Evaluation of Expandable Microsphere Pressure Sensor for Arterial Pulse Wave Measurements

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***Abstract*—This study presents an evaluation of an expandable microsphere pressure sensor for pulse wave measurements. The sensor is designed for non-invasive and long-term monitoring, with a pressure-sensitive layer fabricated of compressible microspheres and elastic polydimethylsiloxane. The performance of the sensor is compared against a reference sensor, and the measured signals are analyzed visually and numerically to gain a better understanding of the sensor's applicability for quantitative arterial assessment. The characteristic features of the pulse wave are visually observable in the measured signals. The analysis results indicate that the microsphere pressure sensor presents the potential in evaluating physiological parameters such as heart rate or arterial stiffness.**

***Index Terms*—pressure sensor, expandable microspheres, flexible electronics, wearable sensors, pulse wave measurement, arterial assessment**

I. INTRODUCTION

The pulse wave, originating from the cardiac cycle and measured from the peripheral circulatory, provides clinically valuable information on the cardiovascular system. Heart rate, heart rate variability, the elasticity of arteries, blood pressure and vascular resistance are reflected in the pulse wave shape and velocity. [1] These physiological indicators can be assessed as characteristic parameters derived from the pulse wave, allowing a quantitative approach to the assessment of vascular health. [2]–[4]

Monitoring the pulse wave long-term is crucial for early diagnosis and effective treatment of cardiovascular diseases. Wearable sensors for long-term monitoring have been proposed [5]–[9]. One promising solution is a pressure sensor whose structure is based on expandable microspheres [10]. This sensor can convert the motion of the human body into an electrical signal and operates on a self-powered principle. The sensor has a flexible structure constructed by layering thin flexible films, thus avoiding the physical mismatch commonly found between electronics and human skin.

Although Liu et al. [10] previously demonstrated the successful measurement of pulse waves using the microsphere sensor, their study lacked validation against a reference device. Therefore, further research is needed to determine the applicability of microsphere sensors for physiological monitoring. The aim of this study is to fabricate the microsphere sensor and comprehensively evaluate its performance in pulse wave measurements, compared to the Finapres® reference sensor.

II. MATERIALS AND METHODS

A. Sensor structure, materials and fabrication

The sensor fabricated and evaluated in this study is based on a previously proposed design [10]. The sensor has a 5-layer structure with copper layers for electrical connections and Fluorinated ethylene propylene (FEP) for flexible substrate layers. The central component of the sensor is a pressure-sensitive layer consisting of thermally expandable and compressible microspheres mixed with elastic polydimethylsiloxane (PDMS). According to the theoretical model proposed by Liu et al., the sensor's output voltage is directly related to the change in the contact area of microspheres. When external pressure is applied, the microspheres deform, resulting in different surface charges between the PDMS-microsphere layer and the FEP layer, subsequently altering the output voltage.

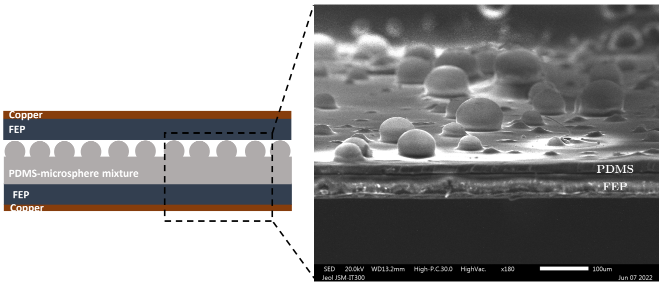

Fig. 1. The schematic cross-section of the sensor structure (left) and a scanning electron microscopy image showing the surface morphology of the pressure-sensitive layer (right).

