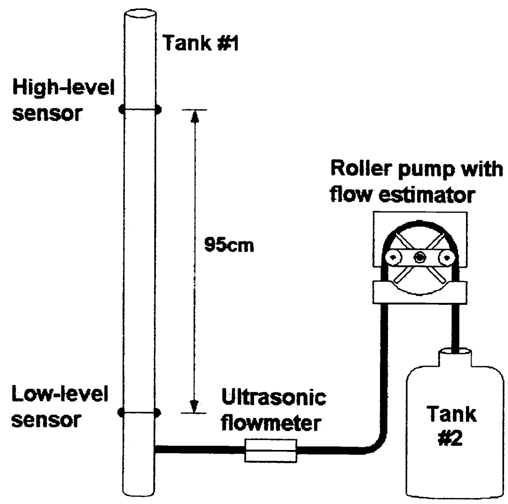

Figure 9. The hydraulic test circuit.

Figure 10 shows, for each pump speed rotation, the reference flow, the measured flow by the ultrasonic flowmeter and the estimated flow by the roller pump. As it can be seen, the flow indicated by the roller pump is a straight line according to its pump speed, as expected due to the estimation of the flow based on the pump speed. The developed ultrasonic flowmeter showed a better result, with its indicated values very close to the reference values. The tests were carried out 10 times for each pump speed, showing a maximum error of 3.5% of full scale between the ultrasonic flowmeter and the reference flow, whilst the blood flow estimator based in the rotation speed of the roller pump presented deviations greater than 20% of full scale.

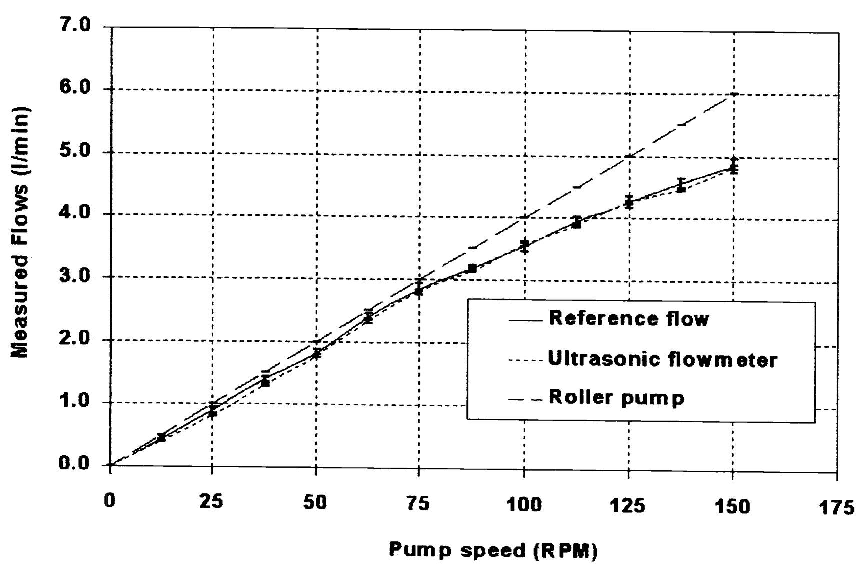

Figure 10. The reference flow, the measured flow by the ultrasonic flowmeter and the estimated flow by the roller pump.

Figure 11 uses the same data used in figure 10, showing the ultrasonic flowmeter data versus the reference flow. There is a great linear pattern through the points, with a correlation factor very close to 1 ($R^2 = 0.9993$).

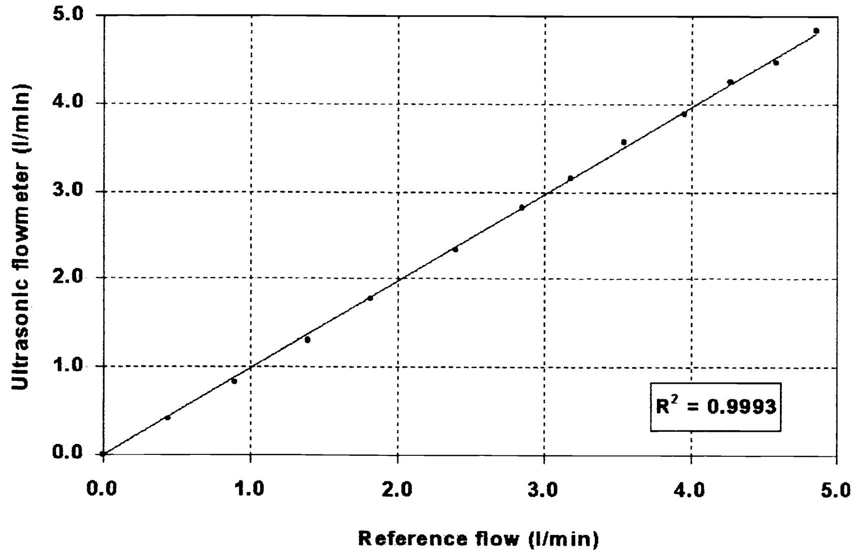

Figure 11. The ultrasonic flowmeter calibration curve.

The values of the reference flow, the ultrasonic flowmeter and the roller pump flow estimator, used in the graphs of figures 10 and 11 are shown in table 1.

Table 1. Values of the reference flow, the ultrasonic flowmeter and the roller pump flow estimator.

Speed rotation (RPM)	Reference Flowmeter (l/min)	Standard deviation (l/min)	Ultrasonic flowmeter (l/min)	Standard Deviation (l/min)	Roller pump (l/min)	Standard Deviation (l/min)
0	0.00	0.000	0.00	0.000	0.00	0.000
13	0.44	0.030	0.41	0.014	0.50	0.000
25	0.90	0.048	0.82	0.017	1.00	0.000
38	1.39	0.040	1.30	0.019	1.50	0.000
50	1.81	0.052	1.78	0.027	2.00	0.000
63	2.39	0.054	2.33	0.031	2.50	0.000
75	2.84	0.092	2.82	0.018	3.00	0.000
88	3.18	0.056	3.15	0.017	3.50	0.000
100	3.54	0.084	3.57	0.029	4.00	0.000
113	3.95	0.072	3.89	0.036	4.50	0.000
125	4.27	0.095	4.26	0.032	5.00	0.000
138	4.57	0.086	4.47	0.026	5.50	0.000
150	4.85	0.116	4.84	0.033	6.00	0.000

4. DISCUSSION AND CONCLUSIONS

Since the beginning of this project, the major goal was the development of an equipment that could be really useful in an extracorporeal circulation system, improving its performance by giving measurements in a trustworthy way, and with a low final cost. We have reached the desired results with our developed blood flowmeter. It is simple to be used, due to the fact that there is no need to cut the EC tube for its coupling, avoiding it to be disposable nor needing sterilization. Instead of using the roller pump estimator, that can present wrong results, the use of our ultrasonic flowmeter is a good alternative. Its use is also practicable for EC systems that use centrifugal pumps. This ultrasonic flowmeter can also be used as a standalone device.

From different available techniques, we have chosen the simplest and cheapest electronic circuits[11] carrying out. One example is the signal processing circuit. Instead of using a fast analog to digital converter and a DSP (digital signal processor) to digitize the Doppler shift signal and measure its frequency through a FFT algorithm[12,13,14,15,16], we have decided to do the signal processing unit with low cost analog devices, using the zero crossing detector[17] and the frequency to voltage converter, as well as the linearization circuit, that has the linearization table recorded in an EPROM, using just a few and low cost devices.

The flowmeter can improve the safety of the extracorporeal circulation procedure, by showing to the perfusionists a trustworthy flow measurement. In a future work, the flowmeter can be joined to others sensors, like an oxygenator blood level and a blood gas saturation sensor, in order to make an automatic pump speed control[18].

ACKNOWLEDGMENTS

We would like to grant the CAPES for the financial support.

