Cardiac and Respiratory Monitoring through Non-Invasive and Contactless Radar Technique

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Abstract

The aim of this study was the evaluation of a microwave (MW) device for vital signs monitoring of patients and for MW signal characterization in terms of physiological content and meaning. Experimental tests were executed on volunteers in selected and controlled conditions and with different device setting. In each test session the MW signal was digitally acquired and saved together with true physiological signals coming from standard medical instrumentation. Single and multichannel data processing were applied in order to extract characteristic features from each signal and to identify any significant correlation. The results show the ability of the method to obtain precise indications on small physiological movements such as breathing or heartbeat; the received MW signal seems to offer specific information about the mechanical dynamics of the cardiac system. With our configuration settings, main limitations of this approach come from its low capacity to penetrate deeply into the body and to the poor spatial resolution.

1. Introduction

The use of microwave signals to detect vital parameters dates back to the '70s; this technique promised to extract information about the movement of a person and even of internal organs of the body in absence of any contact with the instrumentation. The results showed the ability of the method to detect, in particular experimental conditions, the respiratory chest movement and something related to the heart beating [1,2,3]. In this context it is placed the project PRIN-2005 [4] which was aimed to the design and development of a new radar system to be applied in a set of different experimental conditions. The project was established by four workgroups, each one devoted to specific task, from MW instrumental design and implementation to objects modeling and signal processing.

2. Methods

The MW device is based on a continuous wave system at 2.4GHz; the radiating power was limited for safety reason and less than the power of popular wireless home telephone. The transmitter and receiver antennas are chosen of Patch Array type in order to privilege the penetrating capability of the radar waves respect to a better signal/noise ratio. The output signal of the instrument appears as a phasor whose angle and amplitude are related to the distance between the antenna and the moving object.

If we assume the receiving wave coming from a single reflection on the chest surface (orthogonal to the incident wave) and the surface movements small compared to the wavelength, the phase change $\Delta\varphi$ of the received wave phasor results directly related to the position change Δs of the chest surface through the formula:

$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta s$$

where λ is the wavelength of the radar signal.

It is to note that static or moving objects present in the measure field can produce cluttering noise disturbing the real relation between phase and chest surface movements. To attenuate this problem the system is provided with an optional clutter filter able to filter out the MW reflection noise coming from static objects. The MW instrument was developed by the Electronic and Telecommunication Department of the University of Florence [5].

Experimental tests were executed on volunteers in selected and controlled conditions and with different device settings. In each test session the radar signal was digitally acquired and saved together with the true physiological signals coming from standard medical instrumentation, like ECG from an electrocardiograph and respiration from a piezoelectric thoracic belt (Fig.1).

The output radar signal shows the two main physiological components, respiratory and cardiac, with different characteristics: big swing for the respiration, small pulses for the heart cycles. The need to record with sufficient detail both components imposed the use of a controlled gain preamplifier which maximizes the input signal and exploits the maximum dynamics of the DAC.

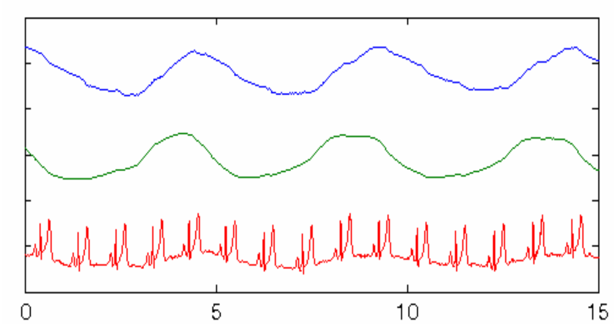

Fig. 1. From top to bottom: phase of radar signal, respiratory signal from piezoelectric sensor and ECG.

In all sessions the experimental protocol requires immobility of the subject in order to limit his body movements which would be translated into significant changes in the baseline of the radar signal. In any case, the digitised MW signal was first processed for de-trending to filter out any change of the baseline.

The next processing step was oriented to normalize the MW signal for its quantitative and morphological characterization, regardless of the input signal amplitude (or gain) between experiments.

From preliminary tests and signal analysis it was clear the difficulty to obtain a good amplitude resolution for the respiratory/cardiac components in presence of artifacts. The instrumentation characteristics, adapting the preamplifier gain to the dynamic of the input signal, privilege large excursions (movement artifacts) respect to the useful information, mainly small cardiac movements. While experimental protocols based on normal breathing allow an easy identification of respiratory cycles and with sufficient precision the cardiac movements, the cardiac shapes characterization was difficult for the low signal to noise ratio.

This condition imposed the division of the research objective according to specific and more appropriate experimental approach. The project objectives were separated:

a) non-invasive and non-contact vital functions (heart rate and breathing) monitoring, that means selectively extraction of respiratory and cardiac components from the radar signal alone.

b) extraction of physiological information, that means search for any characteristic signs on the radar signal associated with specific physiological functions or events.

As already mentioned, these two objectives require specific experimental protocols, like subject test condition, instrumentation setting and signal processing. In this paper the second objective is mainly described, the first one being the object of a previous work to which the readers are referred for details [6].

After informed consent, subjects (4 male, 1 female) were enrolled for experimental testing; they were placed in a seated position in front to the radar antenna at a distance of about 1 meter; they were asked to remain quiet and relaxed.

For each subject a series of recordings was performed: normal breathing (faced and with different angle, left and right), apnea (inspiration and expiration phase). The tests were carried out with simultaneous recording of radar signal, respiratory signal and electrocardiogram (1 lead).

The reflected microwave is modulated both in amplitude and in phase, mainly by the movements of the chest wall. According to the dielectric properties of the body layers, the reflection is not complete and part of the MW radiation is transmitted into the chest and successive reflections occur. In literature some papers [7] assume a complete reflection on the chest wall and relate the phase change of the received radar signal only to chest wall movements due to respiration and heart pulses (apexcardiogram). However, the short distance of the heart muscle from the anterior chest surface and the dielectric characteristics of tissues [8] make possible some wave reflection from internal heart wall [3].

In the following there is a synthetic description of the signal processing procedure applied to the radar signal for the characterization of its respiratory and cardiac components.

Respiratory signal: filtering (0.1-0.5Hz), automatic identification of respiratory cycles, extraction of measures (time occurrence of cycles, cycle durations and amplitudes);

ECG signal: filtering, QRS detection, extraction of measures (RR intervals).

Radar signal: the phase was unwrapped and detrended. Amplitude Fourier spectrum was computed and the respiratory frequency was estimated searching for the spectral peak in the frequency band 0.1-0.5Hz. A weighting function was used to take into account the probability distribution of the respiratory frequency.

The mean cardiac frequency (fcm) was obtained by searching the peak in the band [0.5-3Hz] on a corrected radar spectrum where some spectral values, at respiratory frequency and its harmonics, were attenuated. The respiratory changes are filtered out from the radar signal by applying the Fourier transform, attenuating the components at respiratory frequency and its harmonics and reconstructing the signal by the inverse Fourier transform. The signal was further filtered in the band 0.5*fcm – 2*fcm; The figure 2 shows an example of cardiac events as obtained by this procedure.

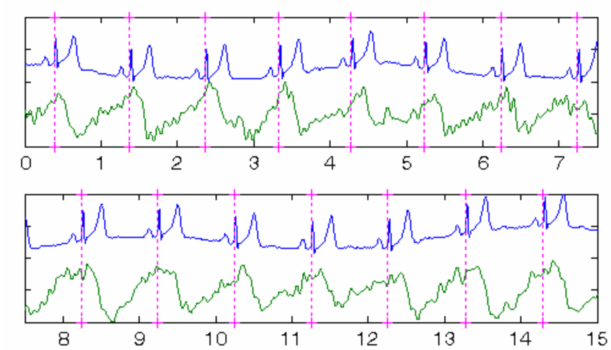

Fig. 2. ECG signal with QRS markers and high pass filtered radar signal.

Finally this signal was averaged synchronously with the QRS complex of the ECG in order to obtain a typical waveform corresponding to the cardiac cycle (Fig. 3).

3. Results

The analysis of these data has shown a great variability among subjects, even if it is recognizable a common morphological structure. This variability between subjects can be attributed to many causes such as different physical constitution, how to breathe, and not least the different size and position of the heart muscle.

In particular, the study of cardiac phenomena was performed with the apnea test, that guarantees a good signal to noise ratio.

Note that the use of these tests does not provoke particular discomfort to the subject, as he is only required to retain its breath for about 10-20 seconds, while maintaining absolute immobility; we believe that this procedure could be easily performed in any laboratory being its complexity similar to other common non-invasive diagnostic tests.

Correlations between events on the radar signal and cardiac phenomena were obtained by isolating each single cardiac event as identified by the ECG waves characteristics that are directly related to the mechanical dynamics of the heart muscle.

Looking at each individual event so identified the radar signal appears quite complex with numerous waves and inflections. This complexity should be naturally associated to the origin of the signal, coming from the contributions of different internal organs movements. In fact the heart muscle is not isolated but linked with muscle and nerve bundles, with veins and arteries to the rest of our body. In addition, the whole movement of the cardiac muscle is not uniform, but different in amplitude according to different contraction of specific heart zones, and of different directions. In its dynamic the axis of the heart changes direction several times following a rough spiral course. Moreover the movements led into peripheral objects "dragged" from the heart in its dynamics should be considered.

