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Full Length Research

Determination of instantaneous arterial blood pressure from bio-impedance signal

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The objective of this study was to determine the instantaneous arterial blood pressure by the peripheral bio-impedance. To achieve this goal, the equation of Ben Salah and Flaud, initially meant to determine the instantaneous aortic pressure according to the signal of thoracic bioimpedance, was successfully applied for the determination of the instantaneous arterial pressure according to the signal of peripheral bio-impedance. The problem was that this equation depends directly on systolic and diastolic pressures which were manually obtained by an electronic sphygmomanometer. Yet the objective was to determine the instantaneous arterial blood pressure without having to measure beforehand diastolic and systolic pressures by the electronic sphygmomanometer. To solve this problem, interpolation function linking respectively the pulse pressure to the impedance variation (with 2,97% error for the determination of the systolic pressure) and the diastolic pressure to the basic impedance were determined (with an error close to zero for the determination of the diastolic pressure). With the proposed method, for each new measurement on a subject we acquire its bioimpedance signal, and then use the interpolation functions to deduce its diastolic and systolic pressures and then, using the Ben Salah equation, in real time, to determine its instantaneous arterial blood pressure. The bio-impedance signal processing, the user interface and the display were managed by LabVIEW.

Key words: Instantaneous arterial pressure, cubic spline interpolation, bioimpedance, electric plethysmography, LabVIEW.

INTRODUCTION

Aortic and arterial pressures are classically determined by invasive methods, based on cardiac catheterization and recently by non invasive methods (Chemla and Lamia, 2009; Siebig et al., 2009; Bogert and Lieshout, 2005). Proposed method in this article is a non-invasive method based on the use of peripheral bioimpedance signal.

Proposed method in this article is a non-invasive method, using the peripheral bioimpedance signal.

The beginning of modern clinical applications of bio-impedance measurements can be attributed to a large part to Nyboer (1970).

The most common application is in the study of the small pulsatile impedance changes associated with heart action. Its goal is to give quantitative and qualitative information about the volume changes in the lung, heart, peripheral arteries, and veins.

The following Nyboer's equation relates the impedance variation (ΔZ) obtained on the thorax or peripheral limbs to the pulsatile blood volume change.

$$\Delta V = \left(\frac{\rho L^2}{Z_o^2}\right)\Delta Z \qquad (1)$$

Where:
ΔV = the pulsatile volume change with resistivity ρ
ρ = the resistivity of the pulsatile volume in Ω-cm (typically the resistivity of blood)
L = the length of the explored section
Z_0= the impedance measured when the pulsatile volume is at a minimum (diastolic or base impedance)
ΔZ = the magnitude of the pulsatile impedance change or impedance variation.

The idea was to link the variation of pressure to the variation of the bioimpedance. Because when ΔV is maximum in the artery (ΔZ is minimum) and the blood pressure

