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Pulse Pressure Monitoring Through Non-Contact Cardiac Motion Detection Using 2.45 GHz Microwave Doppler Radar

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Abstract—**The use of a Continuous Wave (CW) quadrature Doppler radar is proposed here for continuous non-invasive Pulse Pressure monitoring. A correspondence between the variation in systemic pulse and variation in the displacement of the chest due to heart is demonstrated, establishing feasibility for the approach. Arctangent demodulation technique was used to process baseband data from radar measurements on two test subjects, in order to determine the absolute cardiac motion. An Omron digital Blood pressure cuff was used to measure the systolic and diastolic blood pressures from which the pulse pressure was calculated. Correlation between pulse pressure and cardiac motion was observed through changes induced due to different postures of the body.**

I. INTRODUCTION

Cardiovascular diseases have been the leading cause of death in the United States for recent years, accounting for about 26% of total deaths in the year 2006. It has been estimated that 314.6 billion dollars would be lost in 2010 due to heart disease in the United States [1], [2].

Prevention and treatment of cardiovascular diseases involves measurement of several key parameters such as blood pressure (BP), stroke volume (SV), cardiac output (CO), Pulse Pressure (PP) and Pulse rate. Continuous non-invasive remote blood pressure monitoring has remained an elusive technology. Almost all home blood pressure monitoring devices use a cuff and hence give out one time reading. More accurate techniques for blood pressure measurement are invasive involving placement of a cannula needle in the artery and used only in hospitals. Blood pressure measurement gives out the systolic and diastolic pressures the difference of which gives the pulse pressure (PP).

Pulse Pressure has been recognized as a more accurate diagnostic tool than blood pressure itself especially in older people [3]. A high PP is associated with cardiovascular risk factors such as diabetes, hypertension and smoking [4]. Measurement of PP along with heart rate also enables us to calculate stroke volume and cardiac output. Studies have shown correlation between the chest cardiac motion and stroke volume [5]-[7]. PP is directly proportional to the stroke volume and hence to the displacement of the heart wall.

A contact microwave Doppler radar has also been proposed for analyzing arterial pulse waves [8] as well as ventricular motion and pulse-pressure [9]. It was determined that good quality pulse pressure waveforms could be obtained with a high degree of correlation with simultaneously recorded intra-aortic pressure waves. Non-contact Doppler radar has been previously used for detection and remote sensing of various vital physiological variables such as respiration, heart rate, blood vessel motion and pressure-pulse [9]-[11]. These systems however, were single channel systems with limited accuracy [12]. The problems with a single channel system were alleviated using a quadrature system. The quadrature Doppler radar has been used for long term monitoring of respiration [13]. Potential applications have also been shown for respiratory tidal volume measurement and determination of subject orientation using radar cross section techniques [14] - [16]. Cancellation of random body motion has also been achieved with recent advances in Doppler radar [17].

In this paper, we explore the feasibility of using non-contact Doppler radar to track changes in PP, based on measurements of absolute chest displacement due to cardiac motion. The correlation between variation in measured pulse pressure and variation in cardiac motion was observed and recorded for two human subjects using 2.45 GHz quadrature Doppler radar. With individual calibration, this technique may lead to non-contact PP measurement technique.

II. CARDIAC ASSESSMENT FACTORS

A lot of studies have been made to understand and describe the mechanics of cardiac system. Most of the studies indicate that values such as stroke volume, cardiac output, blood pressure are correlated. The relationship between stroke volume and pulse pressure has been found to be linear and is given by [18]

$$SV = C \times PP \qquad (1)$$

where C is the compliance of the walls of the ascending aorta. Even though some factors affect its value, C can be assumed to be a constant for a specific individual. The cardiac output (CO) is the amount of blood ejected by heart

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in one minute and is given by the product of heart rate (HR) and stroke volume (SV).

$$CO = HR \times SV \tag{2}$$

Regression models have been consistently used to describe the cardiac process. Recently, the ratio of stroke volume to pulse pressure has been proposed as an indirect measure of total arterial compliance [19]. This ratio was calculated as

$$SV / PP = (0.013 \times \text{body wt. [kg]}) - (0.007 \times \text{age[y]}) - (0.004 \times \text{heart rate}) + 1.307 \tag{3}$$

From Eq. 3, we can see that by monitoring a few physiological variables such as heart rate and pulse pressure, we can easily track the SV/PP ratio and CO for a specific individual. It has been shown using apexcardiography that displacement of precordium overlying the apex of the heart mimics that of left ventricle [9]. The proven correlation between chest wall displacement and volumetric measurements leads to the idea of measuring systemic pulse pressure by monitoring absolute cardiac displacement in the precordium. The challenges include accurate sub-millimeter chest displacement recovery, and the correlation of the chest displacement and pulse pressure. In order to measure a change in PP, two experimental positions were proposed. Position 1 was chosen to be a normal sitting position with upright back without a support. In Position 2, the person had to lie on his stomach and stretch the chest upwards with hands supporting on sides. The positions are shown in fig.1. Blood pressure measurements were made with an Omron digital blood pressure in order to see any marked changes in pulse pressure. Table I lists the blood pressure readings and the corresponding pulse pressure. It can be seen that there was a change in the pulse pressure with change in position for the subjects. Several measurements were taken for each position. The average of three readings is shown here. After validating that the pulse pressure is indeed changing for the two positions, a Doppler radar setup was made to observe changes in radar data.

