A phantom with pulsating artificial vessels for non-invasive fetal pulse oximetry

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***Abstract*— Arterial oxygen saturation of the fetus is an important parameter for monitoring its physical condition. During labor and delivery the transabdominal non-invasive fetal pulse oximetry could minimize the risk for mother and fetus, compared to other existing invasive examination methods. In this contribution, we developed a physical-like phantom to investigate new sensor circuits and algorithms of a non-invasive diagnostic method for fetal pulse oximetry. Hence, the developed artificial vascular system consists of two independent tube systems representing the maternal and fetal vessel system. The arterial blood pressure is reproduced with a pre-pressure and an artificial vascular system. Each pulse wave can be reproduced, by digital control of a proportional valve, adjustable viscoelastic elements, and resistances. The measurements are performed by pressure transducers, optical sensor units, and a coplanar capacitive sensor. Transmission and reflection measurements have shown that the fetal and maternal pulse waves can be reproduced qualitatively. The measured light represents the transabdominal modulated signal on an abdomen of a pregnant woman.**

I. Introduction

Pulse oximetry is a common method in modern medicine for measuring pulse rate and oxygen saturation of arterial blood. In various stages of pregnancy and during labor and delivery it is still a challenge to determine the arterial oxygen saturation of the fetus. An oxygen deficiency could have fatal consequences regarding the development of the fetus. The arterial blood gas analysis is a reliable method to determine oxygen saturation, but the invasive procedure is a risk for mother and fetus. Only reasonable indications warrant the use of an invasive diagnostic method. Up to the present there exists no non-invasive medical procedure to determine the fetal oxygen saturation. Current clinical methods are invasive or require a preliminary invasive procedure.

The fetal reflective pulse oximetry could be a solution for this dilemma. The measurements can be performed trans-vaginal or trans-abdominal. The latter is non-invasive and reduces the risk for mother and fetus [16]. A sensor circuit for non-invasive fetal pulse oximetry is described by Ley et al. [4]. For evaluating the sensor circuit and the separation algorithms a physical-like phantom is required, which reproduces the maternal and fetal pulse waves.

Various experimental systems have been designed to reproduce pulsatile flow and pulse waves in an artificial artery for studying hemodynamic effects or non-invasive photometry [8], [12]. Different research groups often used displacement pumps to reproduce arterial flow and pressure. For example, it is possible to generate pulsatile waveforms with a roller pump and a stepping motor. Due to the mechanical properties and function, the measured pressure and flow waveforms are limited [15]. With a digital controlled piston pump arterial flow can be reproduced more accurately. The pressure in a vascular system is a result of coupled elastic elements and resistances. An elastic element simulates the Windkessel function of the aorta. The elastic tube represents the arterial blood vessel and the clamp models the flow resistance of the artificial vascular system. Pressure and flow can be adjusted due to the elongation and motion speed of the piston pump. Additionally both system parameters are influenced by the air within the compliance, the aperture of the valve, and the other hardware components [1], [11]. Oura et al. developed a compact mock circulation system for pulse spectrophotometry [7].

A piston pump compresses a silicone tube in an acryl pipe, which generates a pulse wave with a small amount of blood similar to human artery. In the work of Suzaki et al. an artificial heart generates the blood pulsation [12]. During the diastolic phase the heart is filled with blood. Subsequently, a short pulse of compressed air pushes a membrane, which injects the blood into the system consisting of a compliance, a pulsation cell, and an artificial lung. The majority of artificial blood circulatory systems have just one circuit, but for non-invasive fetal pulse oximetry two circuits are required, whose pressure ratios and pulse rates are independently adjustable.

II. MATERIAL AND METHODS

A. System design

The arterial blood pressure wave is simulated with a modified Windkessel model presented by Parlikar et al. [9]. This model, shown in Fig. 1, consists of two arterial com-

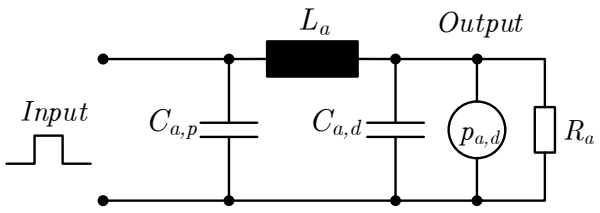

Fig. 1. Model of the artificial vascular system with the proximal compliance $C_{a,p}$, the inductor L_a, the distal compliance $C_{a,d}$, the pressure output value at the distal compliance $p_{a,d}$, and the total peripheral resistance R_a. The input represents the pulsatile cardiac output.