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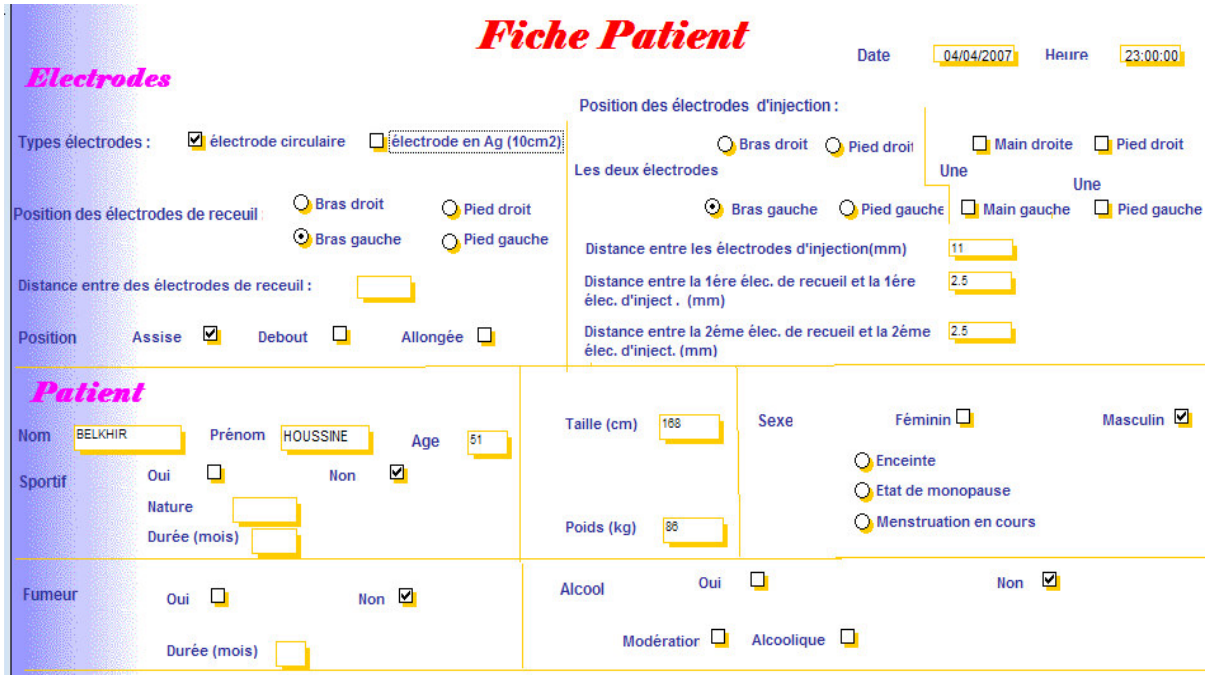

Figure 1. The access base, Z-BIOBASE.

pressure is at its maximum: the systolic pressure. And when ΔV is minimum (ΔZ is maximum), the blood pressure is at its minimum: the diastolic pressure. Knowing that the ΔZ waveform is similar to the aortal blood pressure curve (Grimnes and Martinsen, 2005).

This paper presents a practical work on the implementation of a new technique for non invasive determination of instantaneous arterial blood pressure directly from the peripheral bioimpedance signal.

MATERIALS AND METHODS

Materials

We used plethysmograph (Siemens, Direktrheagraph 933) in this study. The instrument has an injection module, generating a square pulse with a 30 KHz frequency and 1 mA intensity. In output, the device delivers an analogic signal representing the variation of the impedance of the explored section. Disposable electrodes (those used for the electrocardiograph) were used for the injection of the square pulse and the collection of bioimpedance signal. An electronic sphygmomanometer model, MP3 FUZZY was used.

The acquisition of the bioimpedance signal on PC was made easier by the use of a National Instrument data acquisition device, the NI USB 6009. This card, placed between the plethysmograph and the PC, assures the digitalization of the bioimpedance signal and its transfer on PC for further processing. The results of the different measurements were stored in an access database, the Z-BIOBASE (Figure 1).

The determination of the coefficients of interpolation was achieved using the version R2007a of Matlab. The bioimpedance signal processing, the display as well as the user interface are managed by the LabVIEW Professional Development System; version: 8.6.

Methods

The objective of this study was to determine the continuous non-invasive arterial pressure by the peripheral bioimpedance.
In a previous research, a theoretical relationship (2) between thoracic electrical bioimpedance signal and instantaneous aortic pressures was established. This study was based on the pressure variation according to radius variation during cardiovascular activity (Salah, 1988, 1986; Flaud, 1979).

$$P(t) = P_{Dia} + (P_{Sys} - P_{Dia})\frac{Z(t)}{Z_{\max}} \quad (2)$$

Where:
P (t): Instantaneous aortic pressure
P_{Sys}: systolic pressure in mmHg
P_{Dia}: diastolic blood pressure in mmHg
Z (t): The instantaneous bioimpedance signal
Z_{max}: The maximum of the bioimpedance signal curve

The P_{Sys} and P_{Dia} were determined by an electronic sphygmomanometer.

Validation for the peripheral use

The validity of this equation was demonstrated for the determination of the aortic pressure according to the thoracic bioimpedance signal. It is necessary to validate it for the arterial pressure and for the peripheral bioimpedance signal.

