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Improved FPGA controlled artificial vascular system for plethysmographic measurements

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Abstract: The fetal oxygen saturation is an important parameter to determine the health status of a fetus, which is until now mostly acquired invasively. The transabdominal, fetal pulse oximetry is a promising approach to measure this non-invasively and continuously. The fetal pulse curve has to be extracted from the mixed signal of mother and fetus to determine its oxygen saturation. For this purpose efficient algorithms are necessary, which have to be evaluated under constant and reproducable test conditions. This paper presents the improved version of a phantom which can generate artificial pulse waves in a synthetic tissue phantom. The tissue phantom consists of several layers that mimic the different optical properties of the fetal and maternal tissue layers. Additionally an artificial vascular system and a dome, which mimics the bending of the belly of a pregnant woman, are incorporated. To obtain data on the pulse waves, several measurement methods are included, to help understand the behavior of the signals gained from the pulse waves. Besides pressure sensors and a transmissive method we integrated a capacitive approach, that makes use of the so called "Pin Oscillator" method. Apart from the enhancements in the tissue phantom and the measurements, we also improved the used blood substitute, which reproduces the different absorption characteristics of fetal and maternal blood. The results show that the phantom can generate pulse waves similar to the natural ones. Furthermore, the phantom represents a reference that can be used to evaluate the algorithms for transabdominal, fetal pulse oximetry.

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1 Introduction

The fetal oxygen saturation is an important parameter to determine the health of the fetus during labor or delivery. Current measurement methods are mostly invasive and non-continuous. They come along with several risks for mother and fetus. Therefore, it is desirable to develop non-invasive procedures for measuring the arterial oxygen saturation of the fetus. The transabdominal fetal pulse oximetry offers this possibility.

As we measure a mixed signal, which contains maternal and fetal components, a separation has to be performed [1]. To achieve this, complex algorithms need to be developed. To test them we need controlled and constant test conditions, as well as measurements to determine the signal behavior of the generated pulse waves. In [2] we presented an artificial vascular system, which models an arterial vascular system of mother and fetus and allows the generation and measurement of reproduced pulse waves.

To accomplish this, a pump builds up pressure in a pre-pressure system. To generate a pulsation of the artificial vascular system, proportional valves are rhythmically opened. The measurements are conducted in a synthetic tissue phantom, which is built of several layers of silicone, to mimic the different optical properties of mother, amniotic fluid and fetus. Several means of measuring the pulse waves are integrated into this phantom. The whole setup is controlled by a FPGA-system, that also records the data.

However, the former phantom [2] does not model the curvature of the belly during pregnancy. To reproduce this condition, the part with the artificial tissue was redesigned and is now incorporating a spherical part. Additionally, a capacitive sensor, molded into the artificial tissue, allows to measure the mechanical dilatation of the artificial vessel continuously. As third improvement two synthetic blood substitutes were developed which emulate the light absorption properties of fetal and maternal blood. These

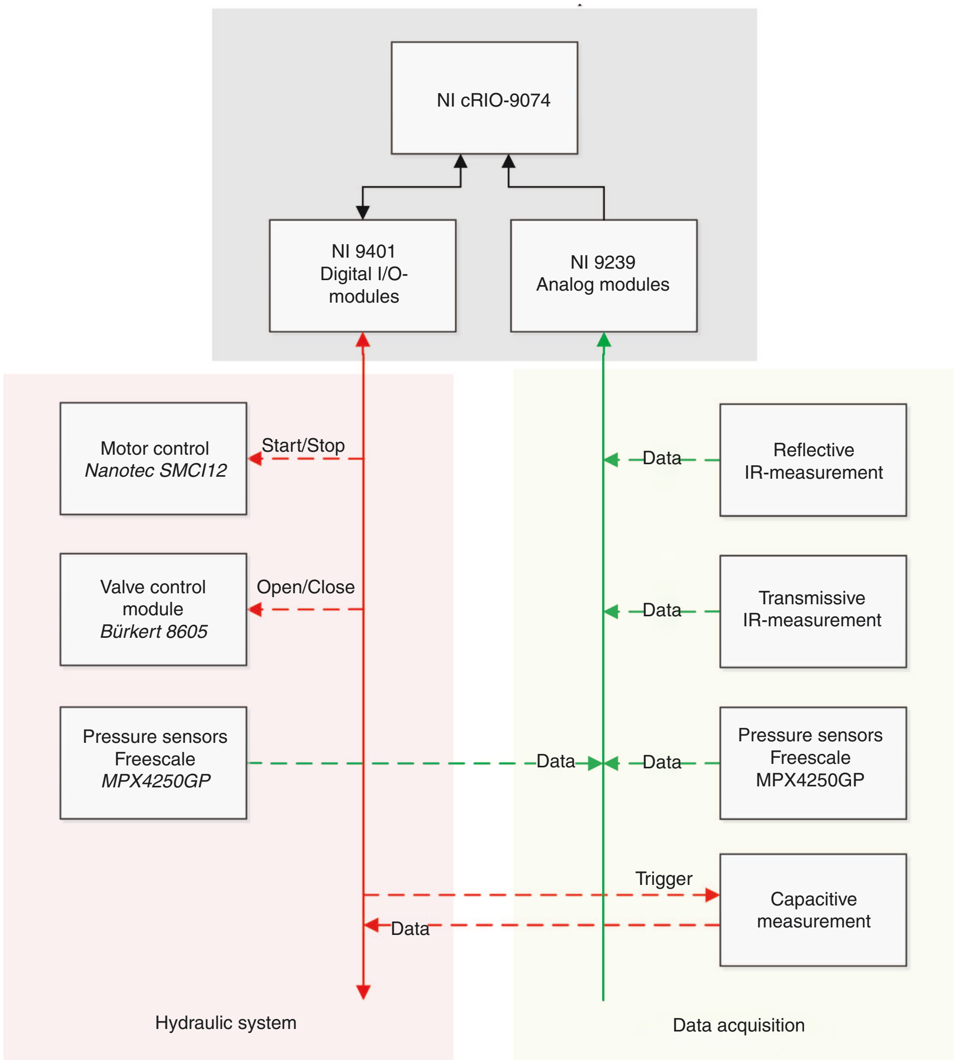

Figure 1: System overview of the complete artificial vascular system with the main controlling unit NI cRIO-9074; The hydraulic system includes all mechanical parts and the data acquisition connects all sensors.

improvements, as well as results, are reported in the following sections.

2 Material and methods

The artificial tissue phantom is a simplified model of the abdomen of a pregnant woman and a part of the complete phantom. A sketch of it is depicted in Figure 2. It consists of three plane tissue layers and one bone layer, which mimic the optical properties of the maternal and fetal tissue [3]. Furthermore, the tissue phantom is separated into two sections. In the front section, there is an additional dome (5) placed on top of the tissue layers. The geometry of the dome is based on the convex shape of the abdomen of a pregnant woman. The rear section has a plane surface and contains three sensor boards for capacitive and photoplethysmographic measurements. Different kinds of tissue, like muscles, fat etc. are combined to a maternal (4) and a fetal layer (2). Furthermore the amniotic fluid is simulated by an additional layer (3) and embedded between the maternal and fetal layer. The tissue layers mainly consist of RTV-2 silicone, used as the host material. RTV-2 is an addition-vulcanising two-component silicone that vulcanizes at room temperature. It is transparent and has an elasticity similar to human tissue. By adding different additives to the RTV-2 silicone its properties can be modulated to comply with the optical properties of the tissue substitutes. The scattering and absorption properties are adjusted by using TiO_2 and cosmetic powder. Each tissue layer contains different additive concentrations as

