Stroke Volume Estimation from the New Noninvasive Cardiopulmonary Stethoscope

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***Abstract*—This paper presents advanced signal processing techniques and associated results for measuring the stroke volume using cardiopulmonary stethoscope (CPS), a new noninvasive multiple vital signs sensor. The CPS is a novel sensor based on RF measurements on patient's chest. It can noninvasively and accurately measure changes in lung water (CLW), heart rate (HR), and respiration rate (RR) as reported in previous studies. CPS cardiac signal was correlated with arterial blood pressure measurements for studying the feasibility of estimating this important parameter noninvasively. Stroke volume measurement was computed using two methods, namely mean arterial blood pressure and area under the curve. Validation results by comparison with arterial blood pressure waveform are presented.**

I. Introduction

Chronic heart failure is one of the leading causes of hospitalization, costs and deaths in the United States. Annually, more than one million patients are hospitalized due to heart failure (HF) and this accounts for a total Medicare expenditure exceeding $17 billion [1] [2]. In order to reduce the healthcare expenditure as well as improve the quality of patient's life using advanced technologies remain one of the most important challenges in the healthcare engineering in the world of 21st century. More emphasize is being put on the need of introducing home based patient monitoring initiatives with the help of the advancement of technology. To achieve such ambitious goals some of the key parts of biomedical technology, such as medical sensors require significant development. Growing use of wireless technology in medical domain would also help in rapid advancement of ambulatory home monitoring of patients which would provide patients with early diagnosis and smart health monitoring options.

To address some of these healthcare advancement goals, the authors previously proposed a microwave VS measurement system and its possible adoption in telemedicine technologies and patient monitoring [3]. The cardiopulmonary stethoscope (CPS), a low cost, multipurpose, and noninvasive microwave sensor technology for measuring important cardiac parameters in addition to multiple vital signs and changes in lung water contents [3]. Previous studies have reported the successful experiments of the technology and associated signal processing techniques for measuring vital signs, such as heart rate (HR) and respiration rate (RP) [3]. In this paper, we present advanced signal processing techniques for an additional important parameter, stroke volume (SV) developed using the signal collected from newly designed textile-based sensors. The textile based sensors can be used as wearable sensor which would facilitate long-term ambulatory patient monitoring.

II. Methods and Materials

The CPS technology is based on continuous monitoring of the reflection and/or the transmission coefficient to indicate changes in the dielectric properties of the lung tissue as well as the motion activities of the heart (blood flow) and respiration activities. An EKG-lead size sensor was placed in contact with the chest and reflection coefficients were measured at 915 MHz and multiple vital signs are derived from a single measurement using a novel digital signal processing (DSP) algorithm reported in earlier studies [3].

A. Microwave Sensor and Data Collection

The phase of the microwave reflection coefficient on patient's thorax at 915 MHz was continuously recorded using a network analyzer (Agilent PNA E8364B) and a custom Graphical User Interface (GUI) developed in LabView. A new textile-based microwave applicator/sensor was developed to be used as a wearable sensor [RG2014]. This new sensor is used in data collection for development and validation of this new cardiac parameters. Measured magnitude of the reflection coefficient (S11) was less than -10 dB from 900 MHz – 2.4 GHz when the CPS sensor was coupled to the patient's chest. At frequencies of 915 MHz and 2.4 GHz, the magnitude of S11 was approximately -15 dB and -20 dB respectively, which indicated proper coupling and minimal reflections due to impedance mismatches [4]. The SAR measurements were within the 1/3 of the FCC limit [4].

Similar to our previous protocols [3], [4] clinical studies on healthy male subjects conducted in this study was approved by the Center for Human Services. The experiment protocol in [4] consisted of two repetitions of normal breathing for one minute, followed by five-ten seconds minimum of breath holding to visualize the heartbeat waveform detected by the CPS [4]. The experiments were conducted while the study participant was sitting on chair.

B. Signal Processing Algorithms for Stroke Volume

Phase signals relevant to cardiac activities were extracted from the microwave signals (the measured raw phase of reflection coefficient) by applying band pass filtering techniques. A fourth order IIR Butterworth filter was used with cutoff frequencies at 0.8 Hz and 15 Hz. The sampling frequency of data acquisition was 20 samples/sec. Delineation of the peak and valley points of the phase signals are shown in Fig. 1.

