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A hydrostatic pressure approach to cuffless blood pressure monitoring

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***Abstract* – This paper presents the underlying principle and accompanying initial validation results towards the development of an optically-based, cuffless blood pressure monitoring method. As opposed to traditional oscillometric techniques, the optical sensor is calibrated with a known patient-controlled hydrostatic perturbation. In particular, the hydrostatic pressure challenge is utilized to parameterize the characteristic sigmoidal vascular compliance curve that links transmural pressure to the measured PPG output. Formulation of the compliance model will be accompanied by experimental results demonstrating the utility of the method.**

***Kewords* – Blood pressure, photo plethysmography, cuffless, wearable sensor**

I. Introduction

Wearable medical sensors (WMS), in particular those related to blood pressure, will permit continuous cardiovascular (CV) monitoring in a number of novel settings. Benefits may be realized in the diagnosis and treatment of a number of major diseases [1,2,3]. Additionally, WMS hold significant potential for increased vigilance for CV catastrophes which could occur for high-risk subjects. Alternatively, WMS could provide information that enables the precise titrations of chronic disease therapies or could be used to detect lapses in patient compliance [4].

WMS solutions, in various stages of technologic maturity, exist for gathering established information related to the patient's cardiovascular state. The Portapres, employing the volume clamp technique for measuring ABP, offers a continuous waveform. The theory and technology, originally developed by Penaz, and commercialized by Wesseling, encumbers a finger and the wrist of the subject, and requires a high bandwidth actuator [5,6]. As with other cuff-based modalities, the accuracy of the Portapres is dependent on proper cuff size. Likewise, it has been reported to cause bruising at the cuff site when worn for extended periods of time [7]. Beyond the Portapres, surrogate measures of ABP, such as pulse wave velocity and the second-derivative of the photo plethysmograph (PPG) are currently in the research stage of evaluation [8,9].

This paper focuses on the initial work towards the development of a noninvasive modality capable of remotely monitoring the arterial blood pressure of a patient without the use of a high pressure cuff. The proposed technique combines a PPG-based signal with a hydrostatic pressure reference for absolute sensor calibration. Description of the effects of hydrostatic changes to a peripheral pressure waveform is performed. Experimental findings demonstrate the promise of the method for the real-time characterization of a patient's vascular compliance curve using a standard sigmoidal model. Once parameterized, it will be shown that the curve can be utilized for the real-time measurement of arterial blood pressure using noninvasive photo plethysmograph (PPG) sensors.

II. Methodology

A. Vascular Compliance Curve Modeling

It is well known that the arterial wall demonstrates a highly nonlinear relationship between vascular volume (V) and transmural pressure (P_{tm}) [10], which is defined as the difference between the internal pressure (P_{hem}), external hydrostatic pressure (P_{hydro}), and any additional externally applied pressure (P_{ext}), as in (1).

$$P_{tm} = P_{hem} \pm P_{hydro} - P_{ext} \tag{1}$$

Typically, this nonlinear relationship can be characterized by fitting a sigmoid function to experimentally derived pressure-volume data (2),

$$V = \frac{b_1}{1 + \exp\left[-b_2\left(P_{tm}\right)\right]} \tag{2}$$

where, b_1 and b_2 are fitting parameters with units of volume and inverse pressure, respectively (Fig. 1). Further examination of (2) indicates that two important limiting cases for this nonlinear model occur when (i.) $P_{tm} >> 0$ and when (ii.) $P_{tm} << 0$. For case i., we see that when the hemodynamic pressure is much greater than the externally applied pressure, the relative volume change of the vessel is very small and therefore, the saturation coefficient, b_1 can be estimated directly from the measurement (3).

$$P_{tm} >> 0 : V = \frac{b_1}{1+0} \Rightarrow V = b_1 \tag{3}$$

Meanwhile, for case ii., we find that when the hemodynamic pressure is much less than the externally applied pressure, the vessel is in a continuous state of collapse (4).

$$P_{tm} << 0 : V = \lim_{P_{tm} \to -\infty} \frac{b_1}{1+\infty} \Rightarrow V = 0 \tag{4}$$