To do that, we conducted simultaneous measurements, on the left arm, of bioimpedance signal, of its maximum, Z_{max}, we also measured the systolic and the diastolic pressure with an electronic sphygmomanometer. We replaced all in the equation (2). We drew the instantaneous pressure and we found that always the maximum

and the minimum of the curve represent the systolic and the diastolic pressures. Thus this equation was then validated to be used for the computing of the continuous arterial pressure from the peripheral bioimpedance signal.

Automatic computing of the instantaneous pressure

Disadvantage of this method is that to get the instantaneous arterial pressure we are dependent on the sphygmomanometer. This does not enable us to determine automatically and in real time instantaneous pressure from only the bioimpedance signal.

In order to avoid this, the idea is to try to link empirically, by interpolation, the diastolic pressure (P_{Dia}) to base's impedance (Z_0) and the systolic pressure (P_{Sys}) to the maximum signal of bioimpedance (Z_{max}).

When we build the interpolation function between (P_{Sys}) and (Z_{max}), and the interpolation function between (P_{Dia}) and (Z_0), each new acquisition of a bioimpedance signal allows us to have Z (t), the (Z_0) and (Z_{max}). Having (Z_0), from the function interpolation we determine the correspondent (P_{Dia}), and having (Z_{max}), we determine the correspondent (P_{Sys}). We replace then, in equation (2), (P_{Sys}), (P_{Dia}), (Z_{max}) and Z (t) by their values and we then compute automatically the instantaneous arterial pressure.

Measurements

In order to build the interpolation function, we carried out a series of simultaneous measurements of the bioimpedance signals, to extract Z_0 and Z_{max} from it, as well as measurements by an electronic sphygmomanometer of the systolic and diastolic's pressures.

These measures concerned three hundred subjects divided into three groups, a healthy one, a sportsmen group (the national team of weightlifting) and a group of patients from Internal Medicine Department of the University Hospital (La Rabta - Tunis, Tunisia).

Cubic spline interpolation

From the different measures we kept only one hundred and forty five, the most reliable ones, which we divided into two groups: A 'learning group' and a 'test group'. A 'learning group' is made up of one hundred people who were used to build the four vectors needed for the interpolations. A vector representing the P_{Dia}, a second one corresponds to the P_{Sys}, a third one for Z_0 and a fourth one to Z_{max}. And a 'test group' made up of forty five people (15 healthy subjects, patients and athletes each) were used to check the effectiveness of the interpolations.

Four interpolation methods were tested: the linear, quadratic, cubic and cubic spline interpolation. Cubic spline gave the best interpolation, but it present some weaknesses in particular with athletes and patients. Notice that the estimation of the diastolic blood pressure shows that it is always good. However, this is not always the case with the systolic pressure. Improvements were required for this reason.

To better estimate the systolic pressure, we do not consider any more P_{Sys} in function of Z_{max}, but we test one time the pulse pressure ΔP in function of the difference between Z_0 and Z_{max} (ΔZ) and in another time, the mean pressure in function of the mean impedance. We use cubic splines to perform the interpolation.

Interpolation of pulse pressure and impedance variation

For the estimation of systolic pressure from the pulse pressure ΔP, deduced by spline interpolation from ΔZ, we proceeded as follows. From the P_{Sys} and P_{Dia} vectors, we create the ΔP vector, where ΔP = (P_{Sys} - P_{Dia}). And from the Z_0 and Z_{max} vectors, we create the ΔZ vector, where ΔZ= (Z_0 - Z_{max}). We will have a cubic spline interpolation between the two vectors. When a new measure is performed, from Z_0 and Z_{max} obtained directly from the bioimpedance signal, we compute ΔZ. Then we use the interpolation function to determine ΔP. Then having P_{Dia} and ΔP we deduce the systolic pressure by: P_{Sys} = ΔP + P_{Dia}. And now having P_{Dia} and P_{Sys} we can use the equation (2) to obtain the instantaneous arterial blood pressure.

