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Microwave Non-invasive Sensing of Respiratory Tidal Volume

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Abstract—**This paper describes the use of Doppler radar to measure respiration rate and air volume. The respiratory volume is measured indirectly via chest wall position. Calibration of displacement to airflow prior to subject measurements and accurate chest wall position information enable mean differences of less than 10 ml; with standard deviation of the difference of 20 ml between radar and reference measurements.**

I. INTRODUCTION

THE respiratory system is far more complicated than can be represented by a single degree of freedom. Nonetheless studies have shown the linear relationship between volume and chest wall displacement during unobstructed breathing. The study of chest wall displacement monitoring [1] indicates that the tidal volume is directly proportional to abdominal displacement, as measured with a laser. Kondo, et. al. [2] demonstrated that anterioposterior displacement at any point on the chest wall was linearly related to volume displacement during unobstructed respiration.

The current practices to measure respiration rates and lung volumes are measurement of airflow and measurement of respiratory effort/movement. Direct measurement of airflow typically uses face masks or mouthpiece, which can be obtrusive and change the subject's respiration. Indirect measurement of airflow, such as thermocouple or capnography, has less adverse affects, but still requires the placement of sensors in front of the nose and/or month. Respiratory effort/movement measurement typically requires direct contact with the patient through various chest bands that may impede unrestricted chest motion.

A piezo-electric sensor [3] was demonstrated for respiration volume measurements. The correlation coefficients were approximately 0.8-0.9 when it was used simultaneously with a pneumotachometer on human subjects. Three significant disadvantages of piezo-electric belt that could prevent quantitative volume measurement are as followed. First, the belt must be positioned just right so it reads the start of each inhalation and does not top-out and compress at the peak of inhalation. Second, performances changes over time with wear. And third, the impedance changes as the belt stretches which could affect the gain of the input stage of an amplifier; considering that the belt is high impedance and so the amplifier is likely to be more sensitive to this factor.

A Doppler radar motion sensing transceiver transmits a radio wave signal and receives motion-modulated signal reflected from a target. The RF wave reflected at a moving surface undergoes a frequency shift proportional to the radial surface velocity. If the surface is moving periodically, such as the chest of person breathing, this can be characterized as a phase shift proportional to the surface displacement [4]. If the movement is small compared to the wavelength, a circuit that couples both the transmitted and reflected waves to a mixer can produce an output signal with a low-frequency component that is directly proportional to the movement. Considering the linear relationship between the chest wall displacement and air volume changes, the output of the Doppler radar system should be proportional to the tidal volume during normal unobstructed breathing. Doppler radar offers benefit of reliable unobtrusive non-contact chest wall displacement measurement.

The following sections present Doppler radar system, signal processing and experimental results.

II. DOPPLER RADAR SYSTEM AND SIGNAL PROCESSING

A. Quadrature Demodulation

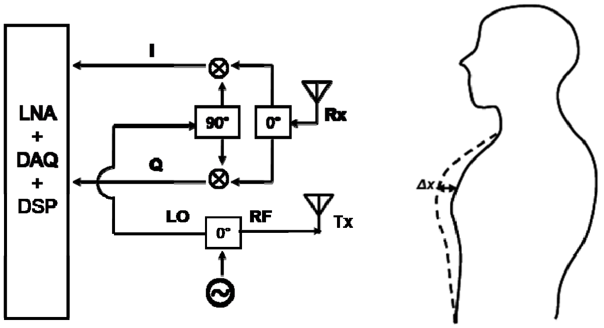

Fig. 1. A block diagram of a quadrature Doppler radar sytem.

Demodulation sensitivity to target's distance (optimum and null spots) in a single channel Doppler radar system can be solved by using a quadrature direct-conversion receiver [5]. A block diagram of a multiple-antenna Doppler radar system is shown in Fig. 1. A continuous wave (CW) radar system transmits a single tone signal at frequency 2.4 GHz. A single signal source supplies both the radio frequency (RF) output and local oscillator (LO) signals. The LO signal

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is divided to each quadrature pair, which is then further divided using 90° power splitter to provide two orthonormal baseband outputs. The reflected signal is amplitude, frequency and phase modulated.

