

Automatic digital-analog impedance plethysmograph

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Abstract. Venous occlusion plethysmography (VOP) is a traditional method widely used to assess limb blood circulation. One common mode to record VOP is by means of evaluating limb volume changes using impedance plethysmography (IP). In this paper the design and implementation of an automatic digital-analog impedance plethysmograph (ADAIP) for VOP is presented. The system is tested using precision resistances in order to calculate its repeatability. Then its global performance is assessed by means of VOP recordings on the upper and the lower limb of a healthy volunteer. The obtained repeatability was very high (95%), and the VOP recordings were the expected ones. It can be concluded that the whole system performs well and that it is suitable for automatic VOP recording.

1. Introduction

Venous occlusion plethysmography (VOP) is a traditional method widely used to assess limb blood circulation [1]. Venous occlusion plethysmography can be equally well applied to the upper or lower limb. Ward *et al.* proposed the use of VOP applied to the arm for the measurement of central venous pressure (CVP) [2]. This technique has been also applied to the lower limb to assess vascular parameters such as calf venous compliance, capillary filtration coefficient, venous capacitance response, fluid filtration and vascular resistance among others [3]. VOP is useful in a wide variety of medical conditions such as venous insufficiency, venous thrombosis or cardiac heart failure (CHF) [4-5], it can also be used to assess the effect of new vasoactive drugs and hormones in humans [1], to measure calf blood flow during exercise [6] or reactive hyperemia [7].

The underlying principle of venous occlusion plethysmography is simple: when the limb venous drainage is briefly interrupted, which is achieved by inflating a cuff placed above the knee, arterial inflow is unaltered and blood can enter the extremity but cannot escape. Before venous occlusion occurs the limb volume remains constant at an initial value (V_0). When the occlusion takes place, a linear growth of the limb blood volume over time, that is proportional to arterial blood inflow, is observed until venous pressure reaches the occluding pressure value and a plateau is established. Once the pressure is released, the venous is drained and venous outflow can be recorded.



One common mode to record VOP is by means of evaluating limb volume changes using impedance plethysmography (IP). This is based on the fact that the limb impedance reflects the filling state of the blood vessels contained [8]. The limb impedance can be known by means of a potential difference recording when a known constant amplitude alternating current (CAAC) is injected into the limb. The alternating current frequency range used for VOP measurement goes from 20 to 100KHz [9].

When IP is used for venous occlusion recording, the voltage measured before the occlusion (V_{bo}) reflects the initial limb volume (V_0). Then, once the occluding procedure takes place, the limb volume varies and, therefore, the instantaneous measured voltage (V_i) also varies. So, after the occlusion, V_i can be divided into V_{bo} -that represents the initial limb impedance (impedance without venous occlusion)- and a variable voltage (V_v) that is a consequence of the body segment impedance changes that occur when the occlusion takes place.

In this paper, the design and implementation of an automatic digital-analog impedance plethysmograph (ADAIP) for VOP is presented. The system is tested using precision resistance in order to calculate its repeatability when a known and constant resistance is measured. Then its global performance is assessed by means of VOP recordings on the upper and the lower limb.

2. Methods

The ADAIP consist of hardware, software and an acquisition device -LabJack U3-HV (Lakewood, Colorado, USA)- that is used to connect the hardware and software between them. The system was designed to work with a tetrapolar electrode configuration which reduces errors due to the nonlinear potential differences generated in the area near to the injecting-electrodes. These errors are observed when a bipolar configuration is used, as a consequence of the electrode-tissue interface polarization impedance [9]. A scheme of the complete system is presented in Figure 1.

2.1 Hardware

The custom-made especially designed hardware is responsible for generating and injecting a constant amplitude alternating current into a body segment, sensing the generated potential difference and raising, maintaining and releasing the cuff pressure as required for VOP recording. The design includes a variable gain implemented with a precision potentiometer and an external dial. The hardware is supplied with a $\pm 15V/0.5A$ voltage source and with a 6V/4Ah battery used only for the air pump.

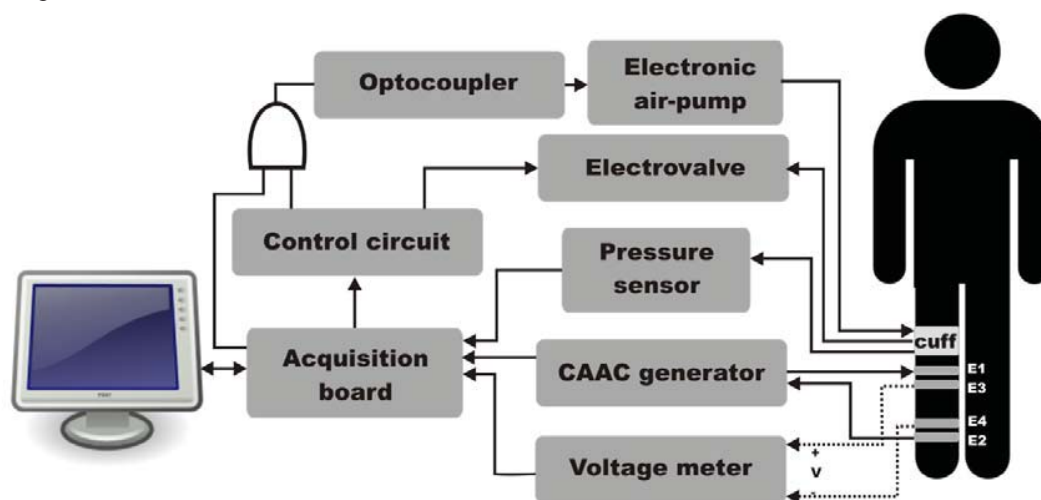


Fig. 1. Scheme of the complete system.

2.1.1. Constant amplitude alternating current (CAAC) generator. This block is the responsible for injecting a 23kHz alternating current into the body segment by means of two electrodes, E1 and E2. This block is composed of a Wien bridge oscillator, a second-order passband active filter (passband: 10-30KHz) and a voltage to current converter. The generated current has a 3mA constant amplitude.

2.1.2. Voltage meter. This block records the instantaneous voltage that is generated in the body segment when the current is injected ($V_i = V_{bo} + V_v$). This voltage is picked up by two electrodes, E3 and E4, placed between electrodes E1 and E2. As the voltage is proportional to the injected current, it is an alternating signal whose amplitude is modulated by the limb impedance changes. The voltage meter can be divided into three parts: an input stage, a demodulator circuit and a subtraction circuit (Figure 2).

The input stage consist of an instrumentation amplifier (voltage gain= 6.9), a second non inverter amplifier with variable gain and a second-order high pass active filter (cut frequency= 16KHz). The demodulator circuit is responsible for providing the amplitude of the voltage V_i which is directly proportional to the electrical impedance of the body segment placed between the electrodes E3 and E4; this is achieved with a full wave rectifier, an envelope detector and a second order low-pass active filter. The subtraction circuit receives two voltage signals: V_i ($V_i = V_{bo} + V_v$) and V_{bo} (V_{bo} comes from the output DAC0 of the acquisition device); it subtracts the signals, amplifies the resultant voltage V_v ($V_v = V_i - V_{bo}$) and sends it to the input AIN2 of the acquisition device. This last circuit consist of an instrumentation amplifier (voltage gain= 20).

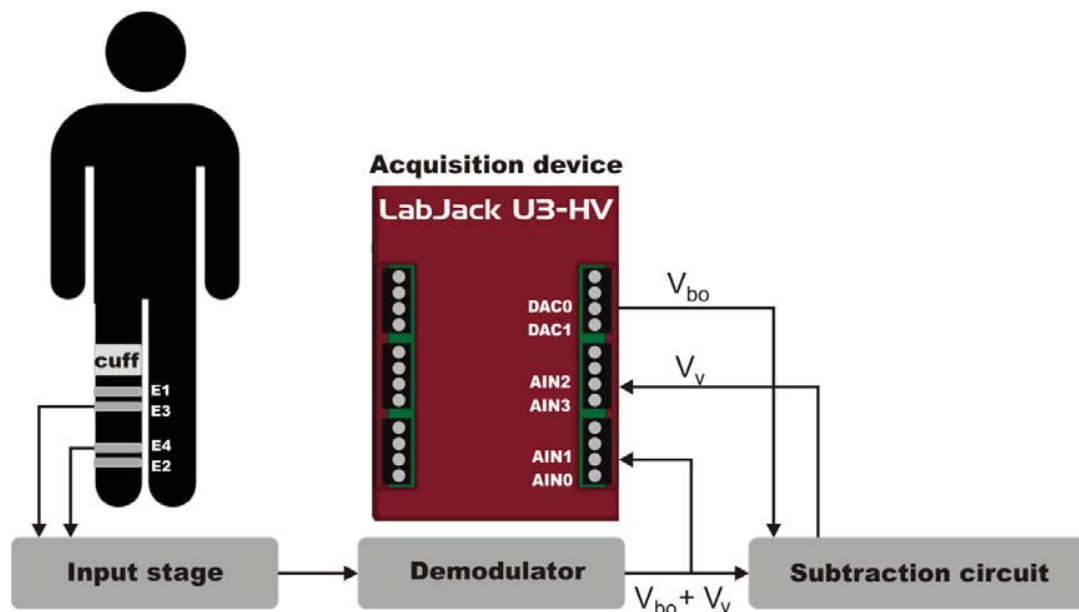


Fig. 1. Stages of the voltage meter module and their connections whit the acquisition device.

2.1.3. Pressure sensor. In this work, the pressure sensor MPXV5050GP from Freescale Inc. (Austin, TX) is used for cuff pressure recording. It consist in a piezoresistive transducer based on monolithic silicon that provides an accurate, high level analog output signal that is proportional to the applied pressure. Its principal characteristics are presented in table 1. Its transfer function is supplied by the manufacturer (equation 1). The supply voltage of the sensor is provided by the output V_s of the acquisition device.

$$V_{sp} = V_s (P \times 0.018 + 0.04) \pm \text{ERROR} \quad (1)$$

Where V_{sp} is the sensor output voltage and ERROR is function of the temperature and V_s which is specified in the datasheet of the sensor.

Table 1. Principal Characteristics of the pressure sensor
MPXV5050GP

Characteristic	Value	Unit
Pressure range	0 - 50	kPa
Supply voltage	4.75 – 5.25	V
Accuracy	± 2.5	% $V_{FSS}^{(*)}$
Sensitivity	90	mV/kPa
Operating temperature	-40 a 125	°C

(*) Full scale span (V_{FSS}) is defined as the algebraic difference between the output voltage at full rated pressure and the output voltage at the minimum rated pressure.

2.1.4. Electrocoupler and electronic air pump. The electronic air pump is used to increase the cuff pressure; it works with 6VDC/30mA and it is controlled by the output FIO6 of the acquisition device and the control circuit through an AND gate (Figure 1). The air pump is only activated when the gate output is high. An optocoupler is connected between the AND gate and the air pump to provide an electrical insulation to the air pump from the rest of the circuit. The air pump is supplied with a 6V/4Ah battery.

2.1.5. Control circuit. This circuit is used to have an accurate control of the cuff pressure, it consist of a comparator circuit and an anti-rebound circuit. The comparator circuit receives two signals: V_{sp} and a reference voltage (V_r) equal to the pressure sensor output when the applied pressure is the desired cuff pressure; V_r is supplied by the output DAC1 of the acquisition device. The anti-rebound circuit is used to remove spurious pulses that can be present at the comparator circuit output when the desired pressure is reached.

2.1.6. Electrovalve. In order to maintain or release the cuff pressure as required, a solenoid electrovalve is used. It is controlled by the output FIO7 of the acquisition device. As the electrovalve works with 6VDC/20mA, and the acquisition device can deliver only 3.16VDC/18mA, a current and voltage amplifier is necessary (not shown) which is implemented using an operational amplifier and a bipolar junction transistor.

2.2 Acquisition device (Labjack U3-HV)

This device connects the hardware and software via an USB connection. It receives and delivers signals that are necessary for the proper performance of the ADAIP. The inputs and outputs used are listed below:

- AIN0: Signal from the pressure sensor.
- AIN1: Signal from the demodulator circuit.
- AIN2: Signal from the subtraction circuit.
- DAC0: Signal to the subtraction circuit.
- DAC1: Reference voltage.
- FIO6: Signal for air pump control.
- FIO7: Signal for electrovalve control.
- VS: 5V supply voltage.

2.3 Custom-made software

The software has been implemented using Labview 2009 (National Instruments, Austin, TX) and a special library from Labjack Corporation (Lakewood, Colorado, USA). It receives, processes and displays signals from the acquisition device (Labjack U3-HV (Labjack Corporation)) and controls the cuff pressure. When a VOP recording is carried out, the software manages, for cuff pressure control, two digital outputs of the acquisition board -FIO6 and FIO7- that deliver -when high- a maximum voltage of 3.16V and a maximum current of 18mA.