Interpolation of mean pressure and mean impedance

For the estimation of systolic pressure from the mean pressure we use two methods as follows:
Using the mean pressure well known formula, from the P_{Sys} and P_{Dia} vectors, we created the mean pressure vector:

Where $$P_{mean} = \frac{(P_{Sys} + 2P_{Dia})}{3}$$

And from the Z_0 and Z_{max} vectors we created the mean impedance vector:

$$Z_{mean} = \frac{(Z_{max} + 2Z_0)}{3}$$

We have done a cubic spline interpolation between the two vectors. Whenever a new measure is performed, from the bioimpedance signal we use Z_0 and Z_{max} to compute Z_{mean}. Then we use the interpolation function to determine P_{mean}. Then from P_{Dia} and P_{mean} we deduce the systolic pressure by $P_{Sys} = 3 \cdot P_{mean} - 2 \cdot P_{Dia}$. And now having P_{Dia} and P_{Sys} we can use the equation (2) to get the instantaneous arterial blood pressure.

Using mean pressure of Chemla (Chemla et al., 2004; Chemla and Lamia, 2009), we followed the above steps but we use the new equation of P_{mean} and Z_{mean}:

$$P_{mean} = \sqrt{P_{Dia} P_{Sys}} \quad \text{and} \quad Z_{mean} = \sqrt{Z_0 Z_{max}}$$

In the next section, we will compare these three methods.

We can summarize the retained method as follows:

Estimating the diastolic pressure P_{Dia} from the base impedance by using the cubic spline interpolation. Estimating ΔP from ΔZ by cubic spline and then deducing the systolic pressure P_{Sys}. Determination of the instantaneous blood pressure from equation (2).

RESULTS

The first task was the study of the relevance of using peripheral bioimpedance to estimate the instantaneous arterial pressure with the same equation expressing the dependence of the thoracic bioimpedance to the instantaneous aortic pressure. This has been verified successfully with three hundred subjects divided into 3

Table 1. The interpolation error of the determination of the pressures by the four methods (results obtained with the one hundred measures of the 'learning group').

	Pressures obtained by linear interpolation (%)	Pressures obtained by quadratic interpolation (%)	Pressures obtained by cubic interpolation (%)	Pressures obtained by cubic spline interpolation (%)
Systolic error	2.17	1.87	1.53	0.92
Diastolic error	9.1	8.62	6.49	0.18

With systolic error = P_{Sys} (obtained by the interpolation method) – P_{Sys} (obtained by the electronic sphygmomanometer). Diastolic error = P_{Dia} (obtained by the interpolation method) – P_{Dia} (obtained by the electronic sphygmomanometer).

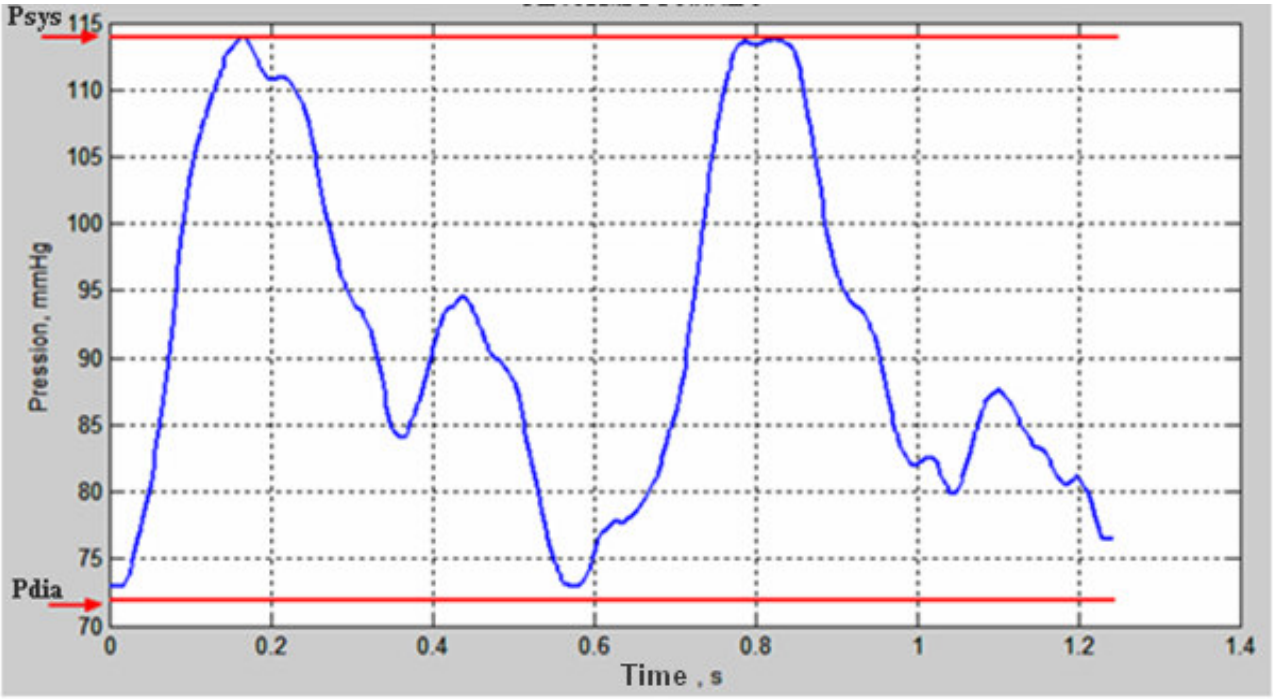

Figure 2. Curve of the instantaneous arterial pressure obtained by the cubic spline.

categories: a healthy group (people between 18 and 25 years, one hundred and eighty subjects) patients (sixty subjects) and athletes (sixty subjects).

For each of these subjects, we measured with an electronic sphygmomanometer, the systolic and diastolic pressures obtained on the left arm, then we replaced the values in the equation (2). Then we have drawn the instantaneous blood pressure curve and from which we determined the minimum that represents the diastolic pressure and the maximum that represents the systolic pressure. We compared these pressures with the values obtained by the sphygmomanometer and we found that the results are very close. We deduced that we can use the equation (2) for peripheral studies.

From the different measures we retained the most precise ones, one hundred and forty five divided into two groups: A 'learning group' used to build the vectors needed for the interpolations. And a 'test group' used to verify the performance of the interpolations.

We had chosen that the selection criteria between the various methods are the minimum difference between the systolic pressure (respectively diastolic pressure) obtained by an electronic sphygmomanometer and the systolic pressure obtained from the bioimpedance signal. First of all we compared the performance of the interpolation between linear, quadratic, cubic and cubic spline interpolation.

The comparison between the various methods allows us to choose the cubic spline which gave the best approximations (Table 1 and Figure 2).

Although the estimate of the diastolic pressure is quasi correct, the determination of the systolic pressure presented sometimes some weaknesses particularly with athletes and patients (Figure 3).

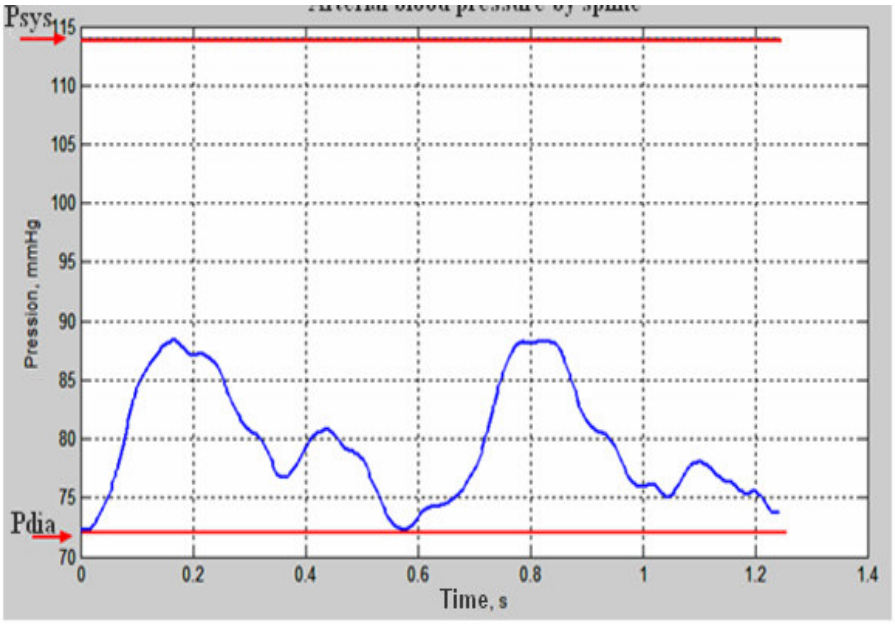

Figure 3. Limits of the cubic spline interpolation (P_{DIA} correct but the P_{SYS} is false).

