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MODELLING THE HUMAN CIRCULATORY SYSTEM

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Abstract: Aortic stenosis, thrombosis and stroke are common fatal diseases which could be predicted if a cheap, easy-to-use, non-invasive measuring method was available that estimates the state of arteries. Up to date ultrasound Doppler is the only such reliable way. Goal of this research is to asses the biomechanical properties of blood vessels via a photoplethysmographic (PPG) signal. An equivalent electrical model is being introduced which simulates the pressure and flow transients in the aorta and the left arm. Effects of a cuff wrapped around the upper arm are also included. The cuff-induced changes in flow conditions are measured by PPG sensor on a fingertip. The diagnosis comprises of the estimation of model parameters from the measured data.

Key words: modelling, parameter identification, ARMAX, blood pressure, state of the arteries.

1 Introduction

Cardiovascular failure (heart attack, stroke, lung embolism) is a leading factor in the death rates of industrial societies. Unfortunately in Hungary along with Poland and the Baltic States the number of deaths of heart or circulatory system origin is the highest in Europe. The most frequent precursors of the above mentioned fatal diseases are hypertension and arteriosclerosis. Although both can be well treated, in the early stage even the change of lifestyle could be sufficient; there are still no reliable measuring methods available. Automatic home blood-pressure meters are widespread, but coming from their measuring method (oscillometry) medical doctors tend to take their results with reservation [1]. Cheap, easy-to-use devices for assessment of arterial stiffness do not even exist.

The goal of our research at the BME supported by the EU is to fill this gap. First thing on our way is to create a simple but sufficient enough model of the human circulation focusing especially on the heart, aorta and the left arm arteries and veins. Given a validated model it is easy to understand the drawbacks of the oscillometric method and to design a more reliable device. Moreover measuring protocols can be developed to identify the parameters of the model thus estimating the flow resistance and capacitance of the blood vessels.

2 Materials and Methods

2.1 The measurement set-up

For home health monitoring issues only non-invasive techniques come in question. That is the reason why we are suggesting the use of a photoplethysmograph (PPG) and a cuff for indirectly measuring blood-pressure (BP) and estimating the arterial stiffness. Although widespread, it is little known about the optical sensor commonly used in OPs, intensive cares and different sports equipments. PPG manifests itself in a clip attached to a fingertip or earlobe where it records the optical reflections (or transmission) of blood vessels. Volume changes in an artery generated by the pulse alter the reflecting conditions of the tissue according to Lambert-Beer law. Signals are derived from the arterial pressure by means of non-linear function compliance. In what follows this curve will be represented by a 2/2 polynomial.

An integrated device was developed to monitor the above mentioned signals and to control the pressure of a cuff.

2.2 Electrical model of the circulation

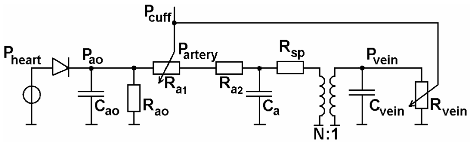

Figure 1. Model of the heart, aorta and left arm arteries and veins

Figure 1. is a simple electrical model of the heart, aorta and the left arm artery and veins. In this representation pressure is replaced by voltage, flow by current. Capacitors represent the puffer effect of aorta, arteria brachialis and veins. Diode stands for the valve, transformer for the capillary net and resistors for flow-resistance, which for a piece of blood-vessel is:

$$R = \frac{8L\eta}{r^4\pi} \tag{1}$$

where L is the length, η the viscosity of blood and r the inner radius of the vessel. To get a feeling for the different R values the resistance-distribution in the circulatory system is given [2]:

Table 1. Resistance-distribution in the circulatory system

Blood-vessel	Relative resistance
Aorta, large arteries	10%
Small arteries (pre-capillary sphincter)	50-55%
Capillaries	30-35%
Veins	5%

The model includes the effects of a cuff wrapped around the left upper arm. By inflation the following sequence of events happen:

1. Normal circulation.
2. Reaching the venous pressure (approx. 20 mmHg) the back-flow to the right atrium is blocked.
3. Above the diastolic pressure (usually 80 mmHg) the arterial flow is being restricted. Distal from the cuff laminar flow becomes turbulent, Korotkov-sounds emerge.
4. Above systolic pressure (usually 120 mmHg) the brachial artery is totally closed, circulation of the arm becomes separated from the rest.

To simulate the above described process R_a and R_{vein} have to be functions of P_{cuff}.

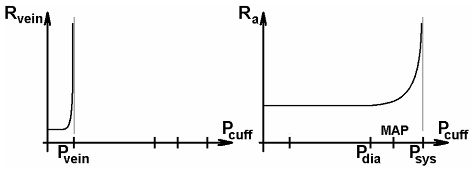

Figure 2. R_{vein} and R_a as functions of P_{cuff}

Taking a closer look at the model it is easy to understand what happens during a cuff-based BP measurement. It can be agreed upon that using a cuff for BP measurement is like using an instrument with low input impedance for measuring voltage. Both are methodically incorrect and return false values. Oscillometry, the most wide-spread BP measuring method has an additional error source too: it measures only the mean arterial pressure (MAP) and just calculates the sys/dia values via prearranged coefficients.

Viability of the equivalent electrical model was confirmed by comparative measurements on a physical circulation-model at the Department of Hydrodynamic Systems [3].

3 Results

For identification purposes the developed model was still too complex, several restrictions had to be made. First the nonlinear behaviour of R_a and R_{vein} was to eliminating. To achieve this, the pressure of the cuff had to be qualified into 3 different states: P_{cuff} below the venous pressure, between the venous and the systolic pressure and over the systolic value. Switches Sw_1 and Sw_2 were included which are controlled according to this quantization: both closed, Sw_1 closed but Sw_2 open, both open. Further the circulation of an arm is insignificant compared to the whole aortic flow. This means that a cuff-intervention in the flow conditions of an arm could tell a lot about C_a, R_a, R_{sp}, C_v and R_v, but hardly anything about C_{ao} or R_{ao}. Thus heart and aorta were replaced by an ideal source:

$$P_{ao} = \frac{P_{sys} - P_{dia}}{2}\sin(\omega t) + MAP \qquad (2)$$

Venous pressure is normally constant 10-20 mmHg but even under extreme conditions it cannot exceed 40 mmHg. This physiological fact left our parameter N not much playground, so we arbitrary set its value to 3. Lastly BP auto-regulation had to be neglected and assumed that during measurement properties of the vessels are unchanged. These assumptions result in the simplified model depicted in figure 3. A PPG sensor is also included.

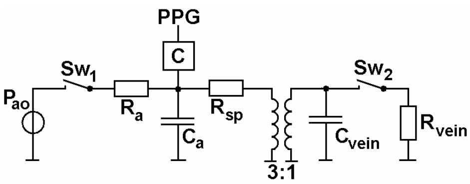

Figure 3. Simplified model of circulation

Identification of model parameters required an unusual approach. According to classical parameter identification a model with unknown parameters is given and the effects of a well defined excitation are measured at the output. Because it was impossible to intervene with the beating of the heart, the actual excitation, two different cuff-based measuring protocols had to be developed. In the first one the cuff was fast inflated above the systolic pressure, held there for about 15 sec and then fast deflated. Figure 4. shows the simulated behaviour of the model and a real measurement for such an excitation. In terms of the abstract model this means the turning off of both switches and after 15 sec their simultaneous turning on. The second cuff-intervention applied, as presented in figure 5. is fast inflation until 50 mmHg (below diastolic), holding it for about 40 sec, then fast deflation.

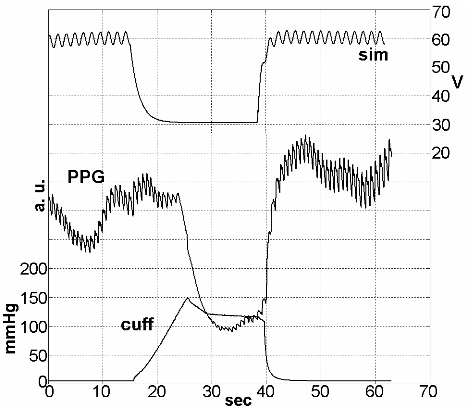

Figure 4. Protocol no. 1. Cuff pressure, simulated model output and measured PPG (response of a young, healthy patient to the excitation)

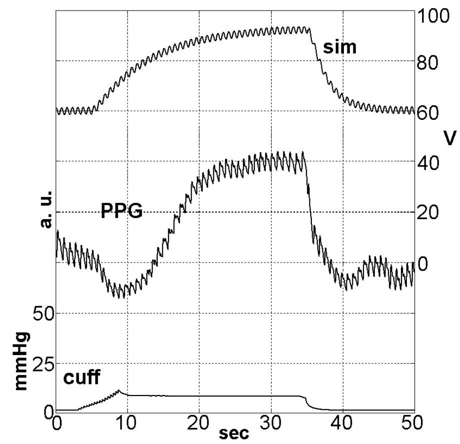

Figure 5. Protocol no. 2. Cuff pressure, simulated model output and measured PPG

During real measurements we were not able to generate rapid cuff inflation only fast deflation could have been achieved. For identification purposes only the later were used.

Responses given to fast deflation in the two different measurements are:

$$P_1 = \frac{1}{s} MAP \frac{s^2\alpha + s\beta + \gamma}{s^2 + s\delta + \varepsilon} \quad (3)$$

$$P_2 = \frac{1}{s} MAP \frac{s^2 + s\delta + \gamma}{s^2 + s\delta + \varepsilon} \quad (4)$$

where symbols α, β, γ, δ and ε are constants derived from the model parameters.

The identification itself is the following recursive algorithm:

1. Measure MAP by means of oscillometric method and set the initial compliance polynomial linear.
2. Transform the PPG signals to pressure values via compliance polynomial.
3. Apply ARMAX frequency domain identification for measurement data no. 1. according to equation (3) and determine the model parameters α, β, γ_1, δ_1 and ε_1.
4. Apply ARMAX frequency domain identification for measurement data no. 2. according to equation (4) and determine the model parameters γ_2, δ_2 and ε_2.
5. Change the compliance parameters in a way that the gradient of estimation error, $\left[(\gamma_1,\delta_1,\varepsilon_1)-(\gamma_2,\delta_2,\varepsilon_2)\right]^2$, becomes negative.
6. If estimation error is exceptional small then STOP, else GOTO step 2.

4 Conclusion

A simple model of circulation including heart, aorta and left arm was developed; effects of a cuff wrapped around the upper arm were investigated. Two different cuff pressure profiles were used: one blocking the whole circulation of the arm the other impeding only back flow through the veins. A measurement set-up comprising of a PPG sensor and a cuff-pressure controller was constructed. Model parameters were estimated from PPG signals recorded on a fingertip by means of MATLAB’s System Identification Toolbox. The method makes evaluation of five circulatory parameters (R_a, R_{sp}, R_{vein}, C_a, C_{vein}) for every individual patient possible. Whether there are significant differences in these model parameters for healthy and sick patients or not that could only be verified through numerous future experiments. Drawback of the method is the fact that only the parameters of the arm can be estimated. Little could be said on the condition of the aorta or the cerebral circulation which are essential and quite desirable. However, if the cuff would be wrapped around a hip, the state of varicose veins could be determined and development of phlebitis or phlebothrombosis be predicted. As further future work the compliance should be described by a more suitable function.

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