BLOOD PRESSURE MEASUREMENT SYSTEM BASED ON OSCILLOMETRIC METHOD

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Resumen

Este trabajo presenta una metodología para la medición no invasiva de la presión arterial, el algoritmo para la obtención de la presión arterial (presión sistólica, media y diastólica) es basado en el método oscilométrico. En el método oscilométrico las presiones son determinadas aplicando un criterio matemático al índice de pulso oscilométrico. En este trabajo es usado el criterio de pendientes para calcular la presión arterial sistólica y presión arterial diastólica. El sistema desarrollado es capaz de obtener los parámetros de presión arterial tanto para humanos como para ratas tipo Wistar, donde las mediciones de la presión arterial en las ratas Wistar se realizan como parte del desarrollo de otras investigaciones científicas en el campo de Química.

Palabras claves: Método oscilométrico**,** no invasivo, presión arterial, presión diastólica, presion sistólica

Abstract

This work presents a methodology for the non-invasive measurement of blood pressure, the algorithm for the obtention of blood pressure (systolic, mean and *diastolic pressures) is based on the oscillometric method. In oscillometric method the pressures are determined by applying a mathematical criterion to the oscillometric index pulse. In this work the slope criteria to calculate systolic and diastolic pressures is used. The developed system is capable of obtaining the blood pressure parameters for humans and rats, where blood pressure measurements in Wistar rats are realized as part of the development of other scientific research in Chemistry field.*

Keywords**:** *Blood pressure, diastolic pressure, non-invasive, oscillometric method, systolic pressure.*