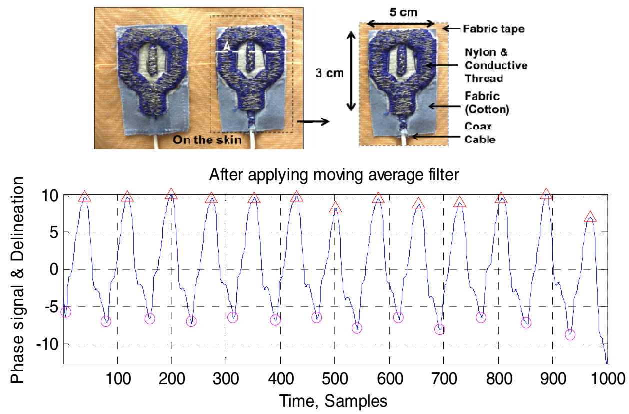

Fig. 1. The fabricated sensors and detection of characteristic points of CPS phase signals corresponding to cardiac activities. Peaks are marked with triangles and valleys are marked with circles.

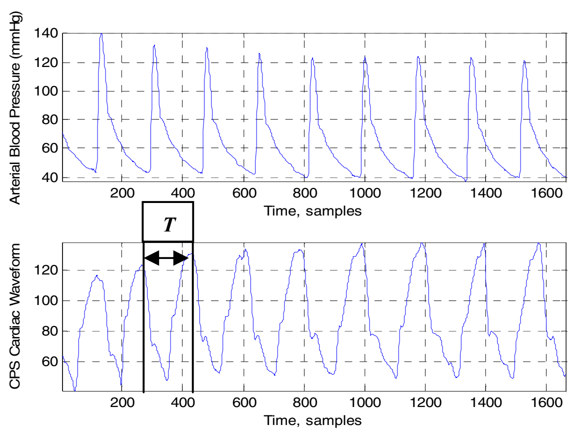

Fig. 2. Comparison of cardiopulmonary stethoscope (CPS) cardiac waveform to the arterial blood pressure (ABP) waveform. Top plot shows the ABP waveform (mmHg). Bottom plot shows the CPS cardiac waveform calibrated with respect to ABP in same unit.

In the preprocessing step, linear trend was subtracted from the composite phase data and DC mean was removed from the signals. The waveform was normalized to the same scale as of the arterial blood pressure (ABP) waveform. A moving average filter of window length 10 was applied to the signal to remove some high frequency components and efficient detection of peak and valley points. Then fiducial points, such as peak and valley was detected in the signal using a waveform delineator proposed and described by Li et al. [5]. The peak to peak distance or interval, T is equivalent to RR interval of EKG signals as shown in Fig. 2. Systolic duration can be computed as, $T_s = 0.3 \times \sqrt{T}$. Where T_s denoted the systolic duration of the curve and T is the beat period as shown in Fig. 2. The new SV parameter was computed by adopting a similar approach described by Sun et al. [6]. Two methods were used: 1) mean arterial pressure (MAP) and 2) integrating the area under the systolic curve [6]. Correction factors were utilized for accurate measurement which included subtraction of the diastolic area under each systolic interval [6].

III. Results

The computation was done in a beat-by-beat analysis method. The results, average stroke volume measurement are presented in Table I along with the minimum and maximum values of the stroke volume distribution. Stroke volume measurement from ABP waveforms were considered for evaluating measurements from CPS waveforms. The percentage error was computed and presented in Table II.

TABLE I. Stroke Volume Estimation using Mean Arterial Pressure Method.

Measurement	Mean	Min	Max
ABP Waveform	69.34	65.89	75.78
CPS Waveform	75.87	66.42	78.94

TABLE II. Percentage Error of the Measurements from CPS with respect to ABP Waveform.

Method	Mean	Min	Max
MAP	8.90	3.26	21.75
Systolic area	14.35	1.19	48.06

IV. Conclusion

We performed similarity analysis of CPS cardiac signals with non-invasively collected blood pressure waveform. The measured cardiac waveform by CPS has revealed significant correlation to the ABP waveform. We argue that the changes in CPS measurements are proportional to the amount of blood pumped by the heart during each cycle or impulse. Therefore it is now possible to non-invasively measure additional cardiac parameter, the stroke volume from the noninvasive CPS sensor.

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