The optimum demodulator for Doppler radar signal was derived in [6]. The study applied different algorithms to extract the respiration signals in deep and shallow breathings. For a subject with deep breathing, non-linear demodulation is more accurate and stable than linear demodulation. However, for a subject with shallow breathing, linear demodulation performs much better than non-linear demodulation. The study also showed that for medium and low SNR, linear estimator is preferable even for deep breathing, and therefore is chosen for this study.

B. DC Correction

The microwave signal has a large average clutter dc offset due to the reflection caused by the environment and the subject's stationary parts. In order to remove the comparatively large baseline shifts and allow for sensitive measurements, the detected signal must be ac-coupled. However, the ac-coupling circuit changes the shape of the actual microwave signal due to the high-pass filter used to remove DC.

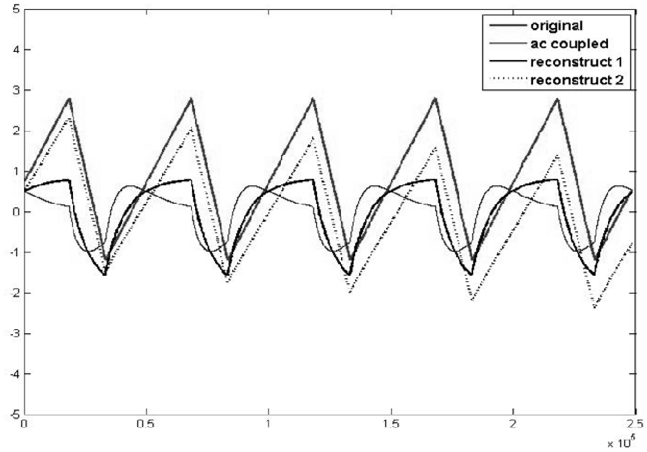


Fig.2. Example of DC corrected operation. The signal, reconstruct 1, represents the output from the first integration, and the signal, reconstruct 2 represents the output from the second integration.

Since the shape and amplitude of the dc-coupling signal are linearly proportional to the shape and amplitude of the volume displacement, it is thus necessary to transform the recorded ac-coupled signal using the transfer function of the ac-coupling circuit to obtain the actual shape of the waveform. The ac-coupling circuit in the pre-amplifier LNA uses an analog 2-pole high-pass filter with a roll-off frequency of 0.03 Hz. Thus the dc-corrected signal can be recovered by integrating the signal twice. Each integral has to take the RC time constant into account. The *RC* was determined from the measured step-response of the LNA and found to be 49.75 ms (the measured roll-off frequency is approximately 0.0201 Hz instead of 0.03 Hz). Fig. 2 shows an example of actual signal, ac-coupled signal, and the dc-corrected signal by transforming the ac-coupled signal using (1) and (2). Notice that baseline of the dc-corrected signal shifts due to the nature of integration. This can be corrected by removing the mean and perform a polynomial fit to the signal.

III. EXPERIMENTAL RESULTS

The experiments were conducted according to CHS#14884 protocol, which was approved by the University of Hawaii IRB. The Doppler radar and DAQ system, illustrated in Fig. 1, used commercially available components. The Doppler radar includes: two 2.4-GHz patch antennas (Antenna Specialists ASPPT2988), one external signal source (Agilent 83640B), two zero-degree power splitters (Mini-Circuits ZFC-2-2500), one ninety-degree power splitters (Narda 4033C), and two mixers (Mini-Circuits ZFM-4212). The baseband output signals are amplified and filtered with low-noise amplifiers (Stanford Research Systems SR560) and then digitized with the onboard ADC of a data acquisition card (National Instruments NI-DAQ PCI-6259). The software to collect and process the data was written in Matlab.