1. Introduction

The determination of Blood Pressure (BP) is a very important element in medicine and biological sciences due to that, information about the heart condition is provided [Ball et al, 2003]. In this sense, animal based researches have a significant impact in the development of new treatments for human diseases [Cong et al, 2009]. Mice share about 98% of the deoxyribonucleic acid (DNA) with humans [16]; these animals have the tendency to be affected for many health problems that affect the humans. According to [Broten et al, 1997], among all biological signals, blood pressure is one of the most important signal because of this is correlated with a long number of ailments and disorders, so that a suitable system to obtain BP signal is highly supportive for the analysis on the effects of new drugs for diseases control, clinical analysis as well as monitoring the behavior of mice. There are many devices and techniques dedicated to BP detection; the most common for rats is based on the use of an invasive catheter-tip inserted into an artery, as well as a tail-cuff device in rats or a cuff attached at the limbs in humans [Cong et al, 2009], [Monassier et al, 2006], [Malakoff, 2015]. On the other hand, in humans, there are several indirect methods for BP monitoring, such as, pulse method, auscultatory method, ultrasonic/Doppler method, oscillometric method, pulse transit time (PTT), among others [Cuesta, 2004], [Fernández, 1985]**.** One of the most common ways to obtain the BP parameters is through the auscultatory method [González, 2008], in this method, the BP is taken by an expert. In [Escobar, 2012], a system for non-invasive measure continuous BP without cuff is mentioned, in this paper the PTT is the base for the development of the system. [Ball et al,2003] presents an algorithm based on oscillometric method for the estimation of BP parameters, in this work height criteria are mentioned for the estimation of the systolic and diastolic pressure, as well as the use of a commercial equipment to perform the validation of the results, the DOCTUS IV [Valdés, 2011]. The aforementioned works present a non-invasive way to obtain the BP parameters; however, this does not exclude the invasive methods as in [Ramírez, 2001], where an algorithm is used to acquire the BP parameters by means of a catheter inserted in a blood vessel of a human being. In animals, the most commonly indirect method for BP monitoring is the cuff technique, in which BP is measured using a variety of methods for sensing the changes in blood flow over the tail or limb, such as photoelectric sensors, oscillometric sensors, Doppler sensors, chamber volume sensors and acoustic sensors [Pickering et al, 2005]. The BP measurements by means of direct method use a radio telemetry technique or via indwelling catheters externally connected over mounted transducers [Monassier et al, 2006], [Pickering et al, 2005]. Different works have been carried out by BP monitoring through the direct method, such as the work presented in [Kramer et al, 1999], that describes one of the first possibilities for recording systolic, diastolic and mean BP, as well as the heart rate, and locomotor activity in freely moving mice, using a commercial telemetry and a data acquisition system, the system presented in the aforementioned work is achieved by an invasive method, in which, the paper describes the surgical technique for implanting a small radio-telemetry transmitter; likewise, the paper presents the differences among the indirect tail-cuff plethysmography method, the direct measurements by fluid-filled arterial catheters and the radio-telemetry used in the developed system. Related with the invasive method, in [Mills et al, 2000] a radio telemetry device is described; the implantable device provides measurements of systolic, diastolic and mean BP, as well as the heart rate and locomotor activity. On the other hand, in [Cong et al, 2009] the authors present the development of a real time wireless implantable blood pressure sensing microsystem for laboratory mice. The aforementioned BP measurement modes are based on invasive methods, in which a surgical procedure and therefore the use of anesthesia is necessary in order to place the implant, which often causes distortions over the BP measurements. Different works about indirect BP measurements are mentioned below. A BP monitoring system using a photoconductive cell, to illuminate mice’s tail by a small electric lamp is presented in [Van Nimwegen et al, 1973], in this system, the measurements are based on the sphygmomanometer method, in which, the pulsations in the arteries of the tail are converted into an electrical signal, after that, BP signal is displayed on an oscilloscope; the use of anesthesia to obtain the measurements is mentioned in this paper. In [Feng et al, 2009], BP measuring in mice is realized with a non-invasive BP monitoring system named CODA; the authors of this work provide an experimental protocol for accurately measure the tail-cuff blood pressure with this commercial system. In the same way, in [Infante et al, 1997] is reported a system that uses tail-cuff BP and an electrocardiogram (ECG), where plethysmographic pulse and BP signal are used in order to calculate systolic and diastolic BP parameters. The aforementioned system is based on sphygmomanometric method to obtain systolic and diastolic BP. According to [Pickering et al, 2005] it should be emphasized that regardless of the method used for measuring BP, systemic anesthesia should be avoided whenever feasible/possible because of the well-documented effects of anesthetics on cardiovascular function. In conclusion the invasive method is more accurate in relation to the tail-cuff, due to the BP measurements that can be continuously achieved and they are obtained directly from the artery, however, the cost of the implementation of this method, due to the implants should be analyzed according to the type of research performed; in addition, some surgical skills and training should be considered especially for small species such as mice. On the other hand, tail-cuff methods have served a valuable role in experimental hypertension research [Pickering et al, 2005], these methods are under development because some of these do not provide diastolic BP. Another aspect to consider in the indirect method is that the rat should be trained in order to avoid stress when the cuff is placed; besides, indirect methods have the advantage of they do not need a surgical procedure and they are less expensive in relation direct methods. Different commercial equipment for BP measurement are presented in the literature, however the cost of these is high and they are completely closed in hardware and software architecture. When an investigation is carried out, the analysis is required and probably the implementation of new elements for the measurement of new variables, therefore, control over the hardware and software of the equipment allows habilitation, development and continuous improvements in this process, in order to obtain a suitable equipment for the needs of the investigation that is carried out. In this sense, and due to the need to obtain the blood pressure parameters in rats for the development of several investigations that are executed in the Universidad Autónoma de Querétaro, this work presents the development of a non-invasive blood pressure system for rats in which the methodology is based on the oscillometric method.

