Continuous blood pressure measurement with ultrasound

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Abstract
Cardiovascular diseases are the main cause of death in Germany. A long-term blood pressure measurement is crucial to identify hypertension which can lead to cardiovascular disease. Conventional techniques use the automatic arm cuff method which is painful and provides only intermittent results. A new method for continuous measurement is developed using a DOPPLER ultrasound sensor on a superficial artery and a small balloon. A voice coil actuator is used to change the balloon pressure using a control loop. Holding the control variable – the ultrasound signal – constant and low by controlling the balloon pressure permits a continuous measurement. The system was tested using a blood pressure simulator with variable pressure curves and abrupt pressure changes. The controller-induced balloon pressure tracks the pressure in the model artery very closely.

1 Introduction
Blood pressure is the most important parameter on cardiovascular diseases which are the main cause of death in Germany. Globally, hypertension is the main risk factor for cardiovascular disease [1]. One method for the diagnosis of hypertension is the 24h blood pressure measurement [2]. The most common technique uses an arm cuff and the non-invasive measurement principle based on RIVA-ROCCI [3]. A portable device automatically inflates the arm cuff every 15 minutes (30 minutes at night) measuring systolic and diastolic blood pressure.

This method suffers from essential drawbacks: the pressure on the upper arm is painful for the patient and provides only intermittent results. During the measurement the patient has to interrupt all movements. This technique is stressful for the patient because the occlusion of the whole arm leads to venous congestion [4]. A new method is required which does not disturb the patient and permits him to follow his daily activities.

2 Method
The new continuous method for long-term blood pressure measurement is based on a noninvasive RIVA-ROCCI method with a new assessment of blood flow. A drawing of the device is shown in figure 1.

2.1 Components of the device
A small pressure balloon made from polyurethane compresses a single superficial artery. The radial artery (ARTERIA RADIALIS) on the wrist is preferred for the measurement. An actuator acts on the balloon changing the balloon pressure very fast. Initially, a loud speaker was used, which will later be replaced by a smaller voice coil actuator.

A DOPPLER ultrasound sensor is used to measure the blood velocity in the radial artery. The ultrasound sensor can be attached planar to the skin and consists of piezoelectric crystals with a natural frequency of 8 MHz. A commercial vascular ultrasound device Hadeo Bidop ES-100V3 (DEGO GmbH Medizin-Elektronik, Germany) was used as processing electronic.

The ultrasound signal is used as the control variable in the controller. The controller changes the electric current for the actuator according to the ultrasound signal from the artery blood velocity.

Figure 1: Drawing of the device. The superficial artery runs closely to the bone. The balloon compresses the artery; the ultrasound sensor measures the remaining blood velocity. The actuator changes the balloon pressure according to the control loop information.

2.2 Measurement principle
The measurement principle is shown in figure 2.

Figure 2: Measurement principle. Blood pressure (blue) has to be measured. Depending on the ultrasound signal (red) the balloon pressure (black) is changed by the actuator using the controller starting at time X.
The pressure balloon is used to compress the superficial artery until the blood flow is close to zero. If the arterial pressure is higher than the balloon pressure the artery will not be occluded – the ultrasound sensor will detect a high blood velocity. To decrease the ultrasound signal to the desired value the balloon pressure has to be increased. The target blood velocity is low but higher than zero ensuring a permanent blood flow to tissue located downstream.

2.3 Blood pressure simulator

Measurements were executed on a blood pressure simulator, figure 3.

A linear motor is used to generate a pressure oscillation over a constant mean pressure using a windkessel cylinder. A model artery is made from polyurethane foil with a thickness of 100 µm. A tissue model consists of gelatin surrounding the model artery. The elasticity of gelatin was adjusted to the elasticity of meat to simulate the surrounding tissue on the wrist. The control loop used a model based controller with a third order transfer function. The identification of the control process for the design of the controller was developed on the blood pressure simulator as well. The controller is implemented on a Rabbit microprocessor (RCM4100 Rabbit Core Development Kit, USA) and connected to a loudspeaker used as actuator. The loudspeaker was a 300W high power subwoofer (Impulse US® Acoustics).

Water is used as model fluid. Polyamide particles (Orgasol® 2000, Arkema, France) are used as tracer particles for the ultrasound signal. The flow velocity is regulated with a variable resistance at the outflow. The fluid is pumped into the water column using a roller pump at constant speed.

The pressure in the model artery, the pressure in the balloon and the ultrasound signal were measured. The measurement site can be moved in two dimensions simulating a movement of the patients arm. The acceleration during the movement was measured with a three-axis acceleration sensor.

3 Results

3.1 Measurement with controller

Figure 4 shows a measurement of a control loop with a third order transfer function. The dotted line indicates the start of the controller. The ultrasound signal (the upper blue curve) shows the decrease of blood flow. The target value for blood flow was $V_{\text{Blood}}=7\text{ml/min}$. The lower figure 4 shows the pressure in the balloon (red) and in the simulator directly upstream from the balloon (blue curve). The balloon pressure is initialized to $p_{\text{Balloon}}=70\text{mmHg}$. After starting the control loop the balloon pressure follows the model arterial pressure very closely. Systolic and diastolic pressure in the model artery is 137/80mmHg. The mean difference for systolic pressure is 5.26mmHg with a standard deviation of 4.41mmHg. The mean diastolic pressure difference is 3.15±1.99mmHg. The change of model arterial pressure before and after starting the control loop is induced by the changed outflow resistance while the model artery is occluded.