The reference signals were recorded simultaneously using a Biopac system. It completely isolated these signals from the radar system to prevent any cross-talk problems. The respiratory signals captured on the reference system includes: air flow rate via a pneumotach transducer (TSD117), and upper and lower chest respiratory movements via two piezo-electric belts (UFI1132). The output from the radar and the belts were then calibrated to match the pneumotach spirometer.

The respiratory signals are shown in Fig. 3. The output from radar and lower chest belt correspond well with the output from the spirometer. The upper chest belt, however, did not produce a clean and well correlate signal – possibly due to one of the three disadvantages of piezo-sensor mentioned earlier.

Tidal volume represents the volume of the air moved during normal breathing and is calculated from the peak-to-peak amplitude of the volume displacement. Fig. 4 shows the tidal volume corresponding to the volume displacement in Fig. 3. The radar signal is well within ±5% of the spirometer. The statistical analysis in Fig. 5 show that the tidal volume of the radar correlates very well with the tidal volume from the spirometer. The Pearson product-moment correlation coefficient (PMCC) is 0.95378, which is better than of the chest belt reported in [3]. The Bland-Altman analysis shows that the mean different of the two tidal volumes is less than 10 ml; with the standard deviation of the differences of 20 ml. For the guassian distribution, the 95% confidence interval is -32 to 50 ml range. All methods worked well for finding the instantaneous respiration rate as shown in Fig. 6. The experiments performed on 10 human subjects showed similar outcome.

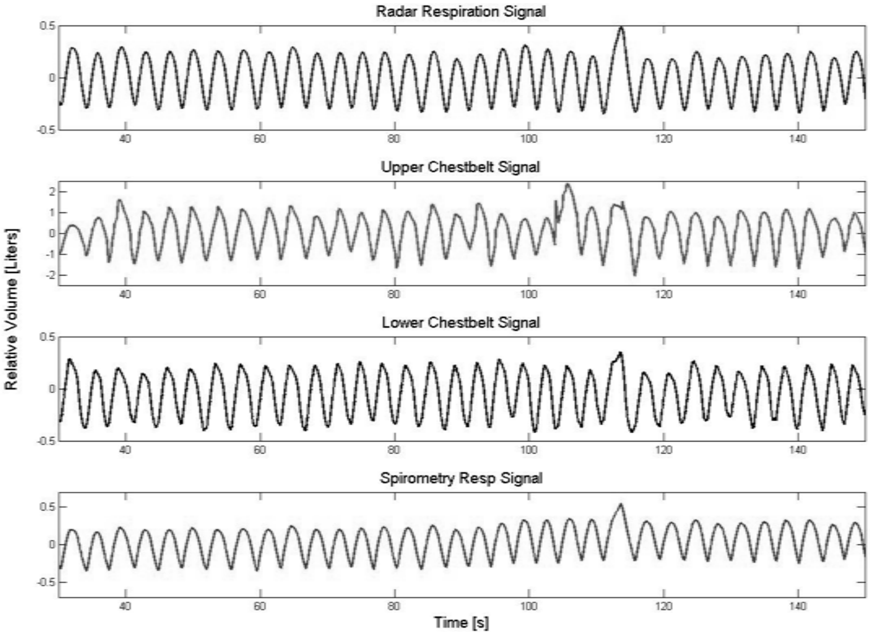


Fig. 3. Relative volume displacement of the radar, upper chest belt, lower chest belt, and spirometer respiration signals.