Oscillometric method

The most employed BP measure method in automatic devices is the Oscillometric method [Gamboa et al, 2007]. This method consists on inflating a cuff 20 to 30 mmHg above systolic pressure to ensure the occlusion of the artery, further to this, the cuff is deflated at rate of 3 mmHg per second. The aim of this method is to find the oscillations at the time the cuff is deflated. In the Oscillometric technique [Valdés,2011], the cuff is slowly deflating, due to this, the walls on the artery begin to vibrate as the blood flows through the artery partially occluded, these vibrations are recorded by the electronic transductor which oversee blood flow. On the other hand, while the cuff is slowly deflated, the oscillations are increased to a maximum amplitude and then decrease until they disappear in the point the cuff is completely deflated and the blood flow returns to normal. In the Oscillometric method the systolic pressure and diastolic pressure are determined by applying a mathematical criterion to the envelope curve that is produce by the oscillometric index pulse of the oscillations that were recorded by the pressure transducer. Figure 1 shows the oscillometric signal, and the parameters involved. In the oscillometric method, the only parameter that is measured is the mean BP, and the systolic and diastolic BP are estimated. Likewise, the way to obtain systolic and diastolic BP parameters according to [Gamboa et al, 2007] are based on height or the slope analysis. Figure 2 shows the way to relate the oscillometric index pulse (OIP) and BP signal in order to find systolic and diastolic BP by the height and slope analysis In the height-based method, the desired pressure values are determined as the pressure of the cuff at which the ratio of the oscillometric index pulse at the peak relative to the maximum index pulse is equal to certain predetermined values, while, the slope-based criterion is determined by looking at the maximum and minimum slope points in the envelope curve. Figure 3 shows the relation between the BP cuff signal and the oscillometric index signal.

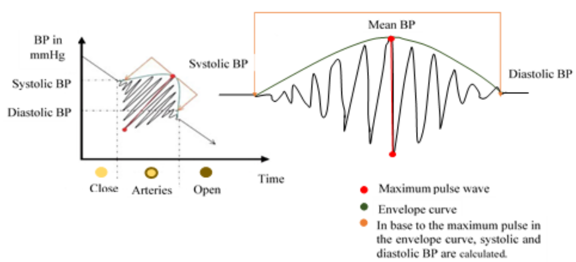


Figure 1 Oscillometric signal.

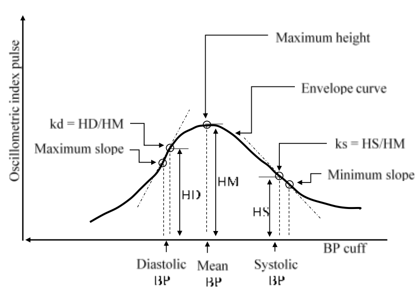


Figure 2 Oscillometric index pulse.

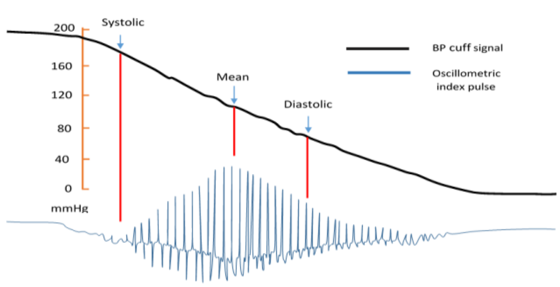


Figure 3 BP cuff signal when it is deflated vs Oscillometric index pulse.

2. Methods

In this section proposed methodology for the obtaining of BP is presented. First, arterial vibration is obtained by means of the occlusion cuff. These vibrations were recorder by a pressure transducer coupled to the occlusion cuff. Next, obtained vibration signal is submitted to a pre-processing stage in which a low pass filter to 10 Hz was used in order to remove high frequency noise induced by the inflation process of the cuff. Filter signal was digitized by a 12 bit-ADC embedded in a Beaglebone black board at a sampling frequency of 1 kHz. Once obtained the digital signal, it was filtered by a pass band digital filter in order to obtain the oscillometric index pulse signal. For this case, digital filter type IIR Butterworth was used. In this point of methodology, the systolic, mean and diastolic pressures was obtained by applying the slope criterion on the envelope of the OIP signal calculated by a peak detection algorithm.

