Cross-Body UWB Radar Sensing of Arterial Pulse Propagation and Ventricular Dynamics

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***Abstract*—Single-chip UWB radar systems have enormous potential for the development of portable, low-cost and easy-to-use devices for monitoring the cardiovascular system. Using body coupled antennas, electromagnetic energy can be directed into the body to measure arterial pulsation and cardiac motion, and estimate arterial stiffness as well as blood pressure. In the current study we validate that heart rate signals, obtained using multiple UWB radar-on-chip modules and body coupled antennas, do indeed originate from arterial pulsation. Through ECG-aligned averaging, pulse arrival time at a number of locations in the body could be measured with high precision, and arterial pulse propagation through the femoral and carotid artery was demonstrated. In addition, cardiac dynamics were measured from the chest. Onset and offset of ventricular systole were clearly distinguishable, as well as onset of atrial systole. Although further validation is required, these results show that UWB radar-on-chip is highly suitable for monitoring of vascular health as well as the heart's mechanical functioning.**

I. Introduction

In recent years a substantial body of experimental work has been done to apply microwave and radar technologies in the field of medical imaging and biosensing. Properties of the microwave frequency band are promising: The non-ionizing radiation is harmless at moderate power levels, but penetrates biological tissue reasonably well. With an increased focus on long-term, mobile, and even home-based monitoring for early detection of diseases, radar-based biosensing applications become particularly interesting due to the potentially low cost and small size of the required hardware. Besides non-contact applications such as heart rate (HR) tracking, sleep monitoring and fall detection for the elderly, in-body radar sensing to study the cardiovascular system has been explored. With cardiovascular disease being the number one cause of death globally, the search for early biomarkers of disease and affordable diagnostic tools is ongoing.

In the past, radar-based cardiovascular sensing research has focused mostly on continuous wave (CW) Doppler radar sensing techniques. Good accuracy has been reported on pulse wave velocity (PWV) measurements using a portable ultra-wideband (UWB) Doppler radar device that measured arterial pulsation from the foot and upper arm, for estimation of arterial stiffness [1]. CW Doppler radar has been proposed for blood pressure estimation from carotid pulse arrival time (PAT) [2] and cardiac motion could successfully be monitored using a CW radar embedded in a patient table, for heart-cycle synchronized CT scanning [3]. All of the aforementioned studies used radar sensing technology with no possibility of collecting spatial information. For imaging applications however, range information is required. Radar imaging is usually performed using UWB radar, achieved through the use of bulky vector network analyzers (VNA). By combining a VNA with a switched antenna array, very crude 2D cardiac imaging has been achieved [4]. The recent innovation of a CMOS implementation of an impulse radio (IR) UWB radar [5], provides the opportunity of in-body radar imaging with extremely small and low-cost electronics. As opposed to CW Doppler radar, IR-UWB radar allows for sensing at a range of different depths in the body and thus for localization of scattering sources in space. When multiple sensors are combined, 2D or 3D imaging through beamforming can be performed. Finally it permits time gating of unwanted signals.

IR-UWB radar-on-chip systems in combination with body-coupled antennas have previously been used to demonstrate intracranial HR detection [6] and heart wall velocity sensing [7]. In the current work we expand on this by studying arterial pulse propagation and ventricular dynamics using UWB radar. In particular, we address the concern that measured HR is in fact modulation of leakage RF signal propagating through air, by chest displacement. This concern has arisen from frequent observations in our lab of respiration signals and nearby movement in in-body measurements. It is well known that the heart beat causes a sub-millimetre chest displacement, and despite efforts to improve the antenna's front-to-back ratio and shield them from leakage, determining the exact source of a HR signal has proved to be difficult. In this paper we validate the source of UWB radar measured HR signals. In addition, propagation of the blood pulse through arteries is demonstrated, as well as precise PAT measurements. Finally, it is shown that ventricular volume and heart motion can be imaged using radar.

II. Methods

To validate that HR modulation found in UWB radar measurements originate from a pulsating subcutaneous structure (in most cases: an artery), and is not in fact a leakage signal being modulated by chest displacement, radar signals must be analyzed in the time domain. Whereas the chest motion signal, will have its waveform onset coincide exactly with ventricular contraction (QRS complex), the arterial signal is expected to be delayed in time by: 1) the cardiac pre-ejection period, and 2) the pulse transit time through blood vessels. With this in mind, an attempt was made to measure HR at various positions in the body, in conjunction with electrocardiography (ECG). Due to different artery lengths, a difference in PAT is expected. Radar signals were collected from:

- Carotid artery (left side of neck)

