

# Measurement of instantaneous heart rate using radar echoes from the human head

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In this study, we demonstrated the feasibility of measuring heart rate using radar echoes from a human head. Noncontact measurement of vital signs using radar has been attracting much attention because such technologies can breakthrough benefits for monitoring health conditions without electrodes or wearable devices. Most existing studies have measured echoes from the torso, particularly the chest wall. However, this is difficult because of multiple interfering reflections from the complex shape of the torso and other body parts, such as limbs. The current study is the first demonstration that noncontact heart rate measurement can be easily achieved using echoes from the human head. There are two important advantages of measurement from the human head; 1) the simple shape of the head makes an ideal radar target with only a single reflection, and 2) the other undesired echoes can be removed using time-gating when an ultra-wideband radar is used. Nonetheless, because the displacement of the human head due to heart rate is small, we developed a millimetre-wave ultra-wideband array radar system, which is installed on the ceiling and used in our measurements with participants.

*Introduction:* Noncontact measurement of vital signs is receiving increasing research interest because it allows for the remote monitoring of the physical and mental state of a person. Numerous studies using radar-based noncontact heart rate monitoring have been reported [1-6]. Most of these studies have used echoes from the human torso, particularly the chest wall. However, few studies have used echoes from other body parts. For example, echoes from the four sides of the torso were used and compared in many previous studies [4-6], while only a small number of studies have used echoes from other body parts such as the thighs [7] and soles [8].

In the field of image processing, one study [9] demonstrated the detection of the heartbeat from a video using the motion of the head, by identifying the motion of feature points in video frames. This method exploits head motion due to blood flow through the carotid arteries. Thus, it can be inferred that the same head motion could also be used in radar-based heart rate measurement. However, to the best of our knowledge, no previous studies have reported the use of radar echoes from the head for measuring heartbeats. To detect a small displacement of the head due to heartbeats, we developed a dedicated 79-GHz multiple-input multiple-output (MIMO) radar to detect slight target motion. We examined ten participants using a radar installed on the ceiling, and demonstrated accurate noncontact measurement of heart rate using radar echoes from the top of the head.

*Radar and measurement setup:* We developed a 79-GHz ultra-wideband MIMO radar system with four transmitting antennas, and four receiving antennas, resulting in 16 ( $= 4 \times 4$ ) channels. The radar comprises two phase-modulated continuous wave (PMCW) radar chips developed by Imec (Heverlee, Belgium) [10]. Each chip realizes a fully integrated  $2 \times 2$  multiple-input multiple-output (MIMO) system using the binary PMCW with a bit rate of 2 Gbps resulting in a range resolution of 7.5 cm. The transmitted signals were modulated using an m-sequence for pulse compression, and Hadamard orthogonal codes for simultaneous multiple transmission from the two chips. We integrated the two chips with a digital control and interface circuit on the same radio frequency (RF) circuit board, producing a  $4 \times 4$  MIMO radar. The antenna spacing was 4.6 mm ( $0.92\lambda$ ), where  $\lambda$  is a wavelength of 3.8 mm. Figure 1 shows the radar system, where four transmitting and four receiving elements are seen. The slow- and fast-time sampling frequencies were 4.2 kHz and 2.0 GHz, respectively.

We measured radar echoes from ten participants. Each participant was instructed to remain seated on a chair and keep breathing normally. Figure 2 shows the measurement setup with the radar module installed on the ceiling. The radar module was located 2.3 m from the floor, and approximately 1.2 m from the top of the head of the participant during testing. To obtain electrocardiogram (ECG) data as a reference, we used

an ECG device (ECG15102017, PLUX wireless biosignals S.A., Arruda dos Vinhos, Portugal) attached to each participant.



Fig. 1 79-GHz MIMO radar module developed and used in this study.



Fig. 2 Measurement setup with a radar module and a seated participant.

*Signal processing:* For measuring small head movements, it is necessary to implement an effective clutter rejection algorithm because the received signals are contaminated by undesired echoes from stationary objects. In the current study, we adopted Hu's method [11], which is considered the most accurate method, especially when the target displacement is small [12, 13]. Although Hu's method only works when there is a single dominant echo, this condition was always satisfied in this study because there was only a single echo from the head in the near range bin, whereas echoes from other body parts were found in the other range bins. In addition, the top of the human head typically has a round shape, which ideally has a single reflection point, avoiding the interference from multiple echoes. We selected the range bin containing the dominant echo, and suppressed clutter components contained in other range bins.