The previously paragraph describe the methodology and the next section show in more detail all the sections before mentioned; first figure 4 shows the methodological diagram of the system for the measurement of blood pressure, which is composed of 4 main modules, “Module of acquisition of the blood pressure signal”, this module was composed of a pump (5 V supply voltage), solenoid valve (5 V supply voltage), an occlusion cuff (for the case of the rat, this was placed in the tail because in this is the distal continuation of the aorta is presented [Olds, 1979], whereas in the humans a occlude band of 22-32 cm was placed in the arm), a MP3V5050DP pressure transducer with typical 3 V supply voltage as well as a maximum pressure range of 50 kPa (375.03095 mmHg) according to the maximum blood pressure range required for both rats an humans this element was suitable for the application. For the control of the pump, the solenoid valve and the digitization of the BP signal was used the low power computer board Beaglebone Black. Regarding the frequency of sampling, according to the American Heart Association (AHA) [AHA Committee,1975] committee, the Task force of the Europe Society of Cardiology and the North American Society of Pacing and Electrophysiology recommend that Electrocardiogram (ECG) sampling frequency range of 250-500 Hz is optimum for accurate characterization of heart rate variability [Ahmad et al,2010]. Follows the Shannon sampling theorem and in relation to the typical frequency spectrum range from heart rate of the signals in humans and in Wistar rats the sample of 1 kHz was sufficient to provide correct estimation for the OIP. The next module corresponds to the "Analog filter", how was describe previously it was a 10 Hz low pass analog filter; the typical frequency spectrum of human heart rate is 1-1.666 Hz whereas the typical frequency spectrum of Wistar rats is 6.33-7.4833 Hz so the analog filter does not eliminate information from the oscillations caused due to the walls of the artery.

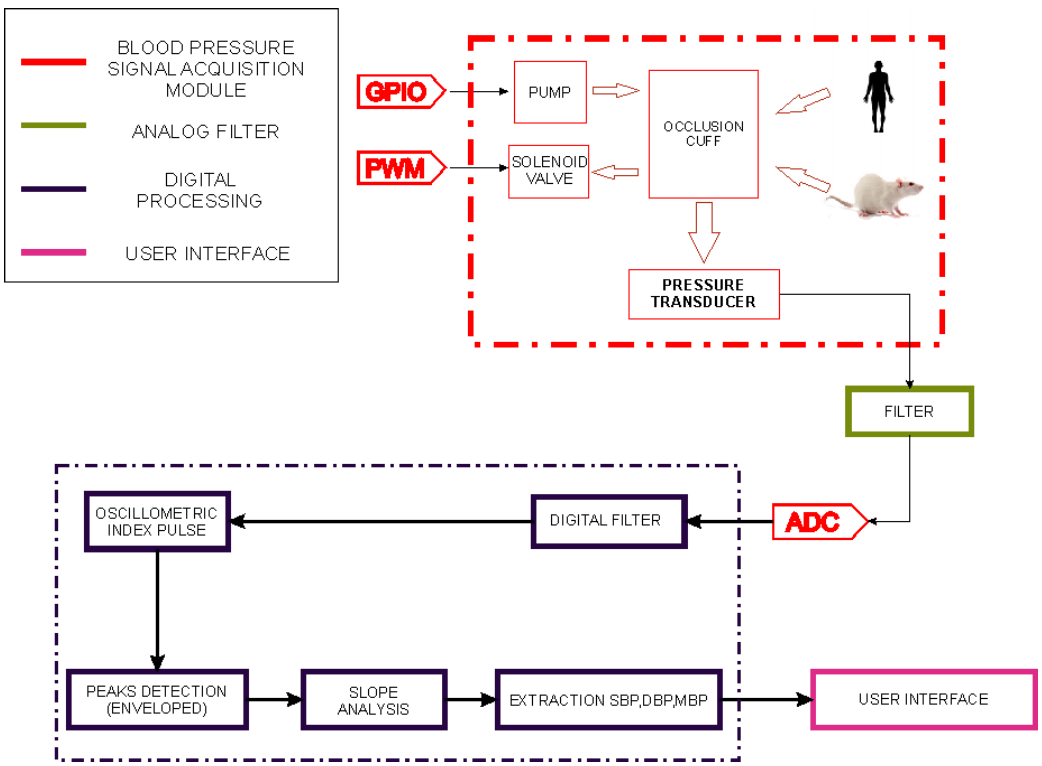


Figure 4 Methodological diagram for the BP measurement.