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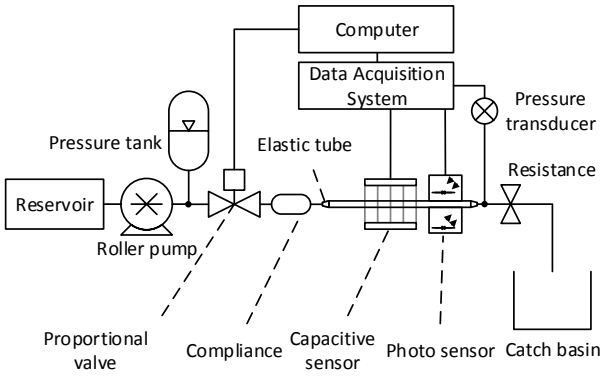

Fig. 2. Concept of the hardware configuration.

pliances, which are separated by an inductor. The highly elastic arteries proximal to the heart are represented by the first compliance $C_{a,p}$. The dynamic inertia of the fluid will be determined by the inductor L_a, influencing the pulse propagation between both compliances. The low elasticity of the peripheral arteries is determined by the compliance $C_{a,d}$. If the inductor becomes zero ($L_a = 0$), this model will be reduced to the two-element Windkessel model with a total arterial compliance and a resistance, mentioned in Frank [3]. The resistance R_a represents the total peripheral resistance of the circulatory system. The heart beat and the impulsive cardiac output will be regulated with a pressure tank as constant pressure source and a digital controlled valve. Finally, the pressure $p_{a,d}$ at the end of the elastic tube is identical to the pressure at $C_{a,d}$. This signal is measured with a pressure transducer or due to the elastic tube via photoplethysmography. Different types of tubes are used for the phantom. The elastic tubes have a wall thickness of $1\ mm$ and are made out of a soft and elastic material. The other tubes in the artificial vascular system are more rigid to reduce pressure losses.

B. Experimental model

The experimental setup, presented in Fig. 2, is an open hydraulic system, consisting of two subsystems to reproduce the arterial blood pulsation. The pre-pressure system consists of a roller pump and a pressure tank. The artificial vascular system consists of a digital controllable proportional valve, viscoelastic elements, a flow resistance, and a signal processing system. The second subsystem is installed twice to reproduce the maternal and fetal pulse wave. A detailed description of the components of each subsystem will be given in the next subsections. The maternal and fetal blood circuit have an identical structure.

1) Pre-pressure system: The roller pump (Type 313, Watson-Marlow GmbH, Germany) is driven with a stepping motor. The pressure tank, with a filling volume of $7.6\ l$, is charged up at a pressure of $150\ kPa$. Inside the pressure tank is a butyl bladder, which enables a constant pressure during the emptying phase. The roller pump is disabled during the opening phase of the proportional valve to prevent reverse flow and mechanical vibrations.

2) Artificial vascular system: The proportional valve (Type 2873, Bürkert, Germany) represents an artificial heart valve and connects the pre-pressure system with the artificial vascular system. Due to the resulting pressure difference between these systems a pulsatile flow can be generated. The opening width of the valve determines the input flow rate and the pressure in the elastic tube. The proportional valve is controlled via computer by a RS-232 control unit (Type 8605, Bürkert, Germany). The opening time is set to $150\ ms$ and $200\ ms$, whereas the closing time can be adjusted to simulate different heart rates for maternal and fetal circuit. The heart rate in both artificial vascular systems can be adjusted in a range of 60 to 130 bpm.

The compliance is an elastic buffering chamber as a storage element in the hydraulic system and reproduces the Windkessel function of the aorta and the proximal arteries. During the systole it stores a certain amount of the stroke volume and during the diastole the released energy maintains the flow in this system. The exponential decay of the diastolic pressure is strongly influenced by the compliance. According to Bowles et al. [2] the compliance can be calculated and adjusted by the amount of air and the pressure.