In the sensor fabrication, the principles from a previously reported sensor [10] were combined with the guidelines provided by the material manufacturers [11], [12]. At first, 200 nm thick copper electrodes were evaporated onto a 50 µm thick FEP substrate. Then, the PDMS base agent and the PDMS curing agent (SYLGARD™ 184 Silicone Elastomer, Dow Corning) were mixed at a weight ratio of 10:1. After that, thermally expandable microspheres (Expancel® 043 DU80, Nouryon) were added with 1% weight ratio. Spin-coating method was used for depositing a thin PDMS-microsphere layer on the FEP substrate. The spin time of 60 seconds and rotation speed of 3500 rpm were used, which resulted in a layer with a thickness of approximately 20 µm. This was followed by heating in an oven at 130 °C for 10 min in order to achieve expansion of microspheres. Then, another FEP-copper layer was placed on top of the sensor and encapsulated with Fixomull transparent medical tape, to ensure that the sensor sides stay in place during the measurements. The dimensions of the fabricated sensor were 1.5 cm^2 (area) and 150 µm (a total thickness). The final sensor and its attachment to the skin are shown in Figure 2 a) and b).

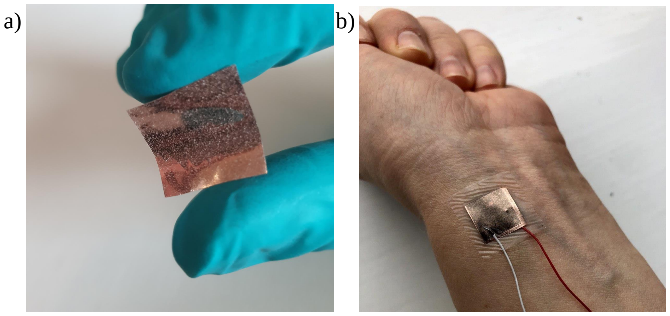

Fig. 2. a) PDMS-microsphere layer onto FEP-copper substrate, b) Sensor attached to the skin above the radial artery.

B. *Pulse wave measurements*

The performance of the microsphere sensor in pulse wave measurement was evaluated against the reference sensor by Finapres® NOVA (Finapres Medical Systems). The measurement of the reference is based on the volume clamp method and it operates with an inflatable finger cuff sensor, which was placed around the left index finger. The microsphere sensor was placed on the wrist, directly over the radial artery. Single-core cables were used for sensor connections, which were then connected to the charge amplifier with a gain of 300 mV/pC. Both signals were sampled using the Finapres NOVA hardware at frequencies of 500 Hz for the microsphere sensor and 200 Hz for the reference sensor. The measurements were conducted on a single participant in a supine position, with a total duration of 30 minutes.

C. *Pulse wave analysis*

The 30 second period of raw data were further processed and analysed by MATLAB software. The pre-processing was conducted in three particular phases: removing baseline wandering, signal smoothing by a Savitzky-Golay filter and removing 50 Hz noise. The framework of feature extraction from the original pulse wave and its second derivative is illustrated in Fig. 3. The pulse-to-pulse interval was defined as the difference in the locations of two consecutive early systolic peaks P_1 as Fig. 3 represents. The (ΔT_d) was defined as the difference in the locations of late P_2 systolic peak and early systolic peaks P_2 and (T_diastole) was defined as the difference in the foot points of the pulse and the dicrotic notch shown in Fig. 3. The radial augmentation index was calculated by the equation $rAIx = \frac{P_2}{P_1} \cdot 100\%$, where P_2 is the amplitude of the late systolic peak and P_1 is the amplitude of the early systolic peak. Lastly, the mean, standard deviation, and range of each waveform characteristic were calculated.

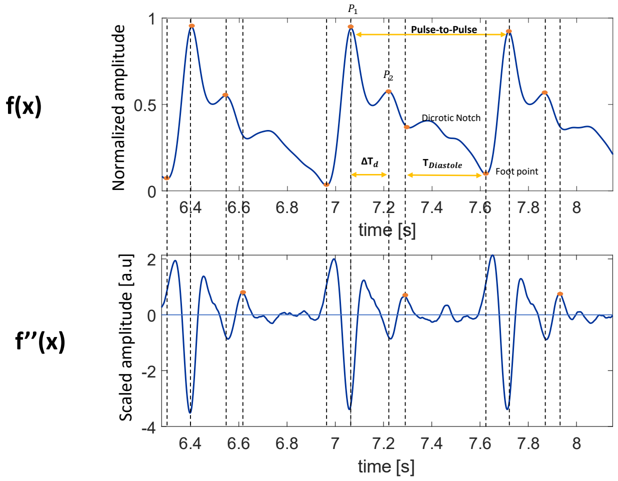

Fig. 3. The principle of the feature extraction from pulse wave and its second derivative.

III. RESULTS AND DISCUSSION

A. *Raw signal comparison*

Fig. 4 a) shows the simultaneously recorded raw data signals from the reference sensor (red) and the microsphere sensor (blue) over a ten-second period. Both signals have been normalized to the range [0-1]. As observed in Fig. 4 a), the microsphere sensor signal exhibits baseline wandering, which may have been caused by the movement of the sensor. During the measurement, the Finapres reference sensor was tightly wrapped around the finger with an inflatable cuff, while the microsphere sensor was attached to the skin using tape without any contact pressure. Additionally, a close-up in Fig. 4 a) reveals noise in the microsphere sensor signal. However, the aim was to remove noise before conducting the actual pulse wave analysis.

The power spectral density (PSD) analysis was performed on the raw and filtered signals for both sensors. The results are shown in Fig. 4 b). Despite the offset between the signals, the PSD distribution shows agreement between the two sensors in the frequency range of interest (<15 Hz). Furthermore, the removal of the 50 Hz interference in the microsphere sensor is demonstrated in Fig. 4 b).

B. *Pulse wave comparison with the Finapres reference*

The results in Fig. 5a) show the signals from both sensors after filtering. The data from the microsphere sensor is normalized around zero, while the data from the Finapres sensor is calibrated in mmHg units, corresponding to finger arterial blood pressure. Both signals exhibit visually identifiable pulse wave features, including the early systolic peak, late systolic peak, and dicrotic notch.

To evaluate the stability and reproducibility of the sensor, ten consecutive pulse cycles were time-synchronized, starting from the foot point, and plotted on the same graph for comparison. Fig. 5b) illustrates the normalized and averaged pulse waveforms for the microsphere sensor (blue) and the

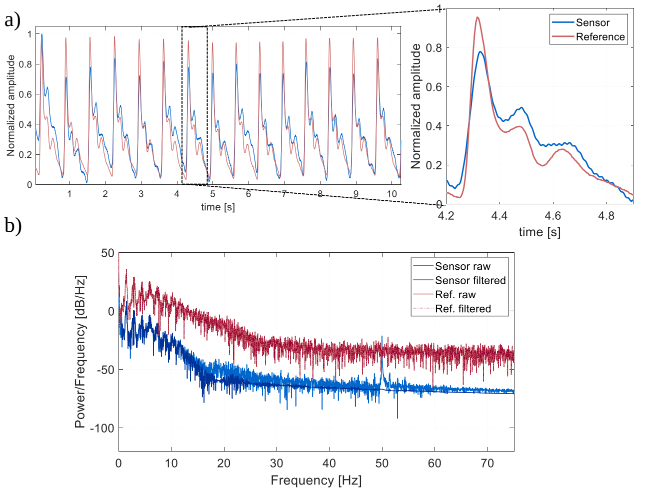

Fig. 4. a) Comparison of simultaneously recorded signals: Microsphere sensor signal (blue) and reference signal (red). b) Power spectral density comparison of microsphere sensor signals (blue) and reference signals (red).

Finapres reference sensor (red). The average waveform is calculated from ten individual and consecutive pulses (represented by thin light gray curves). The microsphere sensor shows greater differences in shape between each pulse. The Finapres cuff sensor, tightly placed around the finger, provides a more consistent measurement compared to the microsphere sensor positioned on the skin surface without contact pressure, making it sensitive to motion noise. While using a cuff could enhance stability and repeatability, the advantage of cuffless measurement lies in user comfort during long-term monitoring of pulse waves.

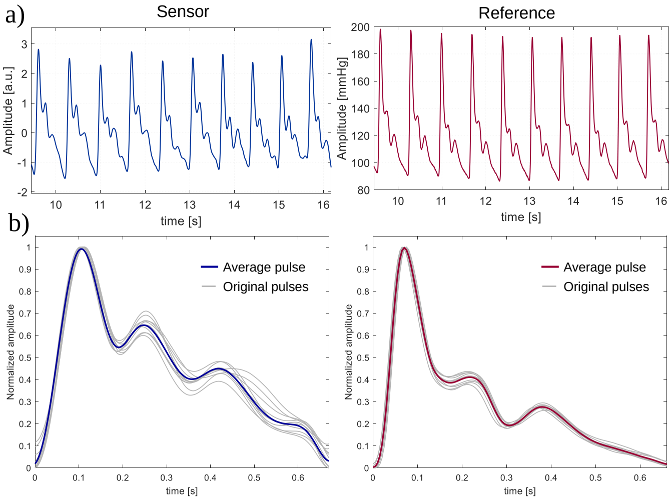

Fig. 5. a) A signal comparison between the microsphere sensor (blue) and the Finapres reference (red) b) Comparison pulse averages of ten consecutive pulses obtained from the microsphere sensor (blue) and reference sensor (red), with the original pulses shown as light grey lines.

C. Evaluation of pulse wave parameters

Fig. 6 shows the correlation between the pulse-to-pulse intervals calculated from the microsphere sensor data and the data from the Finapres reference sensor. The 30-second signal period contained 42 pulse-to-pulse intervals, shown as data points. The regression line shows the linear regression fitting to the equation $y = ax+b$. The R^2 for fitting is 0.9964 and the Pearson correlation coefficient for data is 0.9982. From Fig. 6, it can be seen that all the data points are located close to the linear line. The correlation coefficient above 0.99 indicates good accuracy for the microsphere sensor in the estimation time of pulse-to-pulse intervals against the Finapres reference.

Table 1 provides a comparison of the mean, standard deviation (SD), and range values for pulse wave parameters calculated from both sensors over a 30-second period. The parameters of the microsphere sensor exhibited greater variability compared to the reference sensor. Especially, the parameters using amplitude features of pulse waves would benefit from more advanced signal processing methods. However, despite these differences, the overall results indicate that the microsphere sensor has the potential to measure pulse waves and conduct automated analysis to determine clinically valuable pulse wave parameters, which can be compared with those obtained from a reference sensor.

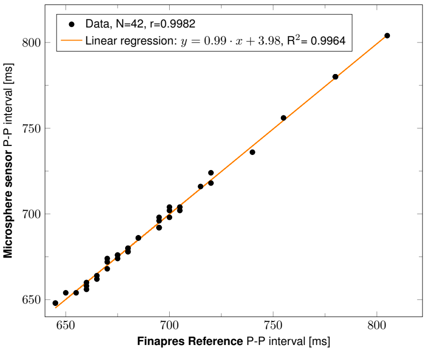

Fig. 6. A comparison between the pulse-to-pulse intervals from microsphere sensor and Finapres reference.

TABLE I
SUMMARY OF PULSE WAVE PARAMETERS

	Microsphere Sensor			**Reference Sensor**		
Parameter	***Mean***	***SD***	***Range***	***Mean***	***SD***	***Range***
rAIx [%]	61.32	5.01	20.03	42.72	3.85	16.32
$\Delta\mathrm{T_d}$ [ms]	153.17	5.48	24.00	147.68	4.34	20.00
$\mathrm{T_{Diastole}}$ [ms]	365.52	45.73	238.00	405.00	36.27	150.00

IV. CONCLUSION

The applicability of the microsphere sensor for pulse wave measurement was investigated, focusing on a comprehensive comparison of the signal quality with a reference sensor. The results indicate that the microsphere sensor has potential for reliable pulse wave measurement and estimation of clinically relevant parameters for the assessment of vascular health.

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