Magnetic plethysmograph transducers for local blood pulse wave velocity measurement

Nabeel P.M, Jayaraj Joseph, Mohanasankar Sivaprakasam

***Abstract*—We present the design of magnetic plethysmograph (MPG) transducers for detection of blood pulse waveform and evaluation of local pulse wave velocity (PWV), for potential use in cuffless blood pressure (BP) monitoring. The sensors utilize a Hall effect magnetic field sensor to capture the blood pulse waveform. A strap based design is performed to enable reliable capture of large number of cardiac cycles with relative ease. The ability of the transducer to consistently detect the blood pulse is verified by in-vivo trials on few volunteers. A duality of such transducers is utilized to capture the local PWV at the carotid artery. The pulse transit time (PTT) between the two detected pulse waveforms, measured along a small section of the carotid artery, was evaluated using automated algorithms to ensure consistency of measurements. The correlation between the measured values of local PWV and BP was also investigated. The developed transducers provide a reliable, easy modality for detecting pulse waveform on superficial arteries. Such transducers, used for measurement of local PWV, could potentially be utilized for cuffless, continuous evaluation of BP at various superficial arterial sites.**

I. INTRODUCTION

Pulse Wave Velocity (PWV) is a measure of arterial stiffness and cardiovascular health. The carotid-femoral PWV is most commonly used as measure of aortic stiffness [1]. However accuracy of PWV measured over a long arterial trajectory is influenced by the ambiguity in the estimated path length and the effect of blood pulse wave reflections. While these effects are not primarily considered in PWV evaluation to estimate stiffness, such limitations strongly influence the results when the measured PWV is used for other applications such as estimation of pulse pressure and other BP parameters. Local PWV on the other hand is measured over short arterial lengths over a small arterial section, thereby reducing ambiguity in path length and also minimizing influence of wave reflections. This makes it significant in the context of cuffless BP measurement. Moreover, local PWV would yield an estimate of the local stiffness of the artery at the site of measurement. Local PWV is currently estimated using pressure transducers [2], optical sensors [3] – [5], Doppler ultrasound [6], MRI based imaging methods [7]. Existing techniques require expensive technology and expertise in operation to get reliable measurements and are not suited for large scale deployment. There is a need to develop a simple, yet reliable method to measure local PWV. Hence we present the design of MPG transducers for low cost measurement of local PWV. The basic principle of measurement and initial design of MPG transducers are presented. The ability of the proposed transducer to detect blood pulse wave and measure local PWV is validated by in-vivo trials on volunteers. The correlation between local PWV and BP measures is also explored.

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II. PRINCIPLE OF MEASUREMENT

The relation between the PWV, path length of the pulse wave (D) and the time delay between the measured waveforms (ΔT) is given by equation 1.

$$PWV = {}^{D}/_{\Delta T} \quad (1)$$

Measurement of ΔT, requires two distinct blood pulse waveforms from two different points on the arterial tree. For such a measurement, two identical magnetic transducers are placed on the carotid artery as shown in Fig 1. The path length of the pulse wave, D is the distance between the transducers, which is restricted such that the magnetic field created by one transducer does not interfere with the operation of the other.

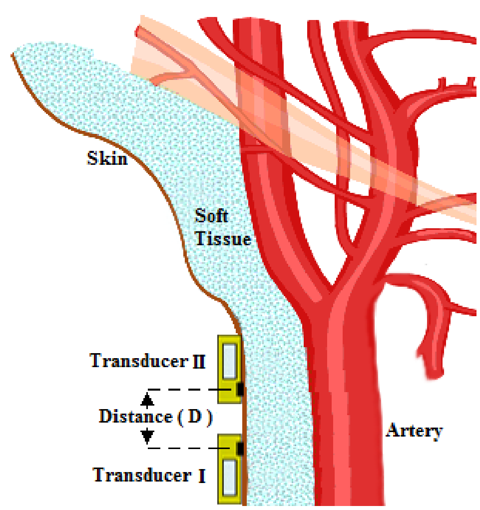

Figure 1. Placement of transdcers over carotid artery to detect blood pulse waveforms and measure local PWV

The proposed MPG transducer consists of a Hall effect sensor and a permanent magnet. Two different sensors are place over the carotid artery as shown in the Fig 1. Volumetric changes caused due to blood flow through the carotid artery alter the magnetic field surrounding to the Hall effect sensor. Hall effect sensor will pick up this field fluctuations and give an output voltages as a representation of blood pulse wave form. The signal from both the sensors are acquired continuously and are processed with a well-defined algorithm for local PWV measurement.