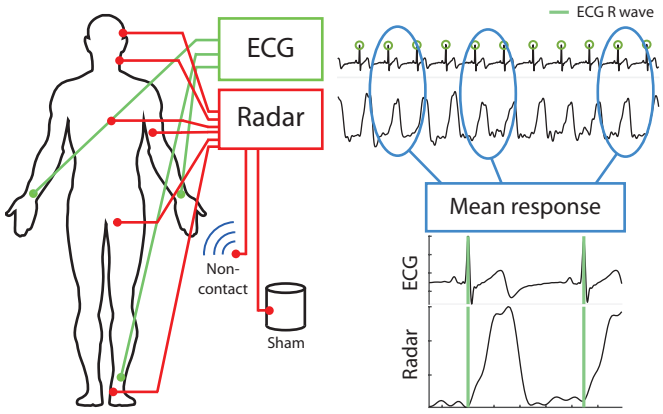

Fig. 1. Schematic of experimental setup illustrating the radar and ECG measurement positions, two off-body control measurements and an example of processed data from ECG and radars. The blue rings indicate heart beat data clustering, resulting in a mean radar response to the cardiac cycle.

- Brachial artery (medial left upper arm)
- Femoral artery (medial left thigh)
- Posterior tibial artery (medial left foot)
- Intracranial arteries (left temple)
- Heart (sternum)

To further validate the source of HR modulation, two off-body recordings were performed:

- Non-contact measurement of the chest (50 cm range)
- Sham recording on a phantom object with dielectrics resembling mean characteristics of the human body

As the RF propagation time through air is negligible compared to the blood pressure wave propagation through arteries, the non-contact measurement is expected to show a clear timing difference with local contact measurements. The sham recording is designed to illustrate the problem with chest modulation of leakage signal, as it closely resembles the brachial artery measurement, without the pulsating artery.

A. Experimental setup

The experimental setup is illustrated in Fig. 1, showing the different on-body radar measurement locations, two off-body control measurements and ECG. The radar measurements were carried out using the Ventricorder radar module, consisting of the Novelda X2 single-chip radar with additional amplifiers in both transmit and receive paths for increased sensitivity. The radar transmits a Gaussian modulated sinusoid with a -10 dB bandwidth of 2.5 GHz. The receiver achieves an effective sample rate of approximately 39 GHz through the use of swept threshold sampling and delay lines [5]. The radar outputs frames of 256 depth samples with a rate of 64 frames per second. Antennas designed specifically for into-body applications were used in the experiment. The body coupled wideband monopole antennas cover the frequency band of the radar module and achieve increased coupling into tissues through the use of a low-loss dielectric spacer with permittivity matching the skin [8]. During the experiment the antennas were pressed onto the skin and held in place using a 3D printed structure and elastic band. The non-contact control measurement used conventional antennas.

All the measurements were performed on a single subject in an RF anechoic chamber to reduce possible multi-path propagation. The subject was asked not to breathe during the recording to minimize artifacts in the processed data caused by chest movement. Data was collected for a duration of 60 s, with three individual recordings for each of the measurement positions.

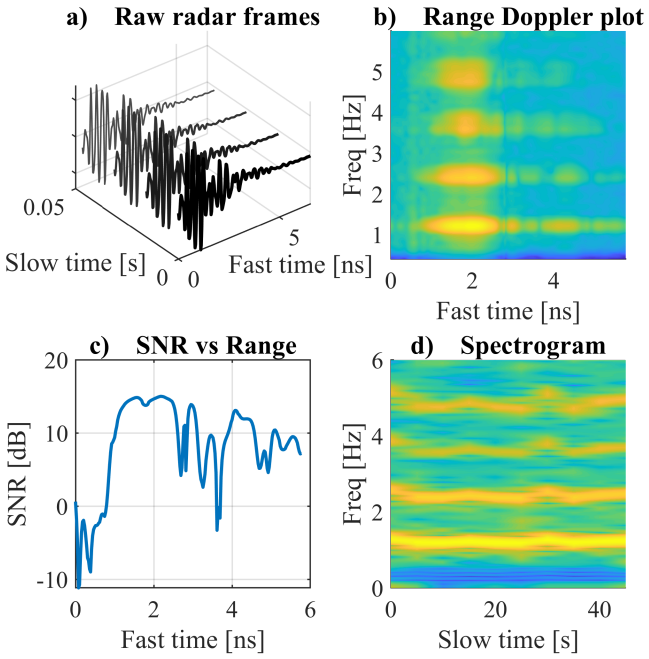

Fig. 2. Illustration of radar data analysis steps: Raw radar frames (a), Range Doppler plot showing spectral content at different fast time samplers (b), SNR of HR signal at fast time samplers (c) and spectrogram at peak SNR (d).

B. Data analysis

The data analysis methods chosen for the current study serve two purposes: (i) detecting and estimating HR, and (ii) identifying time-domain characteristics of the arterial pulse waveform. A frame rate of 64 frames per second ensured a high enough sampling rate to capture most of the time-domain characteristics of the waveform.

Raw radar frames (Fig. 2a) were first demodulated into complex baseband data and filtered with a matched filter. Amplitude and phase data were calculated as the complex magnitude and four-quadrant inverse tangent. Radar frames contain both static and dynamic signals which overlap in fast time. As the arterial pulsation signal is purely dynamic and occupies a limited bandwidth, one can bandpass filter the data in slow time to extract the signal of interest and remove static clutter. For this, an IIR filter with passband of 0.6 – 8 Hz was used.

Spectral analysis of detrended and windowed amplitude data was performed in sliding 6 s windows, in which HR may be assumed stationary. Frequency spectra of these 6 s windows of data were averaged to obtain the mean range Doppler plot (Fig. 2b). The sampler containing the most prominent HR signal was found by estimating SNR for each sampler as the ratio between the power at the fundamental frequency and its harmonics, to non-harmonic spectral content (Fig. 2c). Samplers with peak SNR were used for spectrograms (Fig. 2d) and HR estimation.

To provide an accurate timing reference the R wave of the QRS complex was chosen as the fiducial ECG marker for its

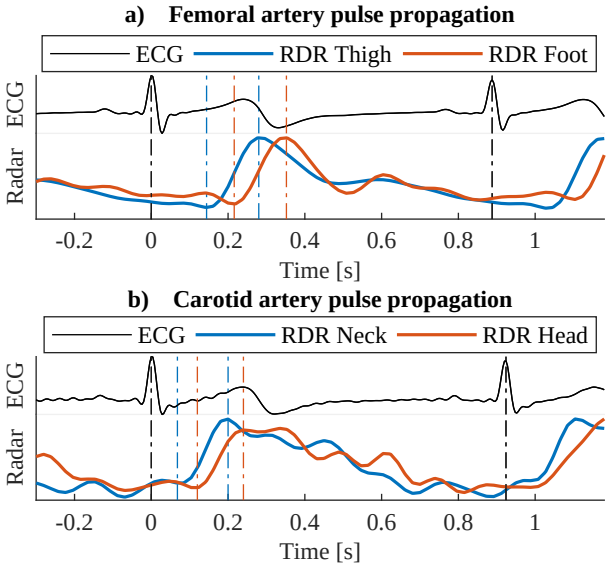

Fig. 3. Demonstration of pulse wave velocity through the femoral artery (a) and the carotid artery (b). The blue traces represents the more proximal measurement point, orange the more distal measurement point. Pulse onset and maximum are indicated by colored dashed lines, ECG R wave is indicated by a black dashed line.

robust detectability. The ECG data was zero-phase shift filtered using a low-pass IIR filter and R wave detection was achieved by finding the local maximum in the ECG data directly preceding a peak in its first approximate derivative. Radar-based HR estimation was compared to ECG-based HR and performance was assessed through mean absolute percentage error.

Amplitude data at peak SNR range was used to study time-domain characteristics of the measured cardiovascular signals. To improve SNR in the radar time-series, data from both radar and ECG were aligned using the fiducial ECG markers and radar data over multiple heartbeats were averaged. To avoid pulse smearing caused by HR variability, individual heartbeats were first grouped based on R-R interval using a 16 ms bin width, and the bin with highest number (generally 10–15) of heart beats was selected for processing. Once an averaged radar response was obtained for each of the measured locations, pulse onset, pulse maximum and pulse offset were determined from zero-crossings in the derivative signal.

III. Results

HR could accurately be measured from each of the six locations on the body, with estimation accuracy (compared to ECG) ranging from 97.0 – 99.4 % (Table). PWV was demonstrated in the femoral artery (Fig. 3a), by a clearly distinguishable delay in PAT between the simultaneously recorded thigh and foot measurement points. Based on pulse onset and pulse maximum, a delay of 72 ms was measured. This translates to a PWV in the femoral artery of 11.1 m/s. A delay in PAT between the head and neck was observed (Fig. 3b), but PWV is harder to define due to the unknown exact path length of the intracranial blood pressure wave. Radar-measured arterial response to the heartbeat, for different measurement locations, is shown in Fig. 4. For all measurements, a robust peak was identifiable. As is reflected through low standard deviations in the arrival time of pulse maxima (Table I),

