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Remote heartbeat monitoring from human soles using 60-GHz ultra-wideband radar

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Abstract: Measurement of heartbeats is essential in cardiovascular magnetic resonance imaging because the measurement must be synchronized with the phase of cardiac cycles. Many existing studies on radar-based heartbeat monitoring have focused on echoes from the torso only, and such monitoring cannot be applied to subjects in magnetic resonance scanners because only the head and soles can be seen from the outside. In this study, we demonstrate the feasibility of the remote monitoring of heartbeats from the subject's soles using a 60-GHz ultra-wideband radar. The heartbeat intervals measured using the radar are quantitatively compared with those measured using conventional electrocardiography.

Keywords: heartbeat, radar, ultra-wideband, magnetic resonance imaging, soles

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

In cardiovascular magnetic resonance (CMR) imaging, image acquisition must be synchronized with heart motion [1] because CMR images become blurred during the cardiac cycle without compensation for the artefacts of heart motion [2]. Most existing technologies of CMR employ an electrocardiogram (ECG), which is a recording of electrical heart activity measured using electrodes attached to the person.

Recent studies on magnetic resonance (MR) scanners have made many efforts to increase the magnetic field strength $|\boldsymbol{B}|$ of MR scanners from a clinical 1.5 or 3 T up to 7 T or even 9.4 T. The increasing field strength makes it difficult to analyze the ECG recorded by MR scanners because a magnetohydrodynamic electrical field $\boldsymbol{E}_\mathrm{M} = \boldsymbol{v} \times \boldsymbol{B}$ is generated by the flow of blood (velocity $\boldsymbol{v}$) and severely interferes with the ECG signal [3]. Various approaches, such as the use of fiber optics [4], Doppler ultrasound, finger plethysmography, and phonocardiograms have been proposed to avoid this problem [2].

Recently, much attention has been paid to the remote monitoring of heartbeats using radar systems [5]-[23] that measure the slight displacement of a patient's skin surface due to heartbeats. However, patients in an MR scanner are surrounded by the interior wall of the scanner, with only the top of their head and soles seen from the outside. In this study, we demonstrate the possibility of the remote measurement of heartbeats from soles using an ultra-wideband radar system. Most existing studies of the remote monitoring of heartbeats use echoes from the torso [5]-[18], whereas there have been no reports on remote monitoring of heartbeats from the soles.

Li et al. [19] and Vinci et al. [20] reported that the back side of a seated subject's torso was the best spot for the heartbeat measurement among four sides (i.e., front, back, left and right). They explained that this was due to a frequency component called the harmonics in the spectrum, which was neither the respiration nor heartbeat component. In contrast, Wang et al. [21] measured heartbeats from the four sides of a seated subject's torso and concluded that the frontal chest wall was better than the back side, which is inconsistent with the studies of [19] and [20]. The different conclusions were explained by Wang et al. as being due to the different operating frequencies (15 GHz [21] versus 27 GHz [19]) and the direct current (DC) suppression algorithm proposed by [21], which suppressed the harmonic components generated by incorrect DC levels. Suzuki et al. [22] measured subjects in supine or prone position on a mattress with antennas placed under the mattress, and reported that the measurements were more accurate for the prone position than for the supine position, indicating that measurement of the frontal chest wall was better. They suggested the reason that the heart was located physically close to the frontal side of the torso.

As seen from the results of the above studies, even heartbeat measurements of the torso have basic unsolved questions, whereas there are few studies on the heartbeat monitoring of other parts of the body such as limbs. Nagae et al. [23] measured echoes from a thigh for heartbeat measurement, and estimated instantaneous heart rates. To improve the heart rate accuracy, the authors of the present study developed an algorithm that uses the topological features of radar signals [17], and the algorithm was successfully applied to measurements using an ultra-wideband radar system operating at a frequency of 26.4 GHz [18], where we measured echoes from the frontal chest wall only. Because the displacement of soles due to heartbeats is expected to be smaller than the displacement of the chest, a more sensitive radar system is required. In this study, therefore, we develop and use a 60

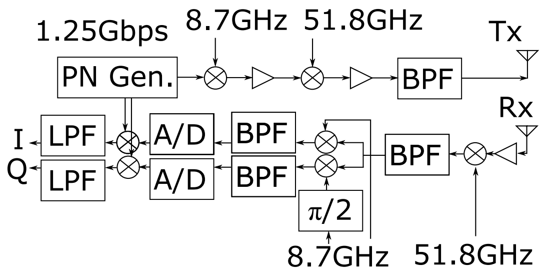

Fig. 1. Block diagram of the 60–GHz radar system used in the measurements.

GHz ultra-wideband radar, which has higher sensitivity to a displacement than the previous radar, making it easier to detect the slight displacement of targets.

2 Sixty-gigahertz Ultra-wideband Radar System

To detect a slight displacement of soles induced by heartbeats, we use an ultra-wideband radar system with an operating frequency of 60.5 GHz. A block diagram of the system is presented in Fig. 1. The radar system generates binary pseudo noise (PN), more specifically an m-sequence, with a bit rate of 1.25 Gbps for modulation of the intermediate frequency (IF) signal (8.7 GHz), which is subsequently upconverted to 60.5 GHz by multiplying by a 51.8-GHz local oscillator frequency (LOF) signal, and fed to the transmitting antenna. The received signal is down-converted by multiplying by the same LOF signal, and is then sent to a quadrature demodulator for multiplying by the IF signal. The resultant baseband signals are A/D converted to digital sequences. The in-phase (I) and quadrature (Q) digital signals are pulse compressed by multiplying by the PN sequence. The pulse-compressed I/Q data are stored in memory.

The antennas have wide beam patterns with a 96.5-degree beamwidth, which is wide enough to cover the whole subject's body. The transmitting power is less than 20 mW, and the range scan interval is 457.0 μs. The range resolution is 12.0 cm, which is high enough to separate soles from other parts of the body and clutter. The received signals are processed according to the topology [17] to obtain the heart interbeat intervals. The wavelength corresponding to the frequency 60.5 GHz is 4.96 mm, for which a displacement of 10 μm is converted to a phase shift of 1.5 degrees in the received signal. Because the typical displacement of the chest wall due to heartbeats is between 100 and 500 μm, our 60-GHz radar system can detect even smaller displacements if the local oscillator phase is stable.

3 Measurement Data and Heartbeat Detection

Figure 2 shows the measurement setup with the 60-GHz radar system and a subject in the supine position on a Styrofoam board. The transmitting and receiving antennas were pointed toward the soles, and placed 60.0 cm apart from the surface of the soles. We recorded ECG data using an RF-ECG EK

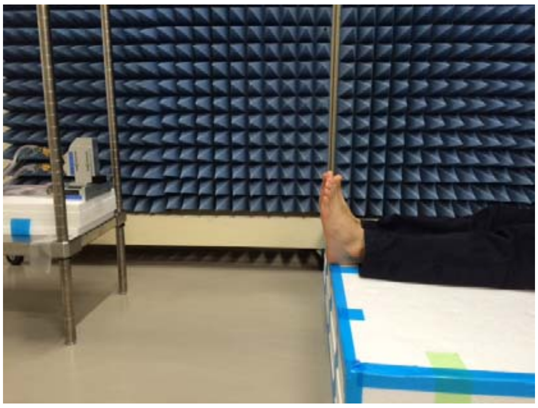

Fig. 2. Measurement setup using 60-GHz radar with a subject in the supine position on a Styrofoam board.

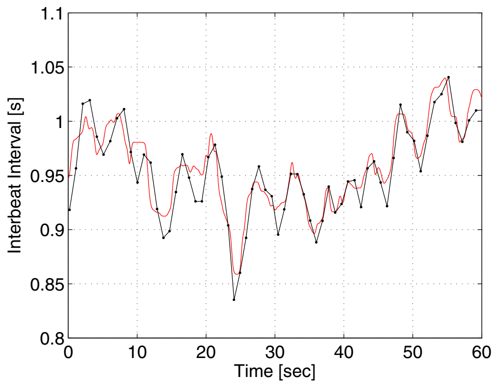

Fig. 3. Time sequences of estimated heartbeat intervals derived from an ECG (black) and radar (red).

device (Micro Medical Device, Inc., Tokyo, Japan) while recording the radar signal. The measurement was performed for 60.0 s, while the subject was breathing normally.

Figure 3 shows the heartbeat intervals estimated from radar and ECG data. In the figure, the black and red lines represent the estimates made with the ECG and radar, respectively. The root-mean-square error was 14.0 ms. Figure 4 is a scatter diagram of the interbeat intervals measured using the radar and ECG. The correlation coefficient was 0.93. The remote measurement of heartbeats from human soles using our 60-GHz radar was thus successfully demonstrated and is a promising technology that overcomes the difficulty of monitoring the heartbeat of a patient in an MR scanner.

Because CMR scanners require trigger signals synchronized with the heartbeat, the processing time of the heartbeat monitoring needs to be short enough for trigger signals to be generated in real time. As explained in [17], the proposed algorithm uses only a few feature points extracted from the signal, instead of the entire signal waveform. Thus, the processing of the proposed algorithm is faster than that of conventional methods based on the fast Fourier transform. In this regard, the proposed approach is considered

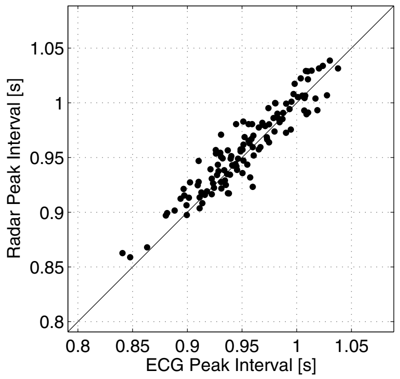

Fig. 4. Scatter diagram of heartbeat intervals estimated from radar and an ECG.

to be suitable for CMR applications. The evaluation of the actual processing time, which depends on the hardware and implementation, will be an important topic of future study.

4 Conclusion

We measured echoes from a subject's soles using 60 GHz ultra-wideband radar system. We recorded ECG data to monitor the electrical heart activity at the same time. We applied a topology algorithm to the radar data and estimated the heart interbeat interval. The accuracy was evaluated by comparing with the ECG estimate. The results suggest the possibility of using the 60-GHz ultra-wideband radar to monitor the heartbeat of a patient in an MR scanner, which is an essential technology in CMR imaging.

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