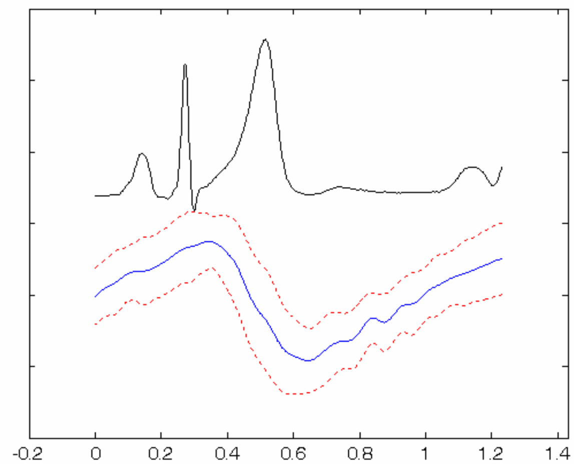

Fig. 3. Normal breathing test: ECG signal (top) and averaged radar signal synchronized on the QRS complex (bottom); the dotted lines represent +/- one standard deviation.

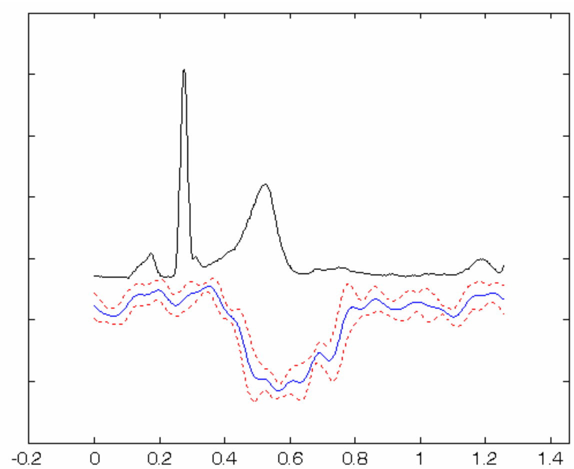

Fig. 4. Apnea test: ECG signal (top) and averaged radar signal synchronized on the QRS complex (bottom).

These considerations help to understand that a global movement signal, like radar signal as viewed by the antenna angle, suffers of countless variations and how different perspectives of this phenomenon could produce drastic changes in the results.

Besides these difficulties, the heart-related radar signal was analysed taking as reference the ECG cardiac electrical events and the knowledge of the associated mechanical phenomena.

In Figure 4, the ECG signal is represented with the QRS-synchronized average (+/- standard deviation, dashed line) of the radar signal recorded from a patient in apnea; the beginning of the cardiac cycle, that is the start of the electrical impulse at the sinus node, is visible as P wave on the ECG trace. In the time period preceding the P wave, the blood is free to flow through the mitral valve and to fill the left ventricle. On the radar trace it is visible an oscillation with a clear increasing trend, which would indicate a slow but continuous movement of the heart walls as the blood fills the ventricle. This increase continues even after that the electrical pulse (P wave) has activated the atrial contraction, probably counterbalanced by the continuous increase in volume of the left ventricle. As soon as the electrical impulse reaches the ventricles (QRS complex on ECG), the heart muscles contract causing a rapid reduction of volume and then an equally fast cardiac wall moving. At the end of the T wave, the closure of the semilunar valves occurs, between the left ventricle and aorta artery and between the right ventricle and pulmonary artery. On the radar trace appears a wave rising immediately after the end of the T wave, which seems to be associated with the movements of the two valves. Next, the radar signal follows a slightly oscillating trend growing up to the next P wave.

4. Discussion and conclusions

The radar pattern description retraces the traditional sequence of the cardiac cycle events, as evident on the electrocardiogram trace. It should be noted that in this new description in terms of "movement", we noticed some remarks not present in the ECG trace and with a possible physiological explanation; this means that the radar signal contains more information, or rather a different kind of information, compared to the ECG signal.

The knowledge of the dynamics of the heart muscle and its immediate periphery is essential to fully understand the significance of the morphology of the radar signal and its variations. Our tests, besides limited, revealed that the radar signal morphology is highly variable depending on the subject and experimental conditions. For example, it may happen that where it is present an increase in amplitude, in another case it is found a reduction; this is most likely due to "visibility" of certain movements compared to others. Note that the radar signal is a sort of average of all radial movements collected from the receiving antenna.

Finally, it should be pointed out that, beyond the variability of the signal, it was found a surprising consistency in the time.

Recordings made on the same person at different times showed radar traces with different morphology but with a timeline of events virtually constant, the single event could appear as a peak or as an inflection, but always at the same time.

This could be an indication of the importance of the information extracted and encourages the continuation of research to give effective meaning to the signs proved and to offer a complementary contribution to the traditional non-invasive diagnostic investigation.

Acknowledgements

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