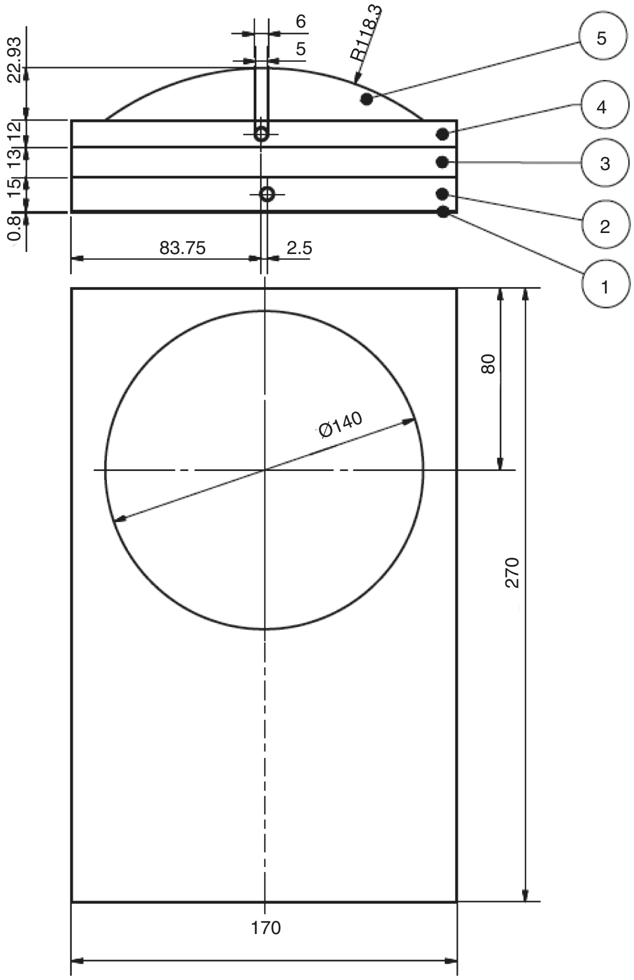

Figure 2: The sketch of the artificial tissue phantom shows the following component parts: (1) bottom layer, (2) fetal layer, (3) amniotic fluid, and (4) maternal tissue with the (5) dome.

Table 1: Additive concentration of the tissue layers in relation to their total mass.

Layer	Additive concentration c in %	
	TiO_2	powder
fetal tissue	0.7268	0.1085
amniotic fluid	0.021	0
maternal tissue	0.7473	0.0695
dome	0.7473	0.0695

shown in Table 1. To simulate the vascular system there are transparent silicone tubes embedded in the maternal and fetal layer. These tubes are connected to an artificial vascular system and a pressure system, which generates the pulse waves of the mother and the fetus. The pulse waves can be measured by detecting the change of the tube diameter, caused by variation of the internal pressure. The bottom layer (1) of the tissue phantom represents a large areal bone similar to the fetal head. In order to improve the signal quality during the reflective photoplethysmographic measurement, a total reflecting metal plate is used as the bone layer. The dome of the phantom has a curvature-radius of 118.3 mm. It is designed for a maximal sensor-detector distance of 100 mm. The thickness of the maternal tissue, which is composed of the dome and the plane layer, adds to 24 mm at the contact points of sensor and detector.

Besides appropriate substitutes for the tissue phantom, there was also the need of a synthetic blood fluid, which reproduces the optical properties of human blood. These are dependent on the different blood components, like plasma or cells, which exhibit varying optical attributes across the light spectrum. As it is very difficult to fully mimic these characteristics, the light-absorbing behavior of blood is mostly reproduced for one specific wavelength. One main topic of this work is the development of two blood surrogates with different absorption coefficients for the fetal and the maternal circuit. The absorption was realized by a mixture of distilled water and black ink. Two different mixtures were produced. One mixture mimics fetal blood with an oxygen saturation of 60%, whereas the second mixture simulates an oxygen saturation of 98% for maternal blood.

The formula used to calculate the concentration of the ink for a wavelength of $\lambda = 633$ nm was as follows:

$$\mu_a^{Tu} = \mu_a^{Tu\%} \cdot c^{Tu} \tag{1}$$

μ_a^{Tu} corresponds to the total absorption coefficient of the blood surrogate, which is composed of the normalized absorption coefficient $\mu_a^{Tu\%}$ and the required concentration of black ink c^{Tu}. The absorption coefficients of human blood with oxygen saturations of 60% and 98% were taken from [4]. A value for the normalized absorption coefficient $\mu_a^{Tu\%}$ was presented in [5]. The resulting ink concentrations for the different optical properties of the human blood are shown in Table 2. The scattering characteristics of arterial blood can be emulated by mixing the blood substitute with additives such as milk or intralipids, as was reported in [6–8]. However, the absorption is the most important property for our first investigations, so we did not model the scattering.

