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NON-INTERFERING CARDIOVASCULAR DIAGNOSTICS AND BLOOD PRESSURE

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Abstract: *A novel non-interfering scheme for recording vascular dynamics and inferring cardiovascular conditions is presented. The method exploits bioimpedance in 50 kHz to 1 MHz range. A carefully designed electrode configuration, filtering and validation scheme allows for localized measurements of distension, pulse wave velocity and pulse shape. Pulse pressure can be inferred from these quantities and with knowledge about the arterial stress-strain relation also the absolute pressure can be determined.*

Keywords: *Cardiovascular, blood pressure, pulse wave velocity, bioimpedance, filtering and validation*

Introduction

Traditional cuff based devices for blood pressure monitoring suffer from two basic drawbacks - despite their widespread use for more than a century. A significant physiological impact on the artery where the measurement is performed is inherent in the method and measurements taken in a medical environment at a single point in time may be affected by the psychological state of the subject on which measurements are taken. Additionally, healthy subjects will generally exhibit some variations in the blood pressure over time and especially a dip during nighttime [1].

Thus, there is a strong need for a device that with a minimum of interference can measure blood pressure over time and under conditions where the subject performs his or her normal doings and in such a way that the subject has no perception of when measurements are taken.

The Sense solution is based on a concept involving three key elements: (1) Measuring variations in the diameter of an artery with a bioimpedance [2] principle (typically the brachial artery) synchronous with the beating of the heart. (2) Converting the distension to pulse pressure from a measurement of the pulse wave velocity (PWV, v) and (3) exploiting the nonlinear stress-strain relation of the artery to infer an estimate of the mean arterial pressure (MAP). Several other relevant quantities like pulse rate variability, augmentation index, central blood pressure and central PWV may be inferred.

Bioimpedance, which implies near field non-propagating wave interaction, penetrates tissue much better than short wavelength (e.g. optical) interaction, which forms the basis for photoplethysmography [3].

Theory and Assumptions

The electrical properties of tissue and blood forms the basis of the sensing method and the mechanical properties of tissues and in particular arteries provides the basis for the inference.

Different types of tissue have different conductivities and permittivities, and not only are they different they also exhibit different dependencies on the excitation frequency [4] (e.g. exploited in electrical impedance tomography). A four electrode configuration is used for measuring distension and cross-sectional areas (Figure 1).

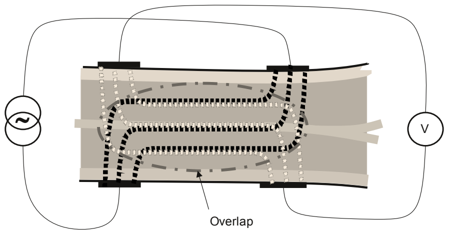


Figure 1. Current excitation and voltage detection with different sets of electrodes. The overlap gives the region within which the potential variations are measured. Electrode separation in the artery direction is typically 10 cm and the circumferential separation is 7 cm.

Pulse wave velocity has been measured both with two different configurations. The first is based on excitation and detection with the same electrodes applying two displaced sets. The other configuration is based on a six-electrode configuration with excitation with one set of electrodes (middle) and detection with two sets of detection electrodes one displaced in the forward direction and the other set in the backward direction [6].

Finite element calculations have been performed in order to investigate the details of the field distributions and robustness in relation to anatomical variations and electrode positioning. Distension measurements appears to be very robust, displacements of electrodes with several centimetres has a minor effect. However, the configuration for PWV is less robust due to the fact that the measurement is performed over a stretch of about 5 cm, which is much smaller than the spatial width of the pressure pulse.

In relation to mechanical properties we note that the blood is essentially incompressible, which also is fulfilled for muscles relative to most other types of tissues. Fat and especially subcutaneous fat is very deformable and also more compressible than muscles and blood. Very important in the present context is the stress-strain relation of arteries [5], which to a good approximation is given by the following expression:

$$P_s = P_0\left(e^{A/A_0} - 1\right) , \qquad (1)$$

where A is the cross-sectional area of the artery, and P_0 and A_0 are parameters; however, which can change e.g. as a consequence of a dilation of the artery e.g. through inhalation of nitroglycerine.

