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Non-invasive vascular resistance monitoring with a piezoelectric sensor and photoplethysmogram

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ABSTRACT

Peripheral vascular resistance is known to be a key indicator of the body's efforts to compensate for cardiovascular stresses, but remains very difficult to assess with existing technology. In this work, changes in vascular tone are estimated non-invasively by observing variation in response of a photoplethysmogram and a novel piezoelectric cardiovascular sensor. A simple model of the piezoelectric sensor and underlying artery and tissue is derived to capture trends in relative amplitude and hysteresis between the two sensors, and metrics for estimating vascular resistance based on these trends are proposed. Vascular resistance tracking results are demonstrated to show strong correlation with invasively-measured systemic vascular resistance in swine subjects.

1. Introduction

The state of the peripheral arteries is known to be a key physiological indicator of the body's response to both acute and chronic medical conditions. For example, the body's vascular tone, or constriction of the arteries relative to a maximally dilated state, is a direct indicator of the body's response to cardiovascular stress. Peripheral arterial constriction or dilation is also the dominant factor in determining the body's systemic vascular resistance (SVR), or resistance felt by the heart in forcing blood through the circulatory system; SVR is a major means of compensation to maintain physiological homeostasis. Situations where rapid changes in vascular tone and SVR are known to have great importance include shock (sepsis, cardiac, traumatic, etc.) [1–3], post-surgical recovery [4,5], and dialysis [6].

Despite the potential value of being able to monitor vascular tone and SVR continuously and rapidly, existing technology for acquiring this information is severely limited. This is especially true of continuous, non-invasive technologies. Peripheral artery diameter can be directly measured only through biomedical imaging, typically ultrasound [7,8]; acoustic techniques have also been proposed for measuring SVR [9]. However, imaging is not available on a continuous basis or in most care settings. The gold standard for SVR measurement is invasive monitoring of cardiac output, central venous pressure, and arterial pressure through catheterization. However, this is available only in intensive care settings, and not universally even then. Researchers have also proposed improvements on vascular resistance measurements by applying more complex models to aortic flow data [10,11]. Non-invasive systems for estimating cardiac output, and from there inferring SVR, have been commercialized based on electrical cardiometry [12] and whole body bioimpedance [13]. However, these track SVR only weakly [14,15], since central venous pressure is not measured, and are also unavailable outside of acute medical care settings.

Researchers have thus pursued methods for estimating SVR and vascular tone using simpler instruments. Prior attempts have generally relied on photoplethysmogram (PPG) data, which tracks changes in artery volume within short-term pulse cycles. Timing of reflection waves as extracted from PPG data has been reported to indicate changes in peripheral arterial resistance, but this was only verified through basic correlations with expected trends among hypertension subjects, not individualized tracking [16]. Methods

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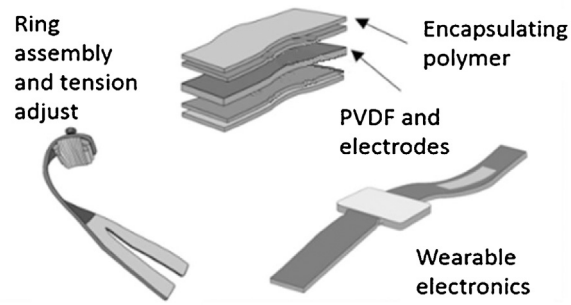

Fig. 1. Compliant polyvinylidene fluoride (PVDF) piezoelectric sensing band for non-invasive artery monitoring.

for extracting SVR from multiple regression of PPG waveform data points have been derived by machine learning techniques, but SVR estimation error ranged from 15%–100% for most subjects [17,18]. Evaluating a vascular tone index by matching models for arterial dynamics to pulse transit time (PTT) and blood pressure (BP) measurements has also been proposed [19]. However, results could at most be correlated with risk factors for high SVR, rather than SVR itself. Another report showed PTT correlation with SVR over time, but only for two individual cases [20]. Estimates of cardiac output and vascular resistance have also been suggested based on ECG and BP cuff data, and used in tracking response to physical activity, but these are recognized as only approximate measures [21].

This paper proposes a technique for tracking changes in vascular tone by combining PPG data with measurements from an adjacent compliant piezoelectric polymer pressure sensor (polyvinylidene fluoride, or PVDF). Non-invasive piezoelectric arterial pressure sensing with sensors fabricated from PVDF films were likewise previously used for waveform monitoring at the human wrist by Sur et al. [22] for pulse and respiration monitoring at the chest by Chiu et al. [23] Even smaller sensing elements have been proposed based on thin-film lead-zirconate-titanate (PZT) in a polymer film [24], nanowire-impregnated polymers [25], and amorphous PZT films [26]. Regardless of transduction method, this work examines the importance of a compliant sensing structure to contrast to existing PPG measurements to track changes in vascular resistance.