Fig. 1 Two Positions for measuring the blood pressure and cardiac displacement.

Measurements on human subjects were performed at University of Hawaii at Manoa under IRB protocol CHS 14884.

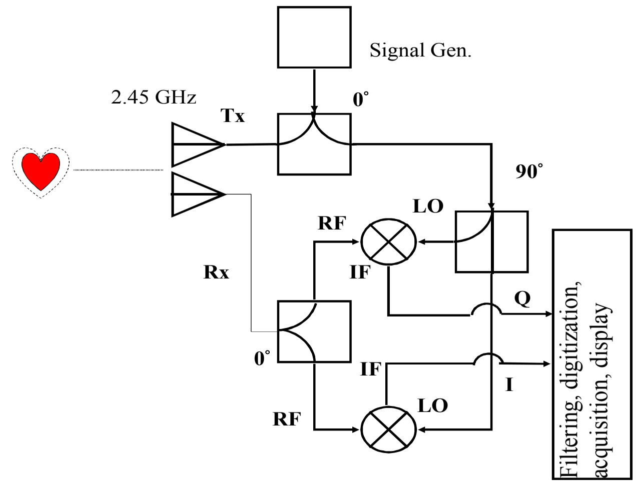

Fig. 2 2.45 GHz Quadrature Doppler radar system

Table I. Measured values from digital BP meter

Subject	Position 1			Position 2		
	S	D	***PP***	S	D	***PP***
1	115	75	***40***	115	68	***47***
2	107	76	***31***	107	71	***36***

III. DOPPLER RADAR SENSING

Quadrature Doppler radar was used to sense the heart wall displacement in the two positions. The radar was constructed using Mini-Circuit splitters ZFSC 2-2500, Mini-circuit mixers ZFM-4212 and a mini circuit 90° splitter ZX10Q-2-27. The transmitting and receiving antenna used were ASPPT 2998 from Antenna Specialist’s having 8 dBi gain and 60° E plane beam width. The system is shown in fig. 2 along with the antenna arrangement with respect to the subject. The antennas had to be moved in order to maintain the same relative arrangement with the subject’s precordium for the two positions. In order to preserve the heart signal content and dc information without saturating the low noise amplifiers (LNA’s) or the data acquisition device (DAQ), two serially connected LNA’s were used. The baseband output was sent to the first LNA with dc coupling and a gain of 20 was used. The output of first LNA was recorded and also sent to the next LNA where the signal was ac coupled and filter settings of 0.3-10 Hz were used. A gain setting of 50 was used in order to increase the signal to noise ratio (SNR) of cardiac related motion signal. The subject was first asked to sit (position 1) in front of the radar. After the radar measurement was taken, the subject’s blood pressure was recorded using the cuff. Then the subject was asked to lie in position 2. A folding cot was used for this purpose. After the subject had been in the position (position 2) for around two minutes, radar data were recorded. A transmitting power of 0 dB was sent to the antenna at 2.45 GHz. The distance between the subjects and the antenna was 1 m. After the radar measurements, data from the cuff was also noted down.

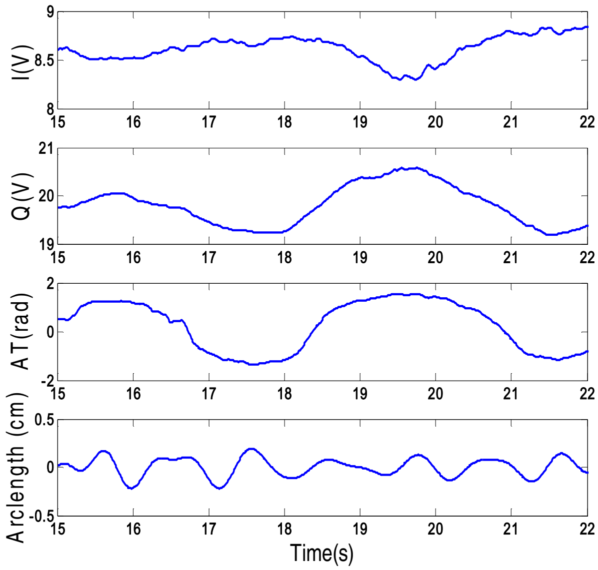

Fig. 3. Results from subject 1 in position 1 a) I, Q, AT demodulated and arc length calculated from the filtered data respectively clearly showing the cardiac motion.