In relation to the propagation of pressure pulses is the Bramwell-Hill equation is essential:

$$v = \sqrt{\frac{\partial P}{\partial A}\frac{A}{\rho}} \cong \sqrt{\frac{\Delta P}{\Delta A}\frac{A}{\rho}} \;, \tag{2}$$

which relates pulse pressure to distension, ΔA, through the Pulse Wave Velocity (PWV). Measuring v, ΔA and (or estimating) A facilitates evaluation of the pulse pressure (assuming that the density of blood, ρ is known).

The observed signals may be perturbed by phenomena alien to the object of the measurement. Respiration will typically have a strong effect on veins, which may appear in the distension signals. A mild counter pressure of from 10 – 20 mmHg is applied through a sensor band. This essentially eliminates the dynamic effects from veins. Body movements may imply a strong perturbation and thus schemes for validating the signals are mandatory.

Signal and data processing

Excitation is typically performed at five frequencies distributed in the interval from 50 kHz to 1 MHz. The detected signals are demodulated with a quadrature scheme: the signals are mixed with two reference signals one in phase and one in phase quadrature. This facilitates estimation of the complex impedance values. The filtering is performed with FIR filters. This fact facilitates filtering with no phase change except for a fixed delay. The high pass filter for dynamic measurements is applied with a Hamming/Hann window in order to minimize ringing in conjunction with the finite filter length. Corner frequencies are typically 1 Hz for distension measurements and 5 Hz for PWV measurements. The low pass filter is asymmetric in order to match the general asymmetric pulse with a corner frequency of from 10 Hz to 100 Hz.

Validation of the signals is performed through a training process where the most likely pulse shape for the specific subject (test person) is obtained. A correlation with individual pulses forms the basis for validation of pulses.

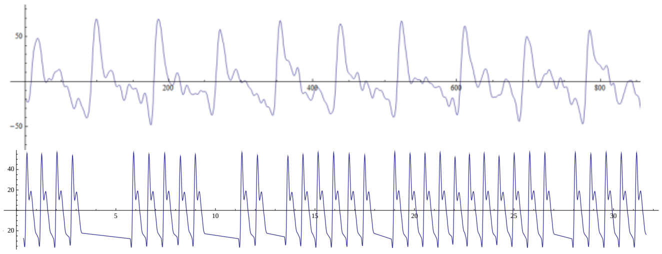
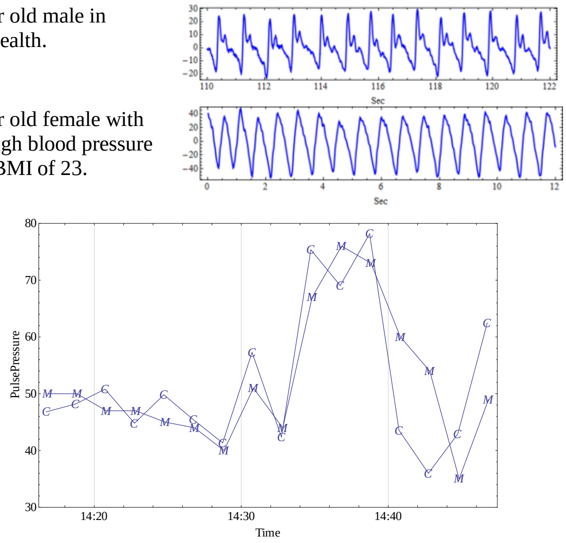


Figure 2. Example of pulses from a 50 year old male. Top: a sequence of undistrubed raw pulses. Bottom: a 35 sec sequence of validated pulses. Note the sequences where pulses are rejected because of body movements.Vertical axis in mmHg, horizontal axis: 10 ms/div.

Pulse wave velocity has been obtained (1) by cross-correlation and fitting to an expected correlation function and (2) by estimating the (very small) temporal differences of the individual pulses, where the locations of the largest gradients are used for estimating the temporal positions. Local Brachial and radial velocity of from 8 m/s to 13 m/s have been obtained.

Examples of Measurements

A large number of measurements have been performed on different subjects. Examples are shown in Figure 3.


29 year old male in good health.

60 year old female with very high blood pressure and a BMI of 23.

Figure 3. Pulse shapes from (top) a healthy young male and (middle) a hypertensive female. Below is shown an example of a measurement during a *cycle test* with the Sense device and as reference *Mobil-O-Graph* measurements [7].

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