In this work, a model is derived to account for the most prominent features of interaction between underlying tissue and a compliant piezoelectric sensor. A simple local model for viscoelastic dynamic behavior of the underlying artery and surrounding tissue is generated and coupled to the piezoelectric sensor model, from which variations in relative amplitude and hysteresis between the piezoelectric and PPG signals are found to show strong correlations with invasively measured SVR data in animal subjects (swine).

2. Sensor description

The authors use a custom-built flexible piezoelectric sensor for acquiring pressure signals during vascular resistance tracking, as well as an off-the-shelf PPG sensor (OXY200 and BioNomadix, BIOPAC Systems Inc.). The piezoelectric sensor may be applied to a variety of sites on the body, such as the wrist, elbow, or ankle. For vascular tone monitoring experiments on it is worn on a finger for human subjects, adjacent to a finger having a PPG sensor, and on the foreleg for swine (analogous to the human wrist), again adjacent to a PPG sensor. It is important to note that given placement of the sensor, estimated changes in vascular resistance obtained from the sensor are strictly speaking based on changes in vascular resistance of the peripheral arteries, which may in some circumstances differ from other contributing factors to SVR. Nonetheless, changes in peripheral vascular resistance and SVR are anticipated to be highly correlated, and in this work validation data available from swine testing was from SVR and indeed was seen to track closely with changes in PVDF and PPG sensor behavior.

The piezoelectric sensor, shown in Fig. 1, consists of a polymer laminate with a piezoelectric PVDF sensing layer (52 μm thick, silver plated, Precision Acoustics) between protective layers of polyimide tape (Kapton Tape, Uline Inc.), which is worn under a Velcro or elastic band. A set screw allows adjustment of the sensor to a relatively consistent level of tension. The sensor is shown applied to a sample swine subject in Fig. 2. Dedicated sensing circuits and a data-logging microcontroller are available, or the sensors can be connected directly to commercial biomedical data acquisition systems (e.g., DA100C, BIOPAC Systems Inc.), with the latter being used to acquire data presented in this work.

A sample time response of the piezoelectric sensor on the foreleg of a swine subject over three cardiac cycles is shown in Fig. 3a. The unprocessed response of the piezoelectric sensor can be considered as approximately the time derivative of pressure at the site, with this differentiation of the underlying piezoelectric pressure response resulting from high-pass filtering effects of internal capacitance and input impedance of the piezoelectric element, discussed further in Section 3.2. However, tissue and artery motion further mediate the signal as they interact with the compliant sensor, in addition to some electrical filtering. Thus, integration of the raw PVDF signal (Fig. 3b) returns a similar but not identical waveform to non-invasive blood pressure measurements (CNAP Monitor, CNSystems Medizintechik AG), in which feedback control holds artery volume constant, or to invasive arterial lines. PPG data from the same swine, shown in Fig. 3c, is comparatively less detailed, which has tended to impede its success in monitoring vascular tone in previous studies. However, as will be discussed, the difference in dynamics between PPG and piezoelectric pressure

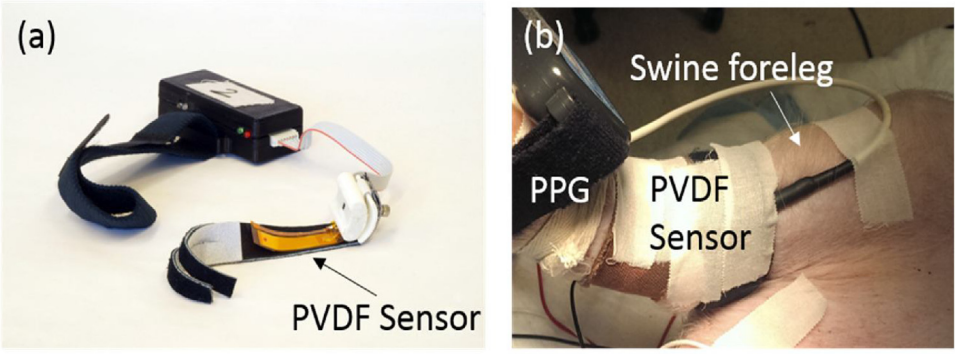

Fig. 2. (a) Example polyvinylidene fluoride (PVDF) sensor; (b) sensor applied to foreleg of swine test subject.