The received signals are V_i , V_v and V_s (voltage from the pressure sensor) which are presented at AIN1, AIN2 and AIN0 respectively. They are sampled at a 25Hz frequency and are sent to the computer into 25 samples packets. The user interface has a START button to initiate the VOP measurement procedure, a STOP button used to cancel the cuff pressure raise, two displays that show the signals V_{sp} (from the pressure sensor) and V_{bo} or V_i (from the demodulator or subtraction circuit respectively) -which of these last two signals is visualized is determined by a button named AC/DC- and a "SAVE" button that allows to store the data for subsequent analysis using ".tdms" files.

When the software is started the AC/DC button is on the position DC and the signal at the input AIN1 is visualized. Once the electrodes are placed on the limb, if no pressure is applied, the software displays the voltage level that represents the initial limb impedance value (V_{bo}) which is presented at AIN1. At this moment, the user press AC/DC button which changes to AC and the voltage V_{bo} is recorded, stored and presented at DAC0 and the signal at the input AIN2 is visualized. When V_{bo} is at DAC0 the subtraction circuit delivers a zero value at AIN2 ($V_v=0$) until venous occlusion starts and, therefore, the visualized voltage (V_i) changes. This is important since venous occlusion leads to voltage variations much smaller than V_{bo} and, in order to visualize them correctly, V_{bo} must be removed.

3. Results

The ADAIP has been tested using precision resistance (1% tolerance) in order to calculate its repeatability when a known and constant resistance is measured. To calculate the repeatability of measurements from recapture data an extending of the statistical tests in [10] is used as in [11]. Two precision resistances have been measured two times per day in two consecutive days for three different gains. The number of measurements and days has been selected as in [12]. The results of the measurements are presented in table 2. The first step for repeatability calculation is to compute a one way ANOVA (analysis of variance; prior to ANOVA analysis variances homogeneity and normality of residuals were tested). Then, the repeatability can be calculated using equation (2) where B and W are the between individuals and within individuals variances respectively, and N is the sample size (N=4 in this case). In table 3 the results from the ANOVA are presented. The repeatability obtained by replacing B, W -from table 3- and N in (2) is 95%.

$$R=(B-W)/[B+(N-1)W] \quad (2)$$

Table 2. Voltage values obtained for the measurement of two resistances in two consecutive days with three different gains.

R	Gain	day 1		day 2	
150	1	0,5	0,6	0,45	0,4
	2	3,8	3,5	3,8	3,6
	4	6,6	7,5	7,6	7
39	1	0,4	0,4	0	0
	4	4,8	4,8	4	4
	8	7,8	8	6,8	7

Table 3. Results from the ANOVA analysis.

<i>Source of variation</i>	<i>Sum of squares</i>	<i>degrees of freedom</i>	<i>F</i>	<i>p</i>
<i>Between individuals</i>	194,4430208	5	271,64487	2,7143E-16
<i>Within individuals</i>	2,576875	18		
<i>Total</i>	197,0198958	23		

The global performance of the ADAIP has been assessed by means of VOP recordings on the upper and the lower limb of a healthy volunteer. The measurement procedure has been approved by the Ethics Committee of the Universidad Nacional de Tucumán (Tucumán, Argentina) and prior to volunteer participation in the trial, a written informed consent form was signed according to the Declaration of Helsinki. The data resultant from the measurements is plotted and presented in Figure 3. It is important to notice that the record of VOP from the lower limb is longer than the one obtained from the arm, it is necessary in order to be able to calculate certain vascular parameters as described by Skoog *et al.* [3]. In Figure 3 it can be observed that once the occlusion take place –point 1- the volume of the limb changes until a plateau is established, then when the occlusion is released –point 2- the volume changes again in the opposite direction. This is the expected waveform of a VOP recording. Finally, a photograph of the equipment and the software user interface is presented in figure 4.