The "Digital processing" this module corresponds to the software analysis of the BP signal, this module was dived in two fundamental parts: the acquisition of the BP signal and an algorithm of analysis of the pressure signal of the deflation cuff. The acquisition of the BP was performed in a real time by the interaction of the Beaglebone Black board and a user interface in Matlab® platform, in the user interface the data analysis option was available, which corresponds to the analysis of the deflation BP cuff signal, the processing that was applied to the signal was by software in the Matlab platform, the first paragraph of this section that describe the methodology describe the elements of this module. Finally, the last modulo "User interface" includes the BP cuff signal and shows the BP parameters. The methodology aforementioned was used for calculate the BP parameters in 2 different cases of study: humans and rats, the digital filter is the only module that was different due to the heart rate is different in both species, so the results are presented for both cases. The experimental set up for the human case was performed in base to the Mexican Norm [PROY-NOM-030-SSA2-217] the norm describe the basic procedure for take the blood pressure, while for the second case the measurements were performed in a Wistar rat weighing 442 grams, the procedure to maniple the rat was in base to the Official Mexican Norm [NOM-062-ZOO-1999]**,** for the test, three occlusion cuff of different internal diameter were use and five test were performed by each occlusion.

3. Results

In this section, the obtained results for both cases of study using the proposed methodology are presented, first section shows the results for tests realized on humans; figure 5 shows the BP cuff signal, where the inflation signal is depicted in red and the deflation signal of the occlusion cuff is depicted in blue. As mentioned in the methodology the signal of interest is the signal of deflation occlusion so the analysis is performed on this signal; following the steps described in the methodology figure 6 shows the OIP depicted in green, envelope curve depicted with circles in red and the derivate for the envelop curve in black. Finally figure 7 shown the values for BP parameters in both signals, deflation cuff signal and OIP, the SBP is depicted in a red circle, the MBP with a black square and finally the DBP with a blue triangle; the red diamond, black cross and blue asterisk represent the moment in which the SBP, MBP and DBP appear in the slope analysis that was made over the envelope curve. For each tests performed the same procedure was followed.

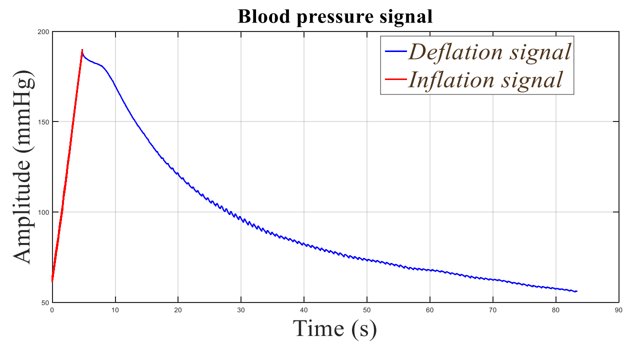


Figure 5 BP cuff signal.

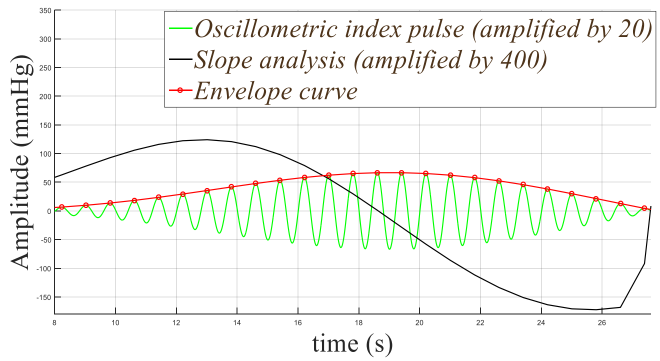


Figure 6 Analysis for obtain BP parameters.