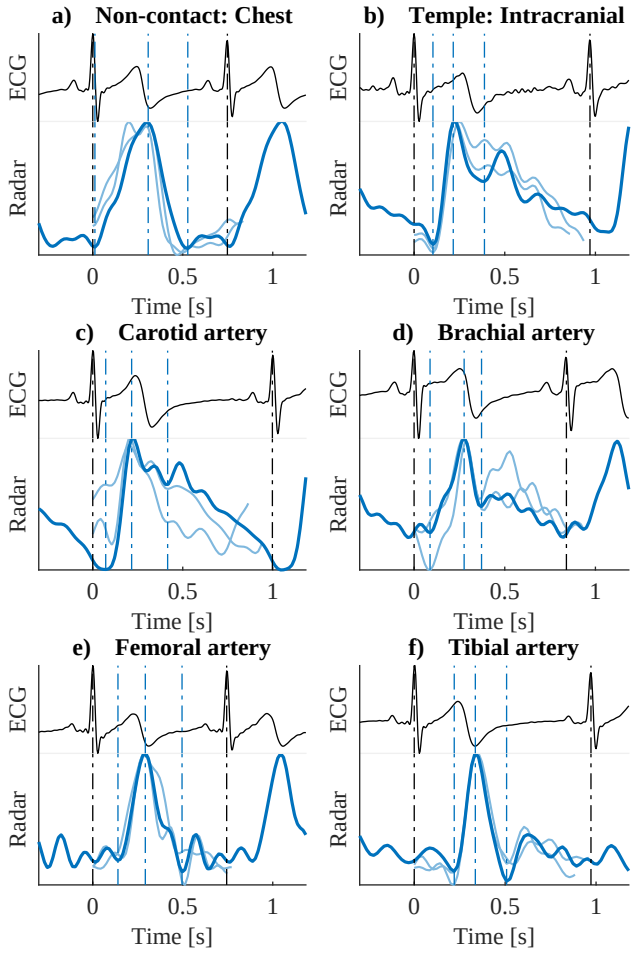

Fig. 4. Pulse arrival time at different measurement locations: Non-contact chest (a), temple of the head (b), neck (c), upper arm (d), thigh (e) and foot (f). Radar time series from three individual recordings are shown (blue), along with ECG (black). Blue dashed lines indicate pulse onset, maximum and offset. Black dashed lines indicate the ECG R wave.

and demonstrated through well aligned traces of individual recordings (Fig. 4), peak detection with the chosen approach is very precise. Slightly higher variation exists in detecting pulse onset, and pulse offset estimation proved challenging for the intracranial and carotid artery recordings. As expected, PAT increases with increasing distance of measurement location to the heart. Mean and standard deviation for peak onset and maximum (relative to R wave) are given in Table I, along with SNR of the HR signal obtained from unaveraged recordings. When comparing the in-body arterial measurements (Fig. 4b–f) to the non-contact recording of the chest wall (Fig. 4a), a clear difference is apparent: The onset of chest displacement coincides with the QRS complex and reaches a peak at the offset of the T wave. The rise period covers the entire systole of the heart. The arterial pulses are clearly delayed (by 73 – 212 ms, depending on location) and show much shorter rise times. Even while searching at different ranges in the received radar signal for in-body measurements, it has not been possible to detect a waveform with similar time domain characteristics as the non-contact chest wall signal. The sham recording (not shown in any of the figures) did not contain a detectable HR signal.

Results for the in-body recording at the sternum, measured directly above the heart, are shown in Fig. 5, along with a

TABLE I
SUMMARY OF MEASUREMENT RESULTS: MEAN (SD)

Measurement location	HR accuracy [%]	$P_{onset}AT$ [ms]	$P_{max}AT$ [ms]	SNR [dB]
(1) Chest	99.38 (0.38)	-4 (16)	304 (7)	8.27 (2.04)
(2) Heart	99.46 (0.18)	-13 (8)	325 (2)	15.40 (0.83)
(3) Intracranial	97.45 (1.89)	105 (2)	232 (16)	5.01 (2.30)
(4) Neck	98.19 (1.05)	89 (16)	205 (9)	5.17 (1.20)
(5) Upper arm	97.15 (0.65)	73 (25)	281 (9)	6.62 (1.04)
(6) Thigh	97.00 (4.13)	144 (22)	288 (7)	1.86 (3.34)
(7) Foot	97.54 (1.99)	212 (10)	341 (9)	-2.07 (2.86)

Measurement locations: (1) Non-contact: Chest; (2) Sternum: Heart; (3) Temple: Intracranial; (4) Carotid artery: Neck; (5) Brachial artery: Upper arm; (6) Femoral artery: Thigh; (7) Tibial artery: Foot. $P_{onset}AT$ and $P_{max}AT$ denote arrival time of pulse onset and maximum, respectively.

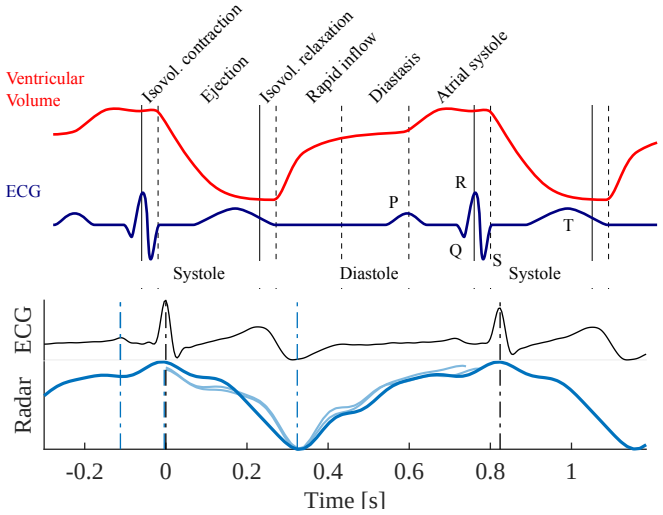

Fig. 5. Wiggers diagram (adjusted from [9]) illustrating the relationship between the heart's electrical activity (ECG) and ventricular volume (top), and in-body heart recording, measured from the sternum (bottom). Local and global minima and maxima in radar data are indicated using blue dashed lines.

Wiggers diagram, which shows the theoretical relationship between the heart's electrical activity (ECG) and ventricular volume. Interestingly, but not surprisingly, the radar data closely resemble the ventricular volume in the Wiggers diagram, showing start and end of ventricular systole, as well as the atrial systole that occurs during the ECG P wave.

IV. Discussion

Arterial dilation due to the blood pressure wave, and thus HR, can accurately be measured at multiple locations on the human body, using an IR-UWB radar-on-chip system in combination with body coupled antennas. Due to proximity to the chest and reduced electromagnetic propagation velocity in biological tissues (factor 4–7 depending on tissue and frequency), target range is not a reliable metric to rule out chest displacement modulation of the neck and upper arm recorded signals. However, from the averaged waveforms and measured PAT, it becomes apparent that only subcutaneous arterial motion is being recorded. For the thigh and foot recordings, arterial motion and potential chest wall motion would not interfere in the radar recordings, so time gating can be used safely to rule out leakage interference. But again, no signal resembling the chest displacement signal was recorded at higher ranges. A final assurance that leakage signals do not cause measurable HR modulation in in-body radar measurements with the current setup, comes from the sham recording: No HR was detected at any of the depth samples. Arterial pulse onset and pulse maximum can be determined with good precision. Through ECG-aligned, selective averaging of radar data, a clean signal was obtained even in very low SNR situations, without peak smearing. From this, it follows that average PWV can accurately be determined between two measurement points, provided that a reliable fiducial point is chosen to characterize the PAT. PWV is a commonly used indicator for arterial stiffness, and has successfully been applied for cuffless blood pressure estimation [2]. A PWV of 11.1 m/s that was found in the femoral artery recordings lies within physiological range, but validation of these results is necessary. Radar has an advantage over alternative measurement modalities due to the option to measure from deeper structures in the body (compared to photoplethysmography), as well as low cost, ease of use, and ability to penetrate through bone tissue (compared to ultrasound).

From the heart recordings at the sternum, it was found that a robust signal could be measured that closely resembles theoretical ventricular volume. The signal maximum occurs slightly before R wave, on the onset of ventricular systole. The signal minimum aligns with the end of T wave (indicating the end of systole). A local minimum was found to coincide with the P wave, and second local minimum (recorded in some but not all signals, depending on depth) is hypothesized to indicate the start of ventricular ejection. After further validation, UWB radar tracking of heart dynamics could prove to be a powerful diagnostic tool, particularly for measuring the mechanical functioning of the heart. When multiple modules are run simultaneously through an array of antennas, it will be possible to focus the signal on particular anatomical structures in the heart, and thus gain an even more detailed insight.

V. Conclusion

Using UWB radar and body-coupled antennas, arterial pulse and pulse propagation could successfully be measured from multiple locations in the body. In addition, ventricular dynamics were recorded from the chest with high precision. This work serves as a first step in developing a portable and low-cost device for long-term imaging of the cardiovascular system, with the potential of early diagnosis of diseases.

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