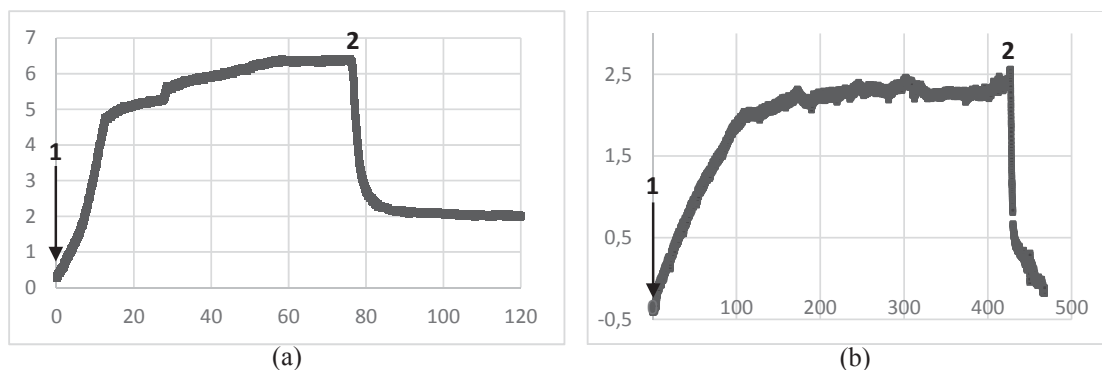


Fig. 3. VOP recordings obtained from (a) the upper and (b) the lower limb of a healthy volunteer using the ADAIP.

4. Conclusion and discussions

In this paper the design and implementation of an automatic digital-analogue impedance plethysmograph has been described. The system present a very high repeatability when a single resistance is evaluated. More tests need to be done in order to obtain the repeatability of the system when the measurements are carried out on humans. The global performance of the system has been assessed through VOP recordings on the upper and the lower limb, the obtained waveform where the expected ones, so it can be concluded that the whole system performs well and that it is suitable for automatic VOP recording.

In the future the system will be used to evaluate the vascular system of patients with certain pathologies, the intention is to compare VOP waveforms obtained from different stages of the disease in order to determine if there are any significant change that could help physicians with the

management of the patient. As the intention is to compare waveforms and not absolute values the calibration of the system would not be necessary, but it could increase its applicability.

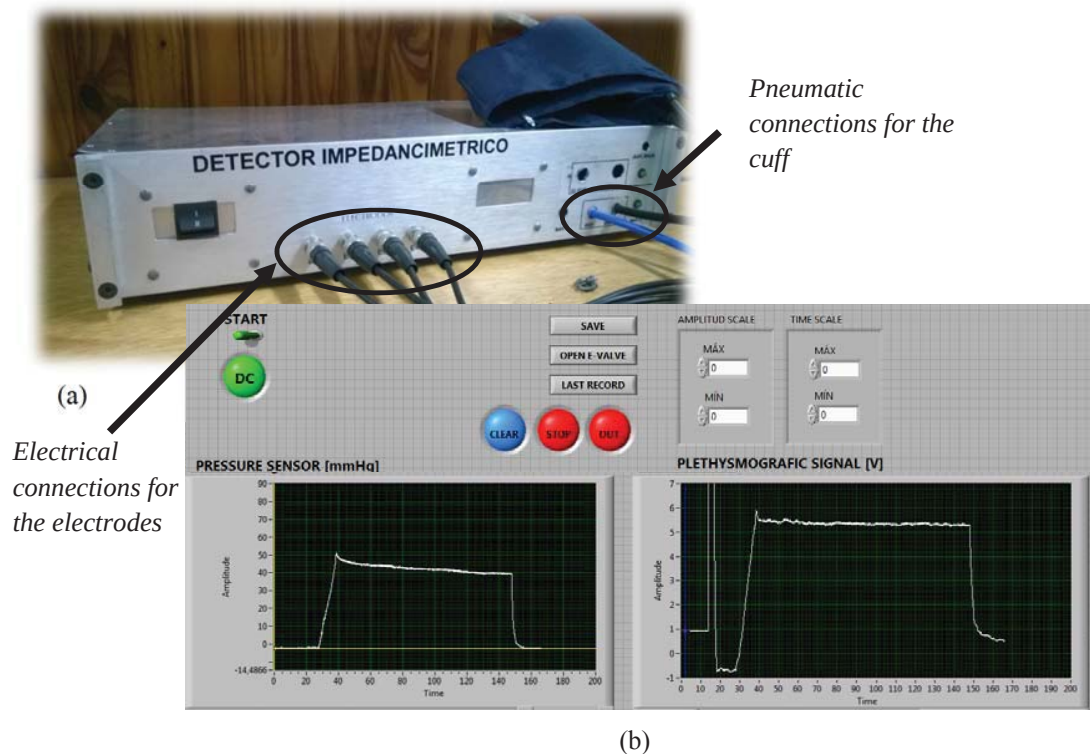


Fig. 4. (a) Photograph of the front face of the hardware with the cuff above it. The pneumatic connections -for the cuff- and the electrical connections for the four electrodes can be seen. (b) Photograph of the user interface of the software.

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