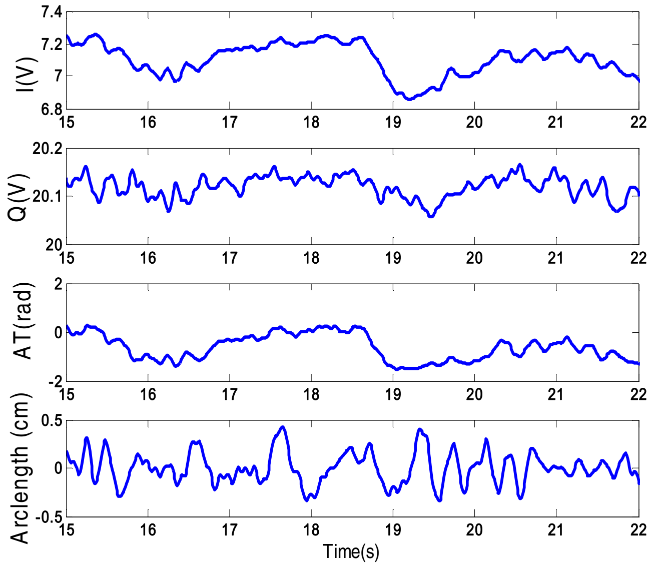

Fig. 4. Results from subject 1 in position 2 a) I, Q, AT demodulated and arc length after filtering is shown respectively. As expected, more noise is present in the data.

Data were recorded using an A/D converter (NI-USB 6259) and MATLAB. A sampling frequency of 100 Hz was used.

IV. Results

The baseband data were processed in MATLAB. In order to keep the scaling of the signals proper, the data from first LNA was multiplied by the gain of the second LNA before adding the signals together. The ac coupled data from the second LNA was digitally filtered using a band-pass FIR filter (0.8 - 2 Hz) to remove respiratory frequencies. Arctangent demodulation was performed employing center estimation [20]. The resultant data were scaled by $4\pi/\lambda$ to yield the displacement. Fast Fourier transform (FFT) was performed on this data and the peak magnitudes and frequency for each window were stored. In the end, average of the magnitude was considered as the displacement of heart wall. The measurement data from subject 1 is shown in fig. 1 for sitting position. Note that only 20 seconds of data have been processed for obtaining the values related to the displacement. Fig. 3 shows the in-phase (I), quadrature (Q), arctangent data (AT) and the arc length from subject 1. After filtering the arctangent data, we can clearly see the cardiac motion components in the signal. Arctangent demodulation is affected by center estimation and circle fitting techniques. Hence, the use of Fourier transform to correctly determine the amplitude of desired signals was proposed. From this calculation, it was estimated that the 'amplitude mean' of frequency content with maximum amplitudes is 0.083 cm.

Fig.4 shows similar data for subject 1 in position 2. The measured mean amplitude/motion in this case was 0.1581 cm. The data from subject 2 was also analyzed in a similar way. The dc data is critical for finding the center of the arc. The accuracy of the fit depends on the noise in the data. The cuff data and radar data for both subjects have been summarized in Table II. From Table II, we can see that for subject 1, an increase in PP by 14 corresponds to an increase of 0.75mm in cardiac motion. To exactly correlate the two quantities, a more accurate model needs to be constructed.

TABLE II
Digital BP meter and Radar data for both subjects

Subject	**Position**	**Cuff**				**Radar**	
		S (mmHg)	D (mmHg)	PP (mmHg)	PP	X_{mean} (cm)	X
1	1	119	72	**47**	**14**	**0.083**	**0.0751**
1	2	133	72	**61**		**0.1581**	
2	1	106	75	**31**	**5**	**0.046**	**0.0543**
2	2	108	72	**36**		**0.1003**	

For subject 2, a variation of 5 in PP corresponded to a 0.5 mm increase in cardiac motion.

For both subjects, an increase was observed in the cardiac related motion along with increase in the pulse pressure. The degree of increase was more for subject1. The pressure and chest displacement for each position, shown in Table 2, indicate a clear correlation. It is also clear that individual calibration will be required to correlate baseline pulse pressure with chest displacement. Since arctangent demodulation provides absolute displacement, this technique is neither sensitive to the distance between the subject and the radar, nor to the absolute power transmitted by the radar. However, subject orientation with respect to the radar line of sight will affect the amplitude of displacement, and thus subject orientation must be taken into account. Further studies will also incorporate subject orientation algorithms based on radar cross sections.

V. CONCLUSION

Continuous progress is being made towards improving healthcare technology and diagnostic techniques. In order to correctly interpret the functioning of cardiac system and its response to various ailments, continuous monitoring is required. Medical Doppler radar has shown the potential to perform this task of continuous non-invasive monitoring. By correlating the radar signatures to cardiovascular assessment factors such as pulse pressure, stroke volume and cardiac output, it is possible to monitor them outside the hospital environment and gain valuable information. In this paper, a successful attempt has been made to correlate the pulse pressure of the body to the motion amplitudes in the cardiac system. The results are preliminary but provide a good direction towards future applications of medical Doppler radar. The equipment and signal processing techniques used in this paper are very basic. Preliminary data on two subjects validates the concept, and a broader scale human study will be carried out to study accuracy of this technique across population characteristics, as well as to carry out individual calibration. There is a scope for improving the accuracy of the system by using more accurate blood pressure measurement equipment and advanced signal processing techniques for better demodulation and analysis. By monitoring the heart rate and cardiac motion simultaneously, we can monitor cardiac output and stroke volume as governed by the equations.

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