Next, the 16-ch signals  $\mathbf{s}(t) = [s_1(t) s_2(t) \dots s_N(t)]^T$  are adaptively combined so that a beam is formed in the direction-of-arrival (DOA) of the dominant echo, which came mainly from the head in this study, where  $N = 16$  the number of channels, and superscript T denotes the matrix transpose. We adopted a calibration-free technique based on the maximum eigenvalue [14]. The method calculates the correlation matrix of signals as  $R_{ss} = E[\mathbf{s}(t)\mathbf{s}(t)^H]$ , where E denotes expectation, and H denotes the complex-conjugate transpose. The eigenvalue decomposition is applied to the correlation matrix as:

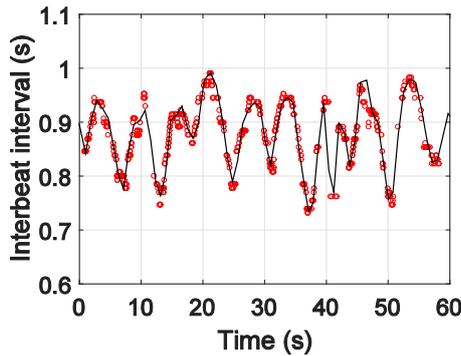
$$R_{ss} = [\mathbf{v}_1 \ \dots \ \mathbf{v}_N] \text{diag}(\sigma_1 \ \dots \ \sigma_N) \begin{bmatrix} \mathbf{v}_1^H \\ \vdots \\ \mathbf{v}_N^H \end{bmatrix} \quad (2)$$

where eigenvalues  $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq \dots \geq \sigma_N$  are sorted in descending order. We used eigenvector  $\mathbf{v}_1$  corresponding to the maximum eigenvalue  $\sigma_1$  as  $y(t) = \mathbf{v}_1^H \mathbf{s}(t)$ , and obtained the output signal  $y(t)$ . Although this method based on the maximum eigenvalue does not perform well when there are multiple interfering echoes, because the signals in our measurement contained only a single head echo, the issue could be avoided. The topology algorithm [15] is applied to the phase of the output signal  $\angle y(t)$  and the heart interbeat interval is estimated.

*Performance evaluation:* We applied the signal processing techniques to the received data from a participant. Using the topology algorithm [16], we obtained the interbeat interval, as shown in Fig. 3. In this figure, the estimation from our radar is shown as red circles, whereas the estimation from the reference ECG is shown as a black line. It should be noted that the heart rate measured using ECG was not constant; it changed quasi-periodically over time, and a similar time-dependent pattern was also obtained using our radar system.

We performed the measurement with ten participants to evaluate the accuracy in estimating the heart rate from our radar system. Table 1 shows the acquisition rate (AR) and root-mean-square error (RMSE) for each of the participants. The AR is the percentage of accurate estimates with an estimation error less than 5%, and the RMSE was calculated only from the data with an error less than 10%. We introduced these conditions to exclude outliers. The average AR and RMSE were 83.7% and 16.3 ms. These results demonstrate the effectiveness of our radar system for the measurement of heart rate using the echo from the head. Please note that the AR and RMSE for participant #2 are worse than those for other participants. We noticed a large and irregular respiration component in the echo from participant #2, which can be the reason for the poor performance.

*Conclusion:* In this study, we demonstrated the feasibility of the measurement of the heart rate from radar echoes from the top of the human head. We developed a millimetre-wave ultra-wideband MIMO radar system, which was found to be able to measure the interbeat interval of participants seated below the radar module. The proposed system achieved estimation of the heart rate with an average AR of 83.7% and RMSE of 16.3 ms.



**Fig. 3** Interbeat interval estimated from radar echo from the head (red circles) and reference measured using ECG (black line).

**Table 1:** The RMS error for estimating the heart rate of participants.

Participant #	Age	Sex	BMI	AR (%)	RMSE (ms)
1	63	M	22.3	85.9	15.2
2	54	F	19.5	33.2	26.0
3	33	F	25.3	86.9	15.6
4	25	M	20.7	89.3	14.4
5	24	M	19.0	90.9	14.6
6	26	M	24.2	95.2	14.3
7	25	M	25.4	93.6	15.9
8	23	M	22.2	96.1	16.3
9	24	M	20.3	72.7	16.5
10	27	M	21.7	93.1	14.0

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