A. Design of transducer

As the proposed transducer is designed for the measurement of local PWV, it should be small in size and easy to use to reliably capture sufficient cycles of the blood pulse waveform. Hence we choose a small permanent magnet (Amazing Magnets – D032A1). The small size also ensures that the magnetic field created by one sensor will not interfere with the magnetic field of the other sensor. The design of sensor is shown in Fig 2. Hall effect sensor (SEC Electronics Inc – SS49E.) of good sensitivity (1.8mV/G) was selected, which was soldered to a PCB. The permanent magnet was placed on the same side of PCB as shown in Fig 2, such that the magnetic lines of force emanating from the permanent magnet is parallel to the axis of sensitivity of the Hall effect sensor. Magnet was placed as close as possible to the Hall effect sensor, to link maximum flux lines with the Hall effect sensor.

For a reliable and repeatable measurement, a strap based design was selected for the sensing device. As shown in Fig 2, the PCB with Hall effect sensor and permanent magnet was attached to an elastic material such as an elastic tourniquet, so that it could be easily wrapped around the neck. The elastic tourniquet also helps to place the sensor over the carotid artery. This strap based probe design ensures continuous measurement of local PWV. Simultaneously extracted blood pulse waveforms from both sensors placed over the carotid artery are shown in Fig 3. The overall system architecture is shown in Fig 4. Sensor outputs were filtered and amplified in an analog domain. Analog front end filters are so designed that the delay introduced by the filters between the two channels are less than one hundredth of a millisecond.

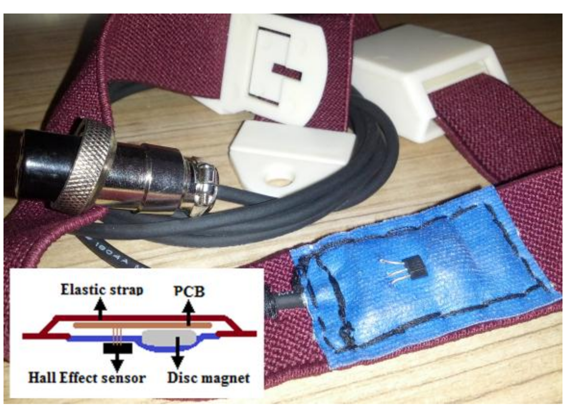

Figure 2. MPG transducer prototype assembled over an elastic torniquet

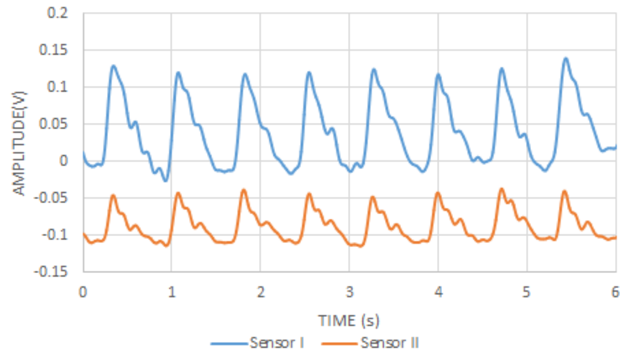

Figure 3. Blood pulse waveform detected by the MPG transducer at the carotid artery of a volunter

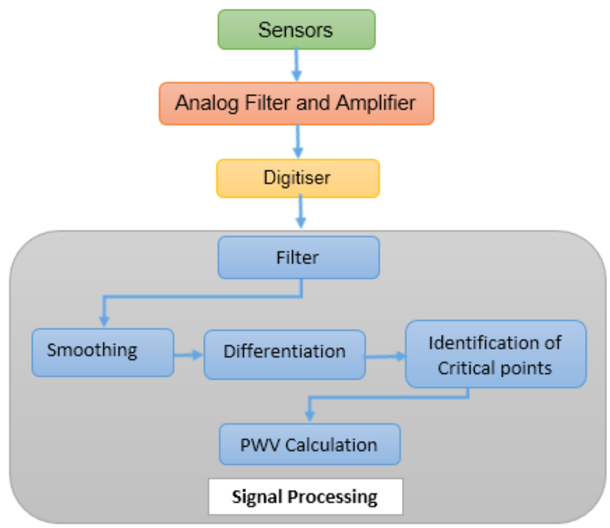

Figure 4. System architecuture

The signals were digitized using NI USB-6216 (M/s National Instruments) data acquisition card with a sampling rate of 20 kS s-1 and resolution of 16 bits per sample. Further filtering, smoothing and other signal conditioning is done with LabVIEW®. The conditioned signal is then saved onto a file and processed using MATLAB®, to identify the critical points and calculate local PWV.

B. Algorithm for local PTT measurement

Careful determination of PWV is important in the study of arterial stiffness and cardiovascular health. PWV was calculated using (1). The distance between the two sensors (D) measured over the body surface is taken as the path length. In order to faithfully measure the PTT between the two detected pulse waveforms, the identification of critical or timing points on the pulse waveforms are required. A well-defined algorithm was used for the identification of the critical point. One cycle of simultaneously captured pulse waveform from both sensors were taken. After smoothing the waveforms using a moving average filter with a suitable window size, first derivative with respect to time was calculated. Again a smoothing operation was done on the first derivative waveforms.