The remaining model parameter, b_2, requires additional knowledge about the pressure-volume relationship. One method for estimating this parameter is to assume that the middle section of the sigmoid is approximately linear, with slope b_2. If valid, the value of b_2 can then be estimated from any two points (pressures) within this linear region. The main difficulty with this approach is that it appears to require *apriori* knowledge of the compliance curve; in particular, it requires knowledge of the pressures containing the central region of the compliance curve. To resolve this point we propose that for a stable hemodynamic state, using a known P_{hydro} input can aid in the characterization of the curve. By superimposing a known hydrostatic perturbation input onto a slowly varying hydrostatic pressure, defined to be the height at which the pressure measurement is acquired relative to the height of the heart, the parameter b_2, and consequently the complete compliance curve, can be determined.

Assume that the relationship between P_{hem} and P_{ext} is constant and that the only time varying input can be considered as P_{hydro}. By providing the hydrostatic perturbation input and accompanying conditions described above, (2) can be reformulated as (5),

$$V = \frac{b_1}{1 + A\exp\left[-b_2\left(P_{hydro}\right)\right]} \tag{5}$$

where A is the constant offset provided by the hemodynamic and external pressure difference. For a small sinusoidal hydrostatic perturbation at two known heights we find,

$$V_1 = \frac{b_1}{1 + A\exp\left[-b_2\left(P_{DC,1} + P_{AC}\sin(\omega t)\right)\right]} \tag{6}$$

$$V_2 = \frac{b_1}{1 + A\exp\left[-b_2\left(P_{DC,2} + P_{AC}\sin(\omega t)\right)\right]} \tag{7}$$

where $P_{DC,n}$ is the slowly varying hydrostatic component and P_{AC} is the amplitude of the superimposed sinusoidal component. At transmural pressures near the upper elbow region of the compliance curve, the amplitude of the volume output goes through an appreciable change. Knowledge of the location of this point now makes it possible to determine the central, linear region of the compliance curve, making it possible to estimate the unknown parameter, b_2. To a first order, b_2 can be estimated from the slope of the central linear region of the PPG compliance curve.

Finally, for complete characterization of the pressure-volume relationship, it is necessary to estimate the operating transmural pressure. As is the case with more traditional oscillometric methods, as the transmural pressure operating on the wall of the vessel goes to zero, the compliance of the vessel increases to a maximum value (Fig. 1). Therefore, given a known and constant sensor band pressure and a range of sensor heights relative to the heart, it is possible to estimate the internal mean arterial pressure by finding the height at which the amplitude of the PPG signal is a maximum (i.e. when $P_{tm}=0$) (6).

$$P_{hem} = P_{ext} \pm P_{hydro} \tag{6}$$

Furthermore, assuming linearity for the central region of the compliance curve, it is possible to use linear regression techniques, in conjunction with the hydrostatic challenge, to arrive at a more robust estimate for the true mean arterial pressure. A regression line can be fit to the amplitudes of PPG signals recorded at known heights within the linear central range of the vessel's compliance.

B. *Experimental Procedure*

Two reflective-type PPG sensors (λ = 660 nm) have been constructed and enclosed within elastic finger cuffs of adjustable bias pressures. Additionally, a 10 psi micro-pressure sensor (Entran EPL-D0) has been attached to the interior of one of the cuffs to provide real-time information related to the applied band pressure. The output of the PPG sensors is conditioned with a standard analog pre-amplifier and band-limiting 2nd order lowpass inverting Bessel filter (F_c = 30 Hz). All signals are sampled at 1 KHz using a 16-bit National Instruments DAQ board.

In accordance with an experimental protocol approved by the Massachusetts Institute of Technology's Committee on the Use of Humans as Experimental Subjects (COUHES Approval No. 3117) and following Federal regulations for the protection of human subjects established by 45 CFR 46, the standard experimental protocol consists of first attaching the two PPG sensors to the fingerbase of each hand (one sensor unit per hand). One of the subject's arms is then placed on a platform of adjustable height (total adjustable range is 100 cm). For the purpose of benchmarking the transformed PPG measurements, a Finapres® blood pressure sensor is attached to a finger adjacent to the PPG unit on the subject's raised arm. The subject's other arm is placed at a comfortable height (near the level of the heart) and serves as a baseline reference for the hydrostatic signal. After an initial rest period of approximately five minutes, data are acquired for arm heights adjusted in increments of 10 cm for approximately one minute at each height. While conducting the experiment, the subject is instructed to slowly raise and lower their raised arm in an oscillatory motion, for a range of heights between zero and five cm, relative to the adjustable height platform.