Table 2. The interpolation error of the determination of the pressures by the four methods (results obtained with the forty five measures of the 'test group').

	Pressures obtained by cubic spline with (Pmax, Zmax)	Pressures obtained by cubic spline with standard (Pmean, Zmean)	Pressures obtained by Cubic spline with Chemla's (Pmean, Zmean)	Pressures obtained by cubic spline with pulse pressure (ΔP, ΔZ)
Systolic error	21.95%	4.1%	42.31%	2,97%
Diastolic error	≈ 0%	≈ 0%	≈ 0%	≈ 0%

To improve the method, we have chosen cubic spline for the direct determination of the diastolic pressure from the basic impedance.

For the systolic pressure we have tested three methods:

- The estimation of systolic pressure from the pulse pressure ΔP, deduced by spline interpolation from the bioimpedance variation (ΔZ).
- The estimation of systolic pressure from the mean pressure (two methods, the standard's one, and the mean pressure of Chemla).
- To estimate the diastolic pressure (P_{Dia}) from Z_0, the cubic spline provided the best results (Table 1).

To estimate the systolic pressure (P_{Sys}) the most precise results were given by the cubic spline interpolation between pulse pressure and bioimpedance variation. Table 2 shows the comparison between the different methods.

The Figures 4, 5 and 6 illustrate for a given subject the obtained curves of instantaneous blood pressure by the three methods.

Then we successfully tried to determine in real time the instantaneous arterial pressure, the systolic and diastolic pressures and several other cardiac parameters by using the following methodology.

The plethysmograph provides an analogical bioimpedance signal which was digitized and transferred to the computer by the NI 6009. The processing, the display and the user interface were managed by LabVIEW.

DISCUSSION

The extension of Equation 2 to the use of the peripheral bioimpedance and the arterial pressure is justifiable because the model of Nyboer described in the introduction section applies perfectly in our case (the left

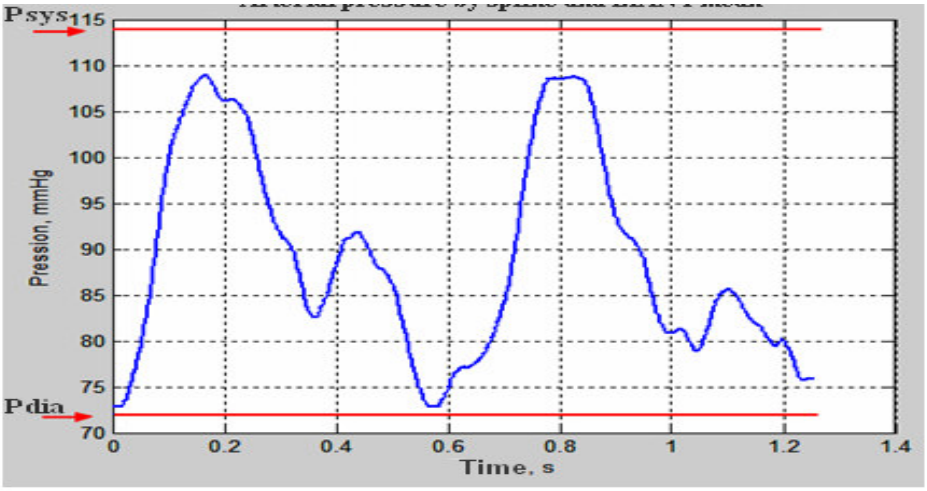

Figure 4. Curve of the blood pressure obtained by the standard mean pressure method.