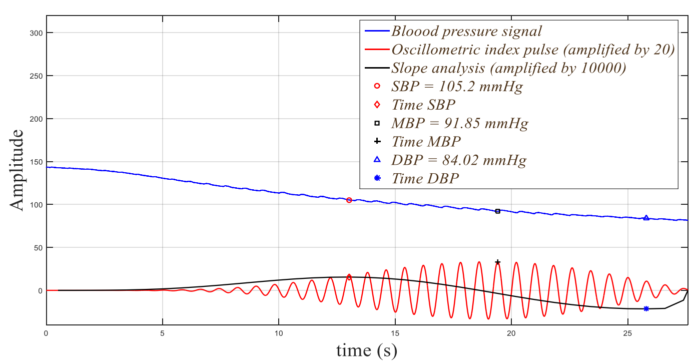


Figure 7 Establishment to the BP parameters in deflation cuff signal and OIP.

In the next section the total results are presented. Figure 8 shown the BP signal for ten samples that are presented and over each signal the BP parameters; SBP is depicted in a red circle, MBP is depicted in a yellow square, and finally DBP is depicted in a blue diamond. Table 1 shows the BP parameters for each test.

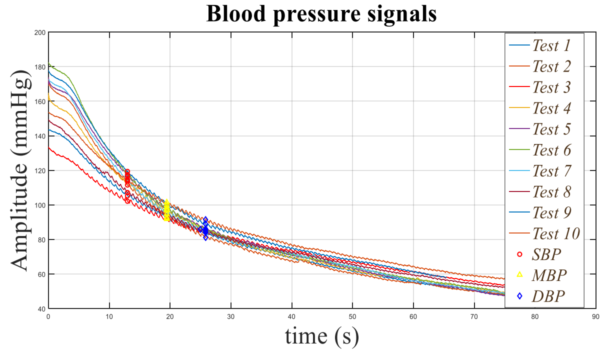


Figure 8 BP parameters obtained for the human case.

Table 1 Results for each test in humans.

Test	**SBP** (mHg)	**MBP** (mmHg)	**DBP** (mmHg)
Test 1	105.2	91.85	84.02
Test 2	111.4	92.7167	85.8
Test 3	102.1	92.3212	85.8
Test 4	113.8	96.8553	86.29
Test 5	116.6	97.5336	85.64
Test 6	117.6	98.4497	84.84
Test 7	113.9	95.0563	84.92
Test 8	107.2	94.4983	84.44
Test 9	119.5	100.021	88.94
Test 10	114.8	101.5107	91.57

In the next section Wistar rat results are presented, figure 9 shows the BP cuff signal, the inflation signal depicted in red and the deflation signal depicted in blue, while the figure 10 shows the oscillometric index pulse depicted in magenta, the derivate to the envelope curve is represent in black and envelope curve is depicted in red circles. Figure 11 shows the BP parameters, SBP is depicted in a red circle, MBP is depicted with a black square and DBP is depicted with a blue triangle, the value for each parameter is shown in the figure, as well as the moment in which each parameter appears in the slope analysis that was made over the envelope curve. Figures 12a, 12b and 12c, shown the results for the BP parameters with the occlusion cuff A, B and C respectively; the figures show the BP signal for each sample and over each signal the BP parameters, SBP is depicted in a red circle, MBP is depicted in a black square, and finally DBP is depicted in a blue triangle. As presented in the methodology for each occlusion cuff five test were performed, the BP parameters are shown in table 2.

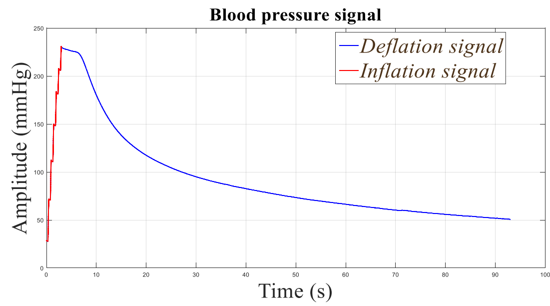


Figure 9 BP cuff signal.