REFERENCES

1. M. H. SOUZA, D. O. ELIAS, *Fundamentos da Circulação Extracorpórea*, Rio de Janeiro, Centro Editorial Alfa Rio, 1995, 441 p.
2. ANDRADE, J. BISCEGLI, J. DINKHUYSEN, J. E. SOUZA, Y. OHASHI, S. HEMMINGS, J. GLUECK, K. KAWAHITO, Y. NOSÉ, "Characteristics of a Blood Pump Combining the Centrifugal and Axial Pumping Principles: The Spiral Pump", *Artificial Organs*, vol. **20**, n. 6, 605-612, 1996.
3. J. A. SHERCLIFF, "The Theory of Electromagnetic Flow-Measurement", Cambridge, Cambridge University Press, 1962, 145 p.
4. E. G. STRANGAS, T. W. SCOTT, "Design of a Magnetic Flowmeter for Conductive Fluids", *IEEE Trans. Instrumentation and Measurement*, vol. **37**, n. 1, 35-38, march, 1988.
5. J. G. WEBSTER (editor), *Encyclopedia of Medical Devices and Instrumentation: Electromagnetic Flowmeter*, New York, John Wiley & Sons, 1988, p. 1320-1323.
6. P. BELEVICH, "Selecting and Applying Flowmeters", *Hydrocarbon Processing*, 67-75, may, 1996.
7. D. GINESI, "Abound in Flow Measurement" *Chemical Engineering*, 88-100, april, 1991a.
8. D. GINESI, "A Raft of Flowmeters on Tap", *Chemical Engineering*, 146-155, may, 1991b.
9. S. T. LANGE, "Making a Choice: Which Ultrasonic Flow Measurement Technology?", *Water/Engineering & Management*, 18-19, april, 1994.
10. D. A. CHRISTENSEN, *Ultrasonic Bioinstrumentation*, New York, John Wiley & Sons, 1988, 235 p.
11. GÜLER, N. F. GÜLER, "The electronic detail of a pulsed Doppler blood flow measurement system", *Measurement Science and Technology*, 1087-1092, june, 1990.
12. P. BASCOM, R. S. C. COBBOLD, "Origin of the Doppler Ultrasound Spectrum from Blood", *IEEE Trans. Biomedical Engineering*, vol. **43**, n. 6, 562-571, june, 1996.
13. COHEN, *Biomedical Signal Processing: Volume I, Time and Frequency Domains analysis*, Boca Raton, CRC Press, 1986, p. 81-139.
14. P. MARKOU, D. N. KU, "Accuracy of velocity and shear rate measurements using pulsed Doppler ultrasound: a comparison of signal analysis techniques", *Ultrasound in Medicine & Biology*, vol. **17**, n. 8, 803-814, 1991.

15. M. G. RUANO, P. J. FISH, "Cost/Benefit Criterion for Selection of Pulsed Doppler, Ultrasound Spectral Mean Frequency and Bandwidth Estimators", *IEEE Trans. Biomedical Engineering*, vol. **40**, n. 12, 1338-1341, december, 1993.
16. H. WU, S. OHTSUKI, "Sensitive Tracking Method for Blood Flow Velocity Estimation Using Pulsed Ultrasound Techniques", *Japanese Journal of Applied Physics*, vol. **36**, part. 1, n. 5, 3218-3220, may, 1997.
17. G. L. COTE, M. D. FOX, "Comparison of Zero-Crossing Counter to FFT Spectrum of Ultrasonic Doppler", *IEEE Trans. Biomedical Engineering*, vol. **35**, n. 6, 498-502, june, 1988.
18. T. BEPPU, K. SEO, Y. IMAI, Y. TAKANASHI, S. HOSHINO, J. OHTA, M. AOKI, S. UCHITA, S. SUZUKI, Y. TAJIMA, N. TOOYAMA, Y. FUKUI, "An Automatic Flow Controller for a Centrifugal Blood Pump", *Artificial Organs*, vol. **21**, n. 7, 630-634, 1997.