For this work we used a maximal dynamic dilation of the fetal aorta of $14.8\ \%$, which was measured between the 30th and 36th week of pregnancy by Tonge et al. [13], [14]. During pregnancy the arterial vessels of the mother are dilated to increase the perfusion of the body [6]. In maternal and fetal circuit we used a transparent silicon tube with an inner diameter of $5\ mm$ and a wall thickness of $1\ mm$. In previous studies it was established that this silicone tube is useable to generate the desired dilation by adjusting the pressure above $90\ kPa$. [15].

The resistance element represents the total peripheral resistance of the modified Windkessel model. The clamp determines the outlet flow, which was adjusted with constant input flow. In the current experimental setup water is used as artificial blood substitute.

C. Measuring setup and processing system

Three optical sensor units are used to measure the pulsatile dilations of the tubes. Each consists of an IR-LED and a monolithic photodiode with an on-chip transimpedance amplifier (OPT101, Texas Instruments, USA). To acquire the dilation of the fetal or maternal tube a transmission measurement setup was chosen. For comparison a reflective measurement setup was also selected, where the IR-LED and the sensor are located above the elastic tubes. A surrounding box fixes the sensor equipment and protects the senor components against ambient light to reduce noise.

The pressure in maternal and fetal circuit is measured by two pressure transducers (MPX4250, Freescale, Germany) against atmospheric pressure. The pressure range is up to $250\ kPa$ with an output voltage range from $0.2\ V$ to $4.9\ V$ and a resulting sensitivity of $18.8\ mV/kPa$. The pressure transducers are placed behind the elastic tube in each circuit. An additional sensor is located in the pre-pressure system to monitor the pressure in the tank.

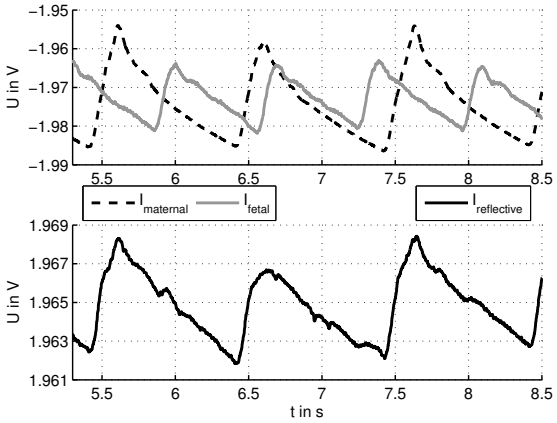

Fig. 3. Measured transmission light intensity of maternal (dashed line) and fetal circuit.

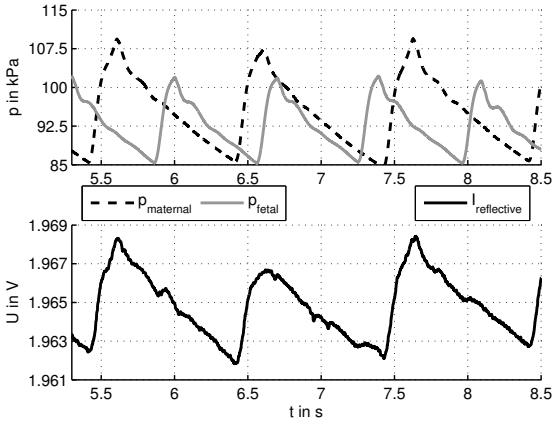

Fig. 4. Pressure of maternal (dashed line) and fetal circuit behind the elastic tube (upper diagram). Simultaneously recorded light intensity of the reflective measurement at the elastic tube (lower diagram).

Furthermore, capacitive measurements were performed by using a coplanar capacitive sensor. The conductive electrode, connected to a microcontroller (MSP430G2553, Texas Instruments, USA), is located beneath the elastic tube next to the photo sensors. The microcontroller measures the time behavior of an established oscillation on the electrode. When the tube expands, the capacity and therefore, the frequency of the relaxation oscillation is changed. Due to the measured frequency the dilation of the tube can be monitored.

The output signals from pressure transducers and photodiodes were recorded by two data acquisition boxes (Ni cDAQ-9191, NI 9239, National Instruments, USA) connected to a computer, with a sampling rate of $2000\ sps$ and a resolution of $24\ bit$. The synchronization between the hardware units was realized with an external trigger signal. During the measurements the converted data were processed and monitored with LabVIEW (National Instruments, USA) in real time.

III. Results

A. Plethysmografic measurements

Fig. 3 represents the transmission and reflection measurements of the maternal and fetal tubes. In comparison to Fig. 4 the light intensities of each circuit correspond to their pressure signals. The minima and maxima of the maternal light curves are clearly evident on the reflective signal. The influence of the fetal pulse wave is also detectable.

B. Pressure measurements

The pressure curve of the maternal and fetal circuit and the light intensity of the reflection measurements are shown in Fig. 4. The pressure range in the maternal and fetal circuit varies from $85\ kPa$ to $109\ kPa$ during a pulse periode. The dicrotic pulse wave is clearly visible in the measured fetal pressure.

C. Capacitive Sensor

These measurements were only performed with the maternal circuit. The raw and filtered signals of the capacitive sensor and the maternal pressure are shown in Fig. 5. For processing the capacitive signal a median filter of 20 datapoints was used. The measurement shows that the capacitive sensor can detect both systolic and diastolic phase of the pulse wave. The microcontroller measured the time to detect 3000 oscillations, which depends on the capacitive value of the coplanar sensor. The pulsating tube changes the resulting dielectrical constant in the field of the coplanar sensor and thereby the capacitive value.

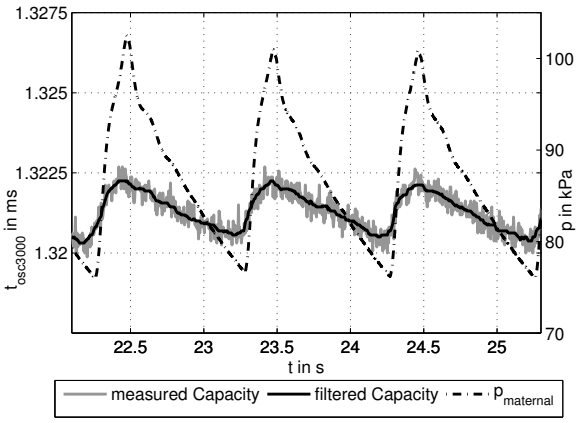

Fig. 5. The raw signal of the capacitive sensor is filtered with a median filter. The qualitative correspondence between capacitive measurements and maternal pressure signal (dash dotted line) is visible. The left ordinate represents the measured time to detect 3000 oscillations, which depends on the capacitive value of the coplanar sensor.

IV. Discussion

In this work a phantom for non-invasive fetal pulsoximetry was developed. To simulate fetal and maternal pulse waves, two independent controllable hydraulic systems were built. The maternal heart rate was set to $60\ bpm$, including an opening time of the proportional valve of $200\ ms$. Fetal heart rate was set to $86\ bpm$, including a valve opening time of $150\ ms$. The fetal pressure has a lower amplitude but a higher frequency than the maternal pressure. Due

to the low elasticity of the elastic tubes, the pressure is required to achieve the same dilation as in human arteries. In Fig. 3 the transmission measurements of each tube and the reflective signal of both tubes are represented. This shows the connection of the single dilation of the tubes on the reflective signal.

In contrary to previous system designs this test-rig can reproduce simultaneously the maternal and fetal pulse wave. Due to this experimental setup, reflection measurements of maternal and fetal circuit can be performed. Additionally, the pulse wave is simulated with an artificial vascular system, without special control of a displacement pump.

The digital control of the proportional valve can reproduce the systolic and diastolic phase of the heart. Pulse waves with different waveforms and flow rates are feasible by configuring separately the opening width and both opening and closing time of the valve. The setup of the maternal and fetal circuit influences the detected light of the reflection measurement. Through the configuration of the viscoelastic elements and the flow resistance normal and pathologic modified pulse waves can be reproduced.

At the present time the elastic tubes are not surrounded by a substitute material. This can result in undesired vibrations of the tubes and disturb the light measurements. Transmission and reflection measurements show the connection between tube dilation and measured light intensity. Furthermore, the latter represents the modulation of the reflected light, which reproduces the transabdominal modulation of reflection photoplethysmography on an abdomen of a pregnant woman. In further investigations algorithms have to be developed to separate the maternal and fetal signal components of the reflected light.

For evaluating the non-invasive fetal pulsoximeter, the water in the presented phantom has to be replaced by artificial substitutes for oxygenated and deoxygenated blood, for example india ink or intralipid [10]. A feasible solution for mimicking human soft tissue are RTV silicone with TiO2 or cosmetic powder as absorber [5], [10].

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