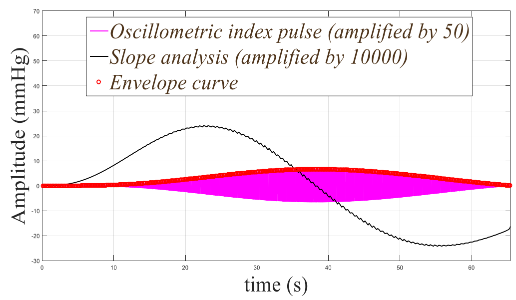


Figure 10 Slope analysis over the envelope curve for obtain the BP parameters.

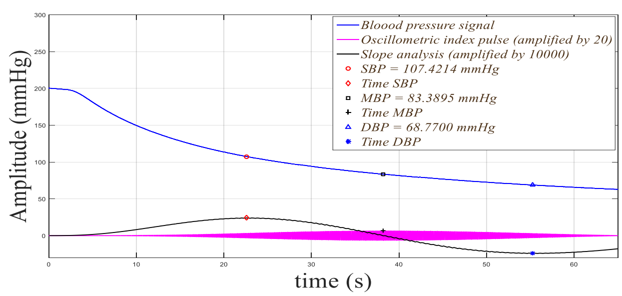
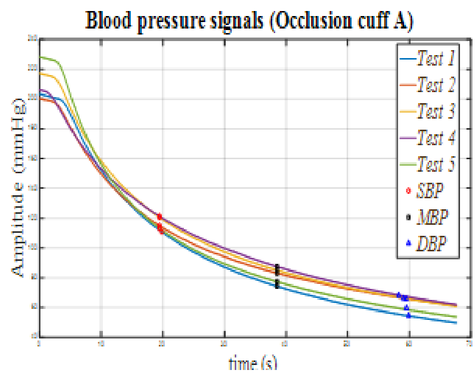


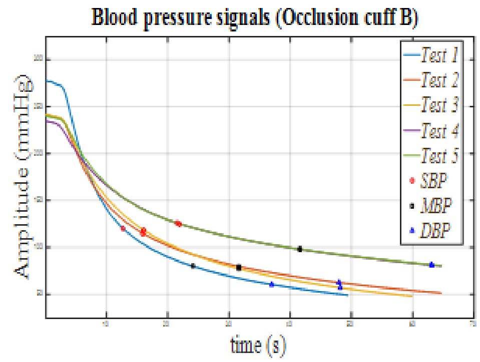
Figure 11 Establishment to the BP parameters in deflation cuff signal and OIP.

4. Discussion

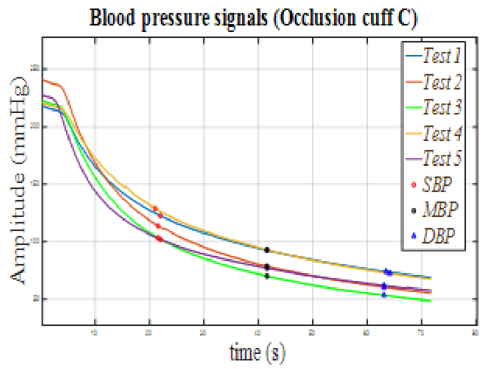
In order to validate the methodology, both cases were compare, for the case in humans, the results were compared with the commercial equipment OMRON, for each sample taken with the development equipment another was taken with the commercial equipment. As shown in table 1 and table 3, the results obtained with the proposed methodology are congruent with the commercial equipment. By means of the arithmetic mean and standard deviation, the ranges of BP parameters for OMRON equipment and the proposed methodology are shown in table 4.



a) Occlusion cuff type A.



b) Oclussion cuff type B.



c) Occlusion cuff type C.

Figure 12 BP parameters for each occlusion cuff.

Table 1 Results for each test in Wistar rat.