3.2 Measurement during simulation of movements

The mean pressure can be altered in the blood pressure simulator. The measuring site can be elevated and lowered in relation to the water level in the water column (indicated by arrows in figure 3). This can be used to simulate abrupt pressure changes as they appear during arm movement in a patient.

Figure 5 shows such a measurement with the ultrasound signal (upper blue curve), the electric current in the loud speaker (middle blue curve) and balloon pressure (red) and model artery pressure (lower blue curve). The mean pressure is changed a couple of times simulating an up and down movement of the wrist. The mean pressure change is approximately $p_{\text{Diff}}=23\text{mmHg}$. This corresponds with a height difference of 31.21 cm. The balloon pressure continues to follow the model arterial curve very closely. The mean systolic pressure difference is 7.08mmHg with a standard deviation of 6.82mmHg; the mean diastolic pressure difference is 5.17mmHg with a standard deviation of 2.86mmHg.
The continuous blood pressure measurement with ultrasound showed a good accuracy for blood pressure readings on a mock circulation and on a subject. The American Association for the Advancement of Medical Instrumentation (AAMI) published a standard for the accuracy of blood pressure measurement devices. A mean difference of 5 mmHg or a standard deviation of 8 mmHg must not be exceeded [5]. The mean diastolic pressure difference of 3.15±1.99 mmHg for simulator measurement with controller (3.1) meets both criteria. The mean systolic pressure difference of 5.26±4.41 mmHg for simulator measurement with controller (3.1) and 7.08±6.82 mmHg with movement simulation (3.2) meet the second criterion. The mean diastolic pressure difference of 5.17±2.86 mmHg for measurements with movement simulation also meets the second criterion.

The measurement on a subject (3.3) shows a reasonable behavior of the mean pressure. The heart-hip-difference of the subject of 42 cm which is close to 40.71 cm calculated from the mean pressure change; the subjects’ heart-head-difference is 30 cm. The calculated height difference from head to heart is only 12.21 cm. The reason for this is that the measured pressure cannot be lower than the initial pressure in the balloon of approximately 60 mmHg. This value cannot be decreased because a lower initial pressure limits the highest possible pressure in the balloon induced by the actuator. For a greater range of balloon pressure the actuator range has to be increased. This will be done by the new voice coil actuator.

The mean systolic and diastolic pressures measured with the new controlled ultrasound technique are within good accuracy to the subjects’ blood pressure measured with a commercial oscillometric device. The difference between both measurements is 12 mmHg for systolic and 9 mmHg for diastolic pressure.

The model based controller with the third order transfer function showed good results for the measurement on the simulator and in the subject. For the new voice coil actuator, the controller will include an iterative learning approach to increase the robustness of the controller. The signal-to-noise ratio of the ultrasound signal should be enhanced to reach a higher reliability of the measurement principle. This can be done by suitable filter techniques or by improving the geometry of the ultrasound sensor and the processing of the signal by the ultrasound electronic. During the continuous blood pressure measurement the patient will be able to move. The blood pressure has to be recorded at heart level. Therefore, a measurement of the distance between the wrist and heart level has to be implemented. This can be done by measuring the elevation of the wrist. With this, the blood pressure readings can be calibrated.

**Figure 5:** Measurement during movement simulation. The upper graph shows the flow rate calculated from the ultrasound signal, the middle graph is the electric current of the actuator, and the lower graph shows the balloon pressure curve (red) and the simulator pressure curve (blue).

Although the ultrasound signal is not decreased to meet the target flow criteria of 7 ml/min, the balloon pressure follows the simulator pressure very accurately.

### 3.3 Measurement on a subject

The controller was tested on a subject who moved the arm during the measurement. The pressure balloon was adjusted over the left radial artery near the subjects’ wrist and fastened with a polyvinylchloride shell. A blood pressure of 130/80 mmHg was measured in the subject with an automated arm cuff technique (Omron M5-i, Germany). The wrist was held at three different heights: at heart, head and hip level. Height differences for the subject were 30 cm for heart-head and 42 cm for heart-hip difference. Figure 6 shows the result of the measurement. The systolic and diastolic blood pressure was evaluated in the segment “arm at heart level”. The calculated mean systolic pressure is 142 mmHg; the mean diastolic pressure is 71 mmHg.

**Figure 6:** Measurement on a subject with ultrasound flow signal (blue) and balloon pressure (red).

The internal arterial pressure could not be measured. Therefore, the mean pressure is evaluated for each segment of wrist level. The mean pressure changes from 88 mmHg at heart level to 79 mmHg at head level and to 118 mmHg at hip level. The corresponding height differences are 12.21 cm for heart-head-difference and 40.71 cm for heart-hip-difference.

### 4 Discussion

The continuous blood pressure measurement with ultrasound showed a good accuracy for blood pressure readings on a mock circulation and on a subject. The American Association for the Advancement of Medical Instrumentation (AAMI) published a standard for the accuracy of blood pressure measurement devices. A mean difference of 5 mmHg or a standard deviation of 8 mmHg must not be exceeded [5].
References