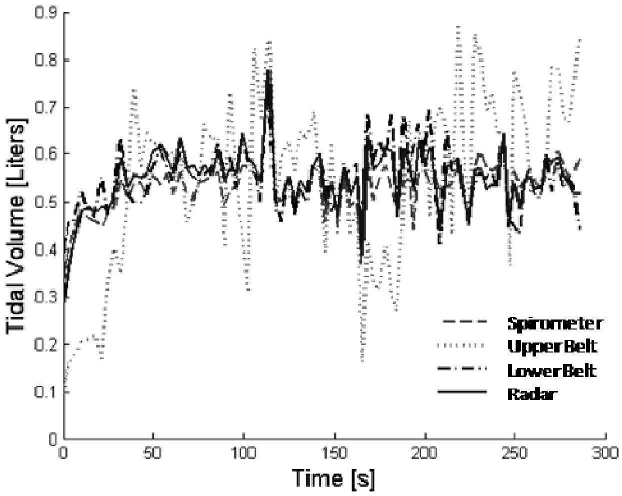
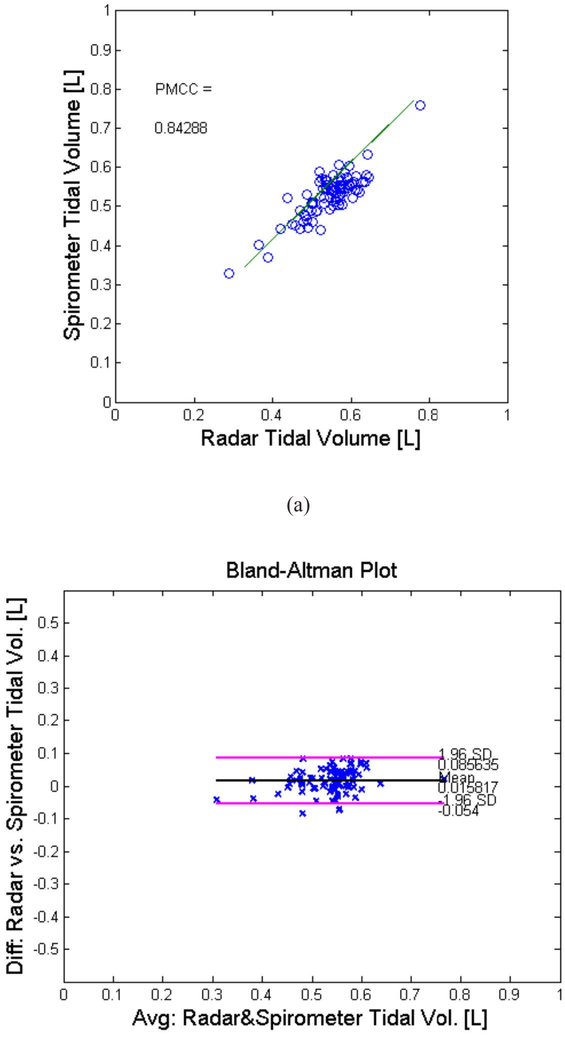


Fig. 4. Tidal volumes of the radar, upper chest belt, lower chest belt, and spirometer respiration signal.



(a)

(b)

Fig. 5. Statistical analysis of the tidal volume: (a) correlation plot, and (b) Bland-Altman analysis

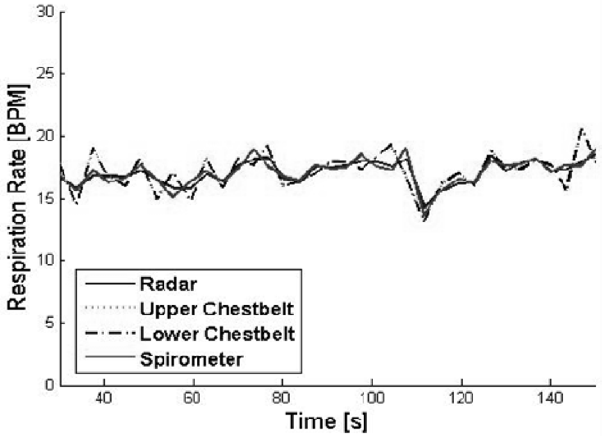


Fig. 6. Instantaneous respiration rates for all methods.

IV. CONCLUSION

The respiratory signal output of Doppler radar system shows linear relation to the volume displacement when compared to conventional airflow and respiratory effort/movement measurements. Calibration of displacement to airflow prior to subject measurements and accurate chest wall position information enable mean differences of less than 10 ml; with standard deviation of the difference of 20ml between radar and reference measurements. Unlike the current practices of respiration rate and lung volume measurements via airflow and measurement of respiratory effort/movement, Doppler radar offers benefit of reliable unobtrusive non-contact measurement.

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