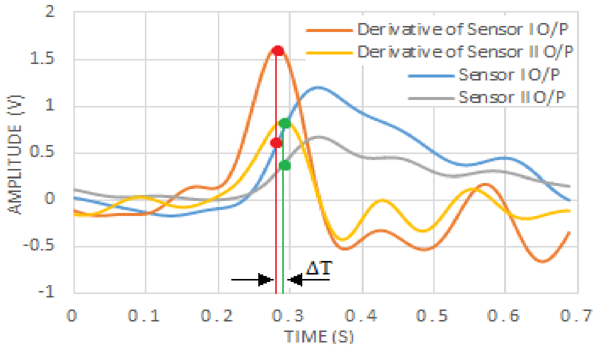

Figure 5. Pulse waveforms and derivative of pulse waveform

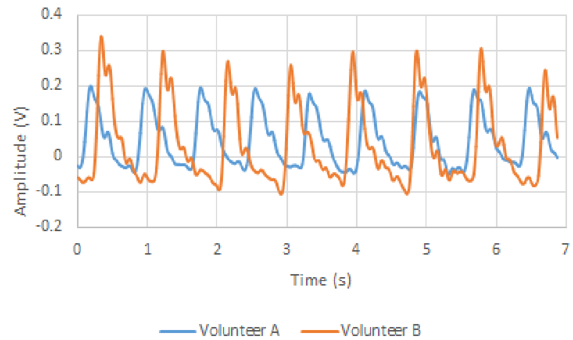

Figure 6. Carotid pulse waveform of volunteer A and volunteer B

The point at which the first derivative of pulse waveform is maximum was selected as the critical point [8]. Time delay between the critical points of pulse waveforms for one cycle of heart beat is taken as the PTT. Using the distance between two sensors (D) and using calculated PTT (ΔT), local PWV was estimated with (1). Identification of this critical points and estimation of local PWV was done in MATLAB®. Pulse waveforms and derivative of pulse waveforms with PTT for one cycle is shown in Fig 5.

The other computerized algorithms which are used for finding out the critical points are based on (a) Point of minimum diastolic value of pulse waveform, (b) Point at which the second derivative of pulse waveform is maximum and (c) Point yielded by the intersection of a line tangent to the initial systolic upstroke of the pulse waveform tracing and a horizontal line through the minimum point. Among all the above algorithms the first derivative method for the identification of critical point provides consistent and repeatable results [8].

III. Experimental Validation

A. In-vivo measurements

In-vivo measurements on volunteers demonstrated the ability of the transducer to capture the carotid pulse waveform continuously. Typical blood pulse waveforms detected from the carotid artery of two volunteers are illustrated in Fig 6. To evaluate consistency of waveform heart rate was evaluated, and results are found to be repeatable.

B. Local PWV measurement

Measurement of local PWV was carried on 15 different volunteers between the age group of 22-30 years using the proposed transducer.

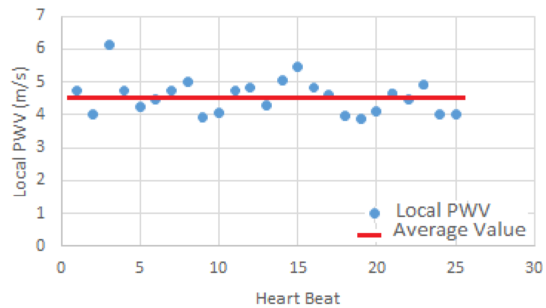

Figure 7. Beat to beat variation of local PWV of volunteer B

The results obtained were in the expected range [9] and hence the ability of the sensor to detect local PWV was validated. Local PWV was measured for multiple cycles and an average was taken over ten cycles on the volunteers, also beat to beat variation of the pulse was noted. The results showed a consistent as well as repeatable characteristic, thereby illustrating the efficacy of the transducer. The mean and standard error of mean of beat to beat local PWV of volunteer B are 4.55 ± 0.1 ms^{-1}. Beat to beat variation of local PWV of the same subject is shown in Fig 7.

C. Local PWV and BP

To evaluate the potential use of this transducer in cuffless BP measurement, the BP of the volunteers were also recorded during in-vivo trials. Before taking the measurements, volunteers were seated and allowed to relax for 5 minutes. When the volunteers were relaxed, BP was measured with a brachial cuff using an automatic BP monitor (Omron® HEM 7111) . Once the BP was measured, the MPG probes were wrapped around the neck and pulse waveforms were recorded. Distance between the sensors was also noted. Local PWV was evaluated using automated algorithms described in Section II to ensure consistency of measurements. Calculated local PWVs and BP parameters are presented in Table I.