Occlusion Cuff A (15 mm internal diameter)			
Test	SBP (mmHg)	MBP (mmHg)	DBP (mmHg)
Test 1	101.8263	84.6687	77.0766
Test 2	107.421	83.389	68.77
Test 3	112.96	82.474	67.231
Test 4	108.552	83.449	70.898
Test 5	103.027	81.719	71.298
Occlusion Cuff B (12 mm internal diameter)			
Test	SBP (mmHg)	MBP (mmHg)	DBP (mmHg)
Test 1	94.5619	77.765	69.3665
Test 2	94.941	78.33	69.603
Test 3	98.4	78.97	69.734
Test 4	107.514	84.094	71.864
Test 5	118.223	83.445	66.056
Occlusion Cuff C (15 mm internal diameter)			
Test	SBP (mmHg)	MBP (mmHg)	DBP (mmHg)
Test 1	106.8976	82.486	70.2802
Test 2	108.53	83.135	68.052
Test 3	99.322	79.102	69.453
Test 4	97.317	85.207	79.152
Test 5	99.862	79.152	76.8

Table 2 Results from OMRON equipment.

Test	SBP (mmHg)	MBP (mmHg)	DBP (mmHg)
Test 1	106	92	85
Test 2	109	93.666	86
Test 3	105	92.333	86
Test 4	114	95.333	86
Test 5	116	98.666	90
Test 6	117	95	84
Test 7	114	94	84
Test 8	106	90	82
Test 9	118	97.333	87
Test 10	114	98.666.91	91

Table 3 Ranges for BP parameters.

OMRON equipment		
SBP(mmHg)	MBP (mmHg)	DBP (mmHg)
111.9±4.931	94.232 ± 3.928	86.1 ± 2.7264
Proposed methodology		
SBP(mmHg)	MBP (mmHg)	DBP (mmHg)
112.210 ± 5.683	95.081 ± 4.232	86.226 ± 2.317

As shown in the table 4, the deviation between the proposed methodology and the OMRON equipment is very small, therefore it is established that the results are congruent. For the Wistar rat, in [Wang et al,2013] the author presents BP measurements which were obtained from the caudal ventral artery and femoral artery in Wistar rats the results are presented in table 5, both methods aforementioned are invasive procedures. Comparing the results presented in table 2 with the results obtained from [Wang et al,2013] table 5, it is perceived that the pressure parameters obtained from the proposed methodology are within the ranges of the invasive method caudal except for test 3 in occlusion cuff A and test 5 occlusion cuff B, which present an error of 4.16 and 9.425 mmHg respectively, on the maximum estimate of the systolic blood pressure, whereas for the diastolic pressure the error was 0.769 and 1.9744 mmHg respectively and were below the estimate established by the invasive method. To delimit the BP ranges for the proposed methodology, the arithmetic mean and the standard deviation were obtained, the results are presented in table 6. Although the results obtained by the system are not completely accurate to those presented by the direct method, these are within the range; the variability of the presented results can be due to several factors, among them that the measurement of the BP by indirect methods allows the animal to remain awake and place the animal in the holder and position the occlusion cuff in the tail, can cause stress in the rat (although the rat was previously trained), whereas with the direct method the rat is kept asleep and therefore the stress is avoided; another factor that may influence variations in BP is the rat itself, since the comparative values were extracted from results reported [Wang et al,2013]**;** however, to observe the dispersion of the system presented in this work as compared to the caudal method (direct method) the BP must be measured with both methods; but the material and human resources were not qualified to carry out this invasive procedure and only a comparative was realized with results reported in the literature.

Table 4 BP Parameters for invasive methods.

Caudal ventral artery		
SBP (mmHg)	MBP	DBP (mmHg)
108.8 – 85.6	100.9 – 78.9	92.2 – 68
Femoral artery		
123.1 – 105.3	107.2 – 85.8	96.1 – 74.3

Table 6 Ranges for the BP parameters.

SBP (mmHg)	**MBP (mmHg)**	**DBP (mmHg)**
103.957 ± 6.803	81.85 ± 2.483	71.042 ± 3.772

5. Conclusions

In conclusion, the oscillometric method is a suitable methodology for the obtention of BP parameters in both Wistar rats and humans. In the work developed, the results obtained for both case studies were compared, in the case of humans with a commercial system having favorable results while in the case of Wistar rats the results obtained were compared by invasive methods were compared, although in this case obtained some variations the next step of the research is to compare the system developed with a commercial system to be able to have the same test subject (Wistar rat) and to take the BP with both systems and in this sense to know the variability of the proposed system.

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