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Cardiac Signature Detection and Study Using Contactless Technology: Millimeter-Wave FMCW Radar

MÉLANIE BRULC [1,2], **THIBAUT DELERUYELLE** [2], **ALAIN LOUSSERT** [2] **(Senior Member, IEEE)**,
PIERRE LAURENT [3], **RÉMI GRISOT** [1,4], **AND JEAN-PAUL CARUANA** [1]

[1]XtreamWave, 83000 Toulon, France
[2]IM2NP-ISEN, UMR CNRS 7334, 83000 Toulon, France
[3]Hôpital Ste Musse, 83100 Toulon, France
[4]Université Côte d'Azur, LEAT, 06000 Nice, France

CORRESPONDING AUTHOR: M. BRULC (e-mail: melanie.brulc@xtreamwave.com)

ABSTRACT The work presented in this article aims to detect the cardiac movement of a person in a noninvasive way and correlate it with a reference signal in the medical field: the electrocardiogram. To achieve this goal, a measurement campaign was carried out on 20 consenting individuals. On the one hand, the mechanical signal, the movement of the subject's chest induced by the heartbeat, is recorded via an FMCW radar, and on the other hand, the electrical signal of the heart is recorded via an ECG acquisition board. Signal processing functions and different filtering will allow the correlation of the radar and ECG signals. This study is conducted on apnea recordings in order to remove the impact of breathing on the movement of the chest. When the subject holds his or her breath, the two important phases of cardiac movement via radar capture can be detected: 1) the systole and 2) the diastole. The delay between the mechanical signal of the heart and the electrical signal of the heart, already explained by medicine, is well noted. The accuracy of motion detection provided by the radar allowed us to highlight the reproducibility of the chest movements detected during a capture. Their correlation with ECG data validates the proposed hypotheses.

INDEX TERMS Biomedical, heart rate (HR) detection, millimeter wave, radar.

I. INTRODUCTION

CARDIOVASCULAR diseases (CVDs) are a worldwide issue. According to the World Health Organization, more than 30% of deaths in the world are caused by CVD. Of the 17 million premature deaths (under 70 years) in 2019, 38% were caused by CVD [29]. In Europe, they caused more than 3.9 million deaths per year, which corresponds to 45% of all causes of death in 2017 [30]. The CVD remains the most common cause of death in the region. In addition, the need to monitor frail people while keeping them at home in order to leave a maximum of available beds in hospitals and also the monitoring of newborns to prevent sudden infant death syndrome [12] are all reasons that explain the current scientific interest in finding solutions to this issue. The study of cardiovascular risks is a subject that has preoccupied the whole world and has animated the scientific community for several years [7], [8], [14], [18], [19], [20], [21], [22], [23], