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

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The feasibility of measuring heart rate using radar echoes from a human head is demonstrated. Non-contact 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 non-contact heart rate measurement can be easily achieved using echoes from the human head. There are two important advantages of measurement from the human head: (i) the simple shape of the head makes an ideal radar target with only a single reflection, and (ii) 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, a millimetre-wave ultra-wideband array radar system is developed, which is installed on the ceiling and used in the proposed measurements with participants.

Introduction: Non-contact 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 non-contact 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 non-contact 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 ($=4\times4$) channels. The radar comprises two phase-modulated continuous wave (PMCW) radar chips developed by Imec (Heverlee, Belgium) [10]. Each chip realises a fully integrated 2×2 MIMO system using the binary PMCW with a bit rate of 2 Gbit/s 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 circuit board, producing a 4×4 MIMO radar. The antenna spacing was 4.6 mm (0.92 λ), where λ is a wavelength of 3.8 mm. Fig. 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. Fig. 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 ~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*

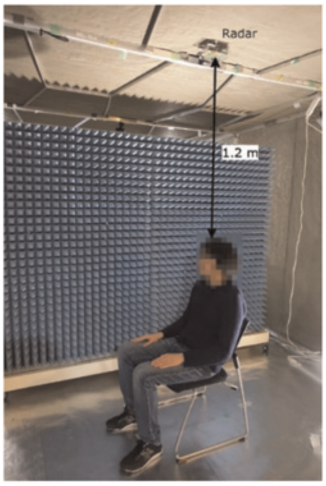

Fig. 2 *Measurement setup with a radar module and a seated participant*

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 $\boldsymbol{s}(t)=[s_1(t)\ s_2(t)\cdots s_N(t)]^{\mathrm{T}}$ are adaptively combined so that a beam is formed in the direction-of-arrival of the dominant echo, which came mainly from the head in this study, where $N=16$ is 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 $R_{ss}=\mathrm{E}\left[\boldsymbol{s}(t)\boldsymbol{s}(t)^{\mathrm{H}}\right]$, where E denotes expectation, and H denotes the complex-conjugate transpose. The eigenvalue decomposition is applied to the correlation matrix as

$$R_{ss}=\begin{bmatrix}\boldsymbol{v}_1 & \cdots & \boldsymbol{v}_N\end{bmatrix}\mathrm{diag}(\sigma_1\cdots\sigma_N)\begin{bmatrix}\boldsymbol{v}_1^{\mathrm{H}}\\ \vdots \\ \boldsymbol{v}_N^{\mathrm{H}}\end{bmatrix} \tag{1}$$

where eigenvalues $\sigma_1\geq\sigma_2\geq\sigma_3\geq\cdots\geq\sigma_N$ are sorted in descending order. We used eigenvector $\boldsymbol{v}_1$ corresponding to the maximum eigenvalue σ_1 as $y(t)=\boldsymbol{v}_1^{\mathrm{H}}\boldsymbol{s}(t)$, 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 [15], 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.

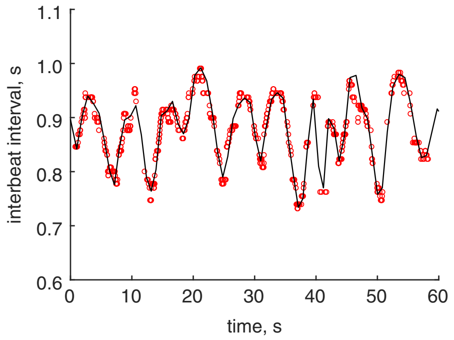

Fig. 3 *Interbeat interval estimated from radar echo from the head (red circles) and reference measured using ECG (black line)*

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 <5%, and the RMSE was calculated only from the data with an error <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.

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

Participant no.	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

Conclusion: In this Letter, 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.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Li, C., Lubecke, V.M., Boric-Lubecke, O., *et al.*: 'A review on recent advances in Doppler radar sensors for noncontact healthcare monitoring', *Trans. Microw. Theory Tech.*, 2013, **61**, (5), pp. 2046–2060
2 Mikhelson, I.V., Lee, P., Bakhtiari, S., *et al.*: 'Noncontact millimetre-wave real-time detection and tracking of heart rate on an ambulatory subject', *Trans. Inf. Technol. Biomed.*, 2012, **16**, (5), pp. 927–934
3 Kranjec, J., Begus, S., Drnovsek, J., *et al.*: 'Novel methods for noncontact heart rate measurement: a feasibility study', *Trans. Instrum. Meas.*, 2014, **63**, (4), pp. 838–847
4 Li, C., Xiao, Y., and Lin, J.: 'Experiment and spectral analysis of a low-power Ka-band heartbeat detector measuring from four sides of a human body', *Trans. Microw. Theory Tech.*, 2006, **54**, (12), pp. 4464–4471, doi:10.1109/TMTT.2006.884652
5 Vinci, G., Lindner, S., Barbon, F., *et al.*: 'Six-port radar sensor for remote respiration rate and heartbeat vital-sign monitoring', *Trans. Microw. Theory Tech.*, 2013, **61**, (5), pp. 2093–2100, doi:10.1109/TMTT.2013.2247055
6 Wang, J., Wang, X., Zhu, Z., *et al.*: '1-D microwave imaging of human cardiac motion: an ab-initio investigation', *Trans. Microw. Theory Tech.*, 2013, **61**, (5), pp. 2101–2107, doi:10.1109/TMTT.2013.2252186
7 Nagae, D., and Mase, A.: 'Measurement of heart rate variability and stress evaluation by using microwave reflectometric vital signal sensing', *Rev. Sci. Instrum.*, 2010, **81**, p. 094301
8 Sakamoto, T., Okumura, S., Imanishi, R., *et al.*: 'Remote heartbeat monitoring from human soles using 60-GHz ultra-wideband radar', *IEICE Electron. Express*, 2015, **12**, (21), p. 201507876
9 Balakrishnan, G., Durand, F., and Guttag, J.: 'Detecting pulse from head motions in video'. Proc. 2013 IEEE Conf. on Computer Vision and Pattern Recognition, Portland, OR, USA, June 2013, doi:10.1109/CVPR.2013.440
10 Guermandi, D., Shi, Q., Dewilde, A., *et al.*: 'A 79 GHz 2 × 2 MIMO PMCW radar SoC in 28 nm CMOS'. Proc. IEEE Asian Solid-State Circuits Conf., Toyama, Japan, November 2016, pp. 105–108, doi: 10.1109/ASSCC.2016.7844146
11 Hu, W., Zhao, Z., Wang, Y., *et al.*: 'Noncontact accurate measurement of cardiopulmonary activity using a compact quadrature Doppler radar sensor', *Trans. Biomed. Eng.*, 2014, **61**, (3), pp. 725–735, doi: 10.1109/TBME.2013.2288319
12 Okumura, S., Sakamoto, T., Sato, T., *et al.*: 'Comparison of clutter rejection techniques for measurement of small displacements of body surface using radar', *Electron. Lett.*, 2016, **52**, (19), pp. 1635–1637, doi 10.1049/el.2016.1461
13 Zakrzewski, M., Raittinen, H., and Vanhala, J.: 'Comparison of center estimation algorithms for heart and respiration monitoring with microwave Doppler radar', *Sens. J.*, 2012, **12**, (3), pp. 627–634, doi:10.1109/JSEN.2011.2119299
14 Takatori, Y., Cho, K., Nishimori, K., *et al.*: 'Adaptive array employing eigenvector beam of maximum eigenvalue and fractionally-spaced TDL with real tap', *IEICE Trans. Commun.*, 2000, **E83-B**, (8), pp. 1678–1687
15 Sakamoto, T., Imasaka, R., Taki, H., *et al.*: 'Feature-based correlation and topological similarity for interbeat interval estimation using ultra-wideband radar', *Trans. Bio-med. Eng.*, 2016, **63**, (4), pp. 747–757