Table 2: Optical properties of human blood, ink and calculated ink concentrations.

oxygen saturation	μ_a^{Tu}	$\mu_a^{Tu\%}$	c^{Tu}
60%	15.3	26.844	0.57%
98%	7.7	26.844	0.27%

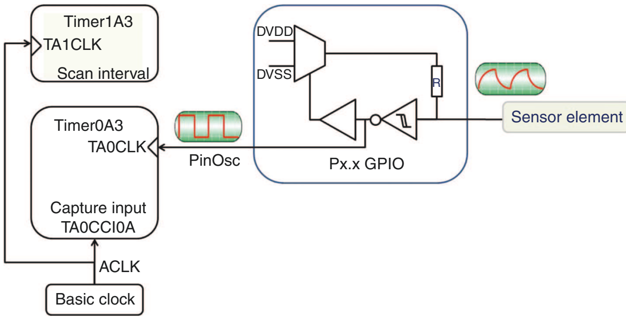

Figure 3: Principle of the "Pin Oscillator" method [9].

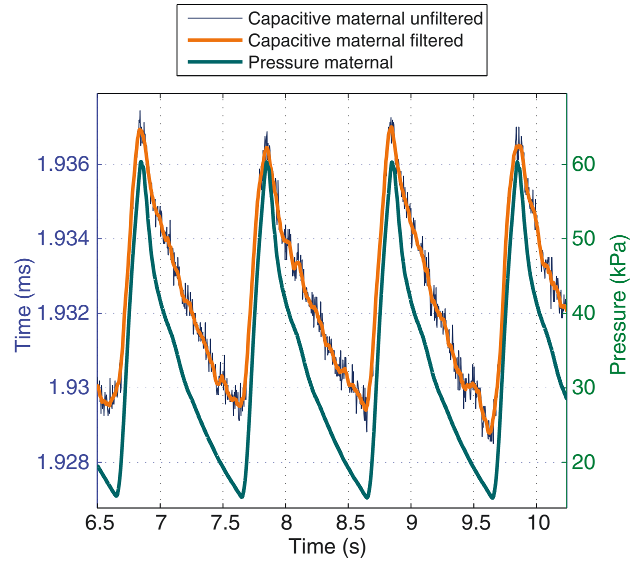

Figure 4: Capacitive and pressure measurements of the maternal circuit.

The former phantom used pressure sensors and transmissive light measurements to gain data on the pulse waves as reference. As a further improvement a capacitive measurement method was now implemented. The principle technique is the so called "Pin Oscillator" method [9] (s. Figure 3). An oscillator is built of a conductive sensor element and a specially designed μC. The oscillation frequency of the system depends on the capacity value of the sensor element, which is directly related to the dilation of the artificial vessel. The microcontroller counts the oscillation cycles, which represent the response time of the sensor. The measurement starts with an interrupt, which is generated by the FPGA-system and sent via a pin of the digital I/O-module. Data transmission is realized by a UART-protocol with the same module. Fetal and maternal vessels are measured separately. In Figure 1 all possibilities for data acquisition of the new phantom are depicted.

3 Results

The development of the new artificial tissue phantom, including the new measurement method, comes along with several benefits. The dome allows measuring conditions that are closer to the anatomy of a pregnant woman. The improved phantom allows the acquisition of further data for evaluating signal processing strategies to separate the fetal and maternal pulse curves gained with transabdominal fetal pulse oximetry.

Figure 4 shows exemplary capacitive and pressure measurements of the maternal circuit. As can be seen, the unfiltered signal shows a noise-like behavior. For better evaluation we applied a moving average filter with the length of 10 samples to mitigate this property. A much smoother signal curve is the result. A comparison between the pressure and the capacitive signal shows a very good congruence among the main peaks. This proves the validity of the capacitive measurement. Due to the high sensitivity of the measurements, the dicrote wave is more distinct.

The two blood substitutes realize different absorption characteristics close to the natural ones and create more realistic measuring conditions. The phantom therefore may be a first step towards a synthetic reference for calibration of pulse oximetry systems. As the measuring time could be expanded to approximately 4 minutes a sufficient amount of data can be acquired, which allows profound statements on the gathered data.

4 Conclusion

In this paper we presented the improved version of a phantom that is capable of producing and measuring artificial pulse waves for the test of algorithms for transabdominal fetal pulse oximetry. In addition to the improved measurement time of several minutes with two different blood surrogates, the capacitive measurement provides us with an extended data base, to improve the evaluation of the reflectively measured data.

Further improvements can be made regarding the scattering characteristics of the blood surrogate. However this is of minor urgency, as it seems that the properties are sufficient in their present state. The phantom with its hydraulic part may also be utilized in other fields of research by adapting the tissue phantom. A potential application could be microwave imaging, however there are also other possibilities imaginable.

Author's Statement
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