Once the data have been acquired, the amplitudes of the hydrostatic and reference waveforms are calculated and averaged over 10 second periods. A median filter is additionally applied to eliminate spurious data results. Finally, the hydrostatic amplitudes are normalized relative to the measured baseline amplitudes. Assuming a standard sigmoidal relationship for the nonlinear vascular compliance, the relevant calibration parameters, as stated in the vascular compliance modeling section, are estimated from the data set and subsequently used to estimate information related to both the patient's vascular state and the underlying arterial blood pressure.

III. Results

A.. Changes in waveform morphology

Utilizing the previously described experimental setup, initial trials have been conducted on three individuals of different age and/or gender which make use of the hydrostatic calibration technique. Waveform data for each hydrostatic height is acquired and the amplitude of the waveform is normalized relative to the control waveform. As can be seen in Fig. 1, the nonlinear compliance of the arteries has a significant affect on both the amplitude and overall morphology of the measured PPG waveform. In particular, we note that the sharp peak present in the waveforms at negative transmural pressures (positive hydrostatic heights) is significantly more rounded than similar peaks at positive transmural pressures (negative hydrostatic heights). Moreover, as can be seen from the figure, the reflected wave that is superimposed onto the primary pressure wave appears to operate within a separate region along the compliance curve. This finding is noteworthy since it appears that plethysmograph waveforms with additional reflections may provide at least two opportunities towards a complete characterization of the compliance curve.

B. Cuffless estimation of mean arterial pressure

The mean and standard deviation values for the normalized PPG amplitude measurements are plotted against the hydrostatic challenge pressure in Figure 2.

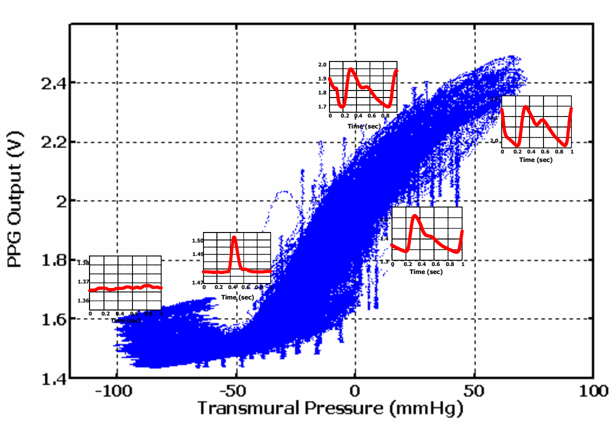

Fig. 1. Experimentally measured arterial "compliance" curve with measured PPG waveforms demonstrating the significant changes in waveform morphology as the transmural pressure is altered.

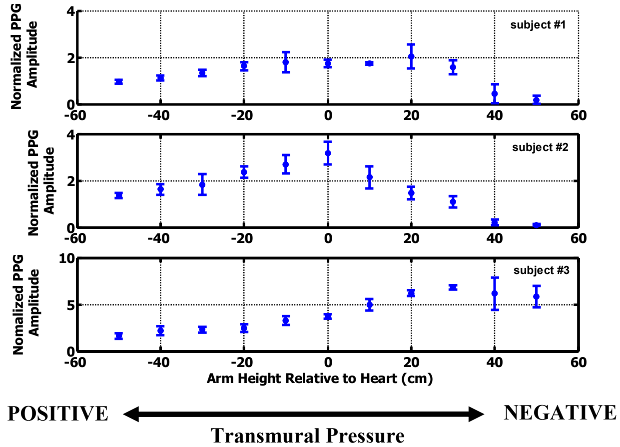

Fig. 2. Comparison of measured PPG-based compliance curves for three different subjects plotted against the changing hydrostatic load.