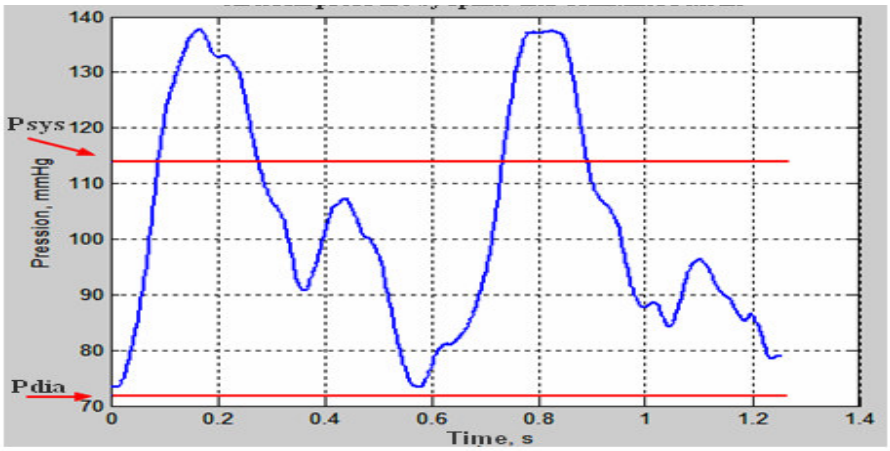

Figure 5. Curve of the instantaneous arterial pressure obtained by Chemla's method.

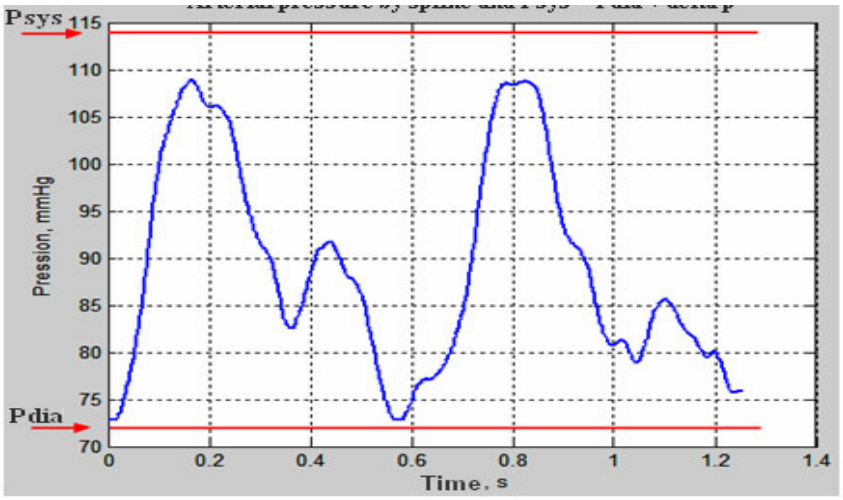

Figure 6. Curve of the blood pressure obtained by the interpolation between the pulse pressure (ΔP) and the bioimpedance variance (ΔZ).

arm) especially if the explored section is not large. That is the distance (L) between the two electrodes of collection must be lower than 5 cm, typically L= 4 cm.

The result of the comparison between the four methods of interpolation was foreseeable, since the cubic splines are largely recognized as being the best functions of interpolation.

Spline interpolation is preferred over polynomial interpolation because the interpolation error can be made small even when using low degree polynomials for the spline. Thus, spline interpolation avoids the problem of Runge's phenomenon which occurs when using high degree polynomials (Runge, 1901).

In the cardiac cycle when the pulsatile volume is at its minimum, which corresponds to the diastolic pressure, all of the conducting tissues and fluids are represented by the minimum volume. This volume can be a heterogeneous mixture of all the non time-varying tissues such as fat, bone, muscle, etc. in the region under measurement. The only information needed about this volume is its impedance Z_0. That is why when we tried to interpolate the diastolic pressure and the impedance base by a spline cubic interpolation, the results found were precise.

For the systolic pressure we thought in the beginning that the use of the standard formula of the average blood pressure was going to offer the best results to us, however the tests carried out showed the opposite.

The interpolation of the pulse pressure according to the variation of the impedance was more precise, because during the systole the pressure increases with the increase in blood volume whereas the impedance decreases. Thus, the dependence is in term of pulse volume and thus of the pulse pressure and the variation of the impedance and not in terms of mean volume mean pressure and mean impedance.

Conclusion

The monitoring of the instantaneous arterial pressure in a noninvasive way remains a precious objective for a best and quick exploration of the cardiac hemodynamic parameters.

We tried through this paper to carry out this objective by using the bioimpedance method.

The described method allows with precision, in real time, in an inexpensive and noninvasive way for the determination of continuous arterial pressure directly from peripheral bioimpedance signal.

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