TABLE I. LOCAL PWV AND BP PARAMETERS

Volunteer	Gender	Age (yrs)	Systolic Pressure (mmHg)	Diastolic Pressure (mmHg)	Mean Arterial Pressure (mmHg)	Local PWV (ms^{-1})
A	M	22	112	69	83.33	5.92
B	M	*24*	116	62	80.00	4.55
C	M	*27*	111	60	77.00	4.02
D	M	*30*	113	74	87.00	5.70
E	M	*29*	108	63	78.00	4.50
F	M	*25*	111	68	82.33	5.08
G	F	*26*	124	70	88.00	5.98
H	M	*26*	104	74	84.00	6.58
I	M	*26*	105	65	78.33	4.31
J	F	*25*	119	71	87.00	5.13
K	M	*23*	124	66	85.33	6.45
L	M	*23*	125	67	86.33	6.51
M	F	22	105	56	72.33	4.20
N	M	25	120	74	89.33	6.53
O	F	23	112	69	83.33	5.63

The BP parameters, Diastolic pressure (Pd), Systolic pressure (Ps) and Mean arterial pressure (MAP) were positively correlated with local PWV. The relation of local PWV to Pd, Ps and MAP are displayed in Fig 8 - Fig 10 respectively. The correlation coefficients (r) of Pd, Ps and MAP with local PWV were 0.75, 0.52 and 0.82 respectively. These results further open an opportunity for using the proposed magnetic sensor as a transducer for use in cuffless continuous BP monitoring devices.

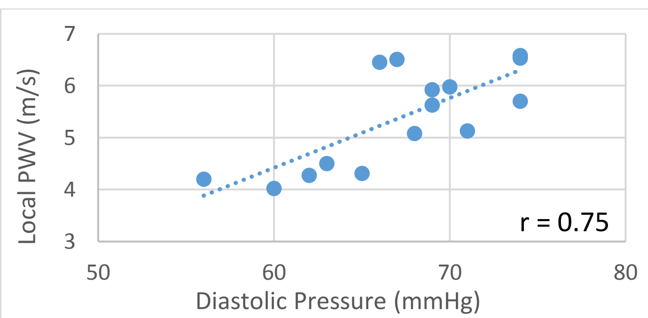

Figure 8. Relation between local PWV and Diastolic pressure

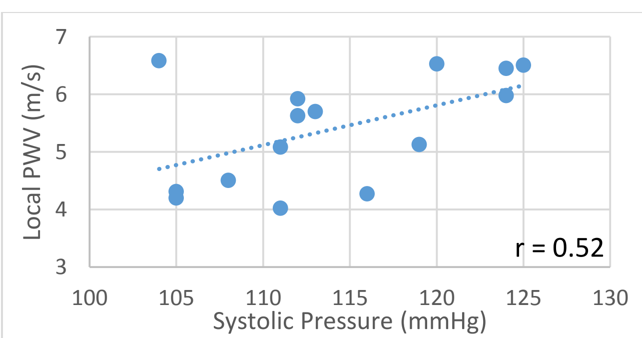

Figure 9. Relation between local PWV and Systolic pressure

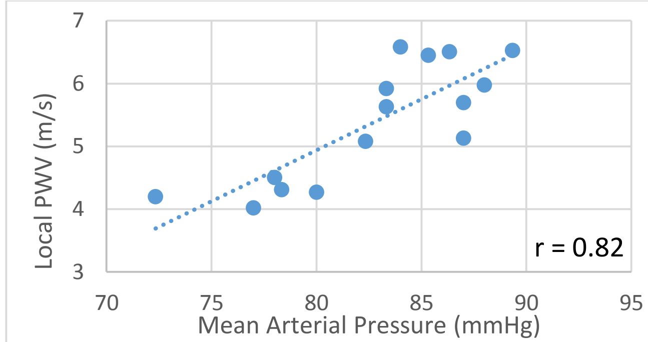

Figure 10. Relation between local PWV and MAP

IV. Conclusion

The design of MPG transducers for reliable detection of the blood pulse waveform and measurement of local PWV was presented. The ability of the proposed transducer to detect the blood pulse was verified by in-vivo measurements on volunteers. The capability of the MPG transducer to detect arterial wall dynamics was explored by measuring the local PWV. The proposed MPG sensors could detect the small delay between the pulse waveforms measured at two points located as close as 25 mm along a section of an artery. In-vivo measurements illustrated that the MPG transducers could provide reasonably accurate measurements of local PWV. Carotid PWV values measured using the proposed sensors were found to be in the expected range. In vivo studies also demonstrated correlation between carotid PWV and BP, indicating potential use of these transducers in continuous cuffless monitoring of BP.

V. References

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