Due to the PPG's inherent sensitivity to sensor placement location the resulting normalized waveforms may differ by simple gain factors, as is the case in the corresponding figure. However, the subject's mean arterial pressure can be estimated irrespective of this gain. As expected, a clear maximum oscillation amplitude exists for each set of hydrostatic experiments. Based on this maximum, the estimated mean arterial pressures for each of the tested subjects corresponded closely to measurements made with a standard cuff (mean percentage difference = ± 3.1%).

C. Compliance Curve Characterization

Table I provides a summary of the parameters estimated from the hydrostatic calibration experiments. Compliance curves based upon these estimated parameters are provided in Fig. 3. These findings suggest that several of the attributes of the PPG-based compliance curve are extremely patient dependent. In particular, it appears that the slope of the linear region of the curve is quite different for subjects of different age groups (Fig. 2). A change in bias pressure noticeably shifts the pressure corresponding to the maximum oscillation amplitude and therefore is an extremely important consideration for final sensor design.

IV. Discussion

Experimental results have demonstrated that significant changes in waveform morphology occur as the hydrostatic pressure changes. For stable conditions, these changes are a direct result of the nonlinear transmural pressure-vascular volume relationship. As the subject's arm is lowered, the transmural pressure increases and the vessel wall becomes more compliant, resulting in a larger waveform amplitude. However, the amount by which the amplitude changes appears to be highly dependent upon the subject.

TABLE I
ESTIMATED COMPLIANCE CURVE PARAMETERS

Subject No.	b_1	b_2	Est. P_{mean}	Act. P_{mean}
1	0.96	0.022	90	95
2	1.36	0.045	90	88
3	1.63	0.047	92	93

For example, Fig. 2 illustrates the pressure-amplitude curves for three test subjects. Subject #1 is approximately 30 years older than subject #2, while subject #2 and subject #3 are of comparable ages, but are different genders. Comparing the slopes of the three curves we find that the data from Subject #1 results in a significantly more gradual slope than the data from subject #2 or subject #3. This finding makes sense since it is well known that arteries tend to become stiffer with age. Although a more complete data set is needed for ultimate model validation, the results to date appear to be quite promising in regard to richness of data.

In addition to compliance curve characterization, it appears that under stable monitoring conditions, the PPG is also capable of providing a reliable estimation for mean arterial pressure without the use of a dynamic cuff. It has been shown that a hydrostatic challenge of known height provides a sufficient shift in the measured mean arterial pressure for sensor calibration. However, it is important to note that in addition to requiring a reliable method for measuring the sensor's height relative to the heart, it is also currently necessary to have knowledge of the pressure applied by the accompanying sensor band. The external bias pressure supplied by the band tends to shift the operating point of the vessel (i.e. changes the transmural pressure). Therefore, without knowledge of this band pressure, it is at best possible to measure a relative pressure as opposed to the absolute pressures derived in this text.

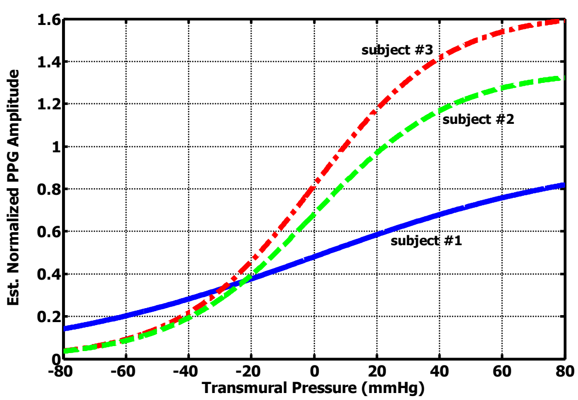

Fig. 3. Arterial compliance curves based on parameters estimated from hydrostatic challenge.

V. CONCLUSION

Work towards a cuffless blood pressure monitor based on PPG sensors has been presented and described. A method for absolute calibration using a known hydrostatic pressure reference has been described and initial experimental evidence has been provided as proof-of-concept. The influence of changes in hydrostatic pressure on peripheral PPG waveforms has been discussed and has been shown to be linked to the nonlinear transmural pressure – vascular volume relationship. It has been proposed that additional information related to the compliance state of a subject's vasculature can be extracted from changes in hydrostatic pressure. It seems that the incorporation of such a multi-modality measurement holds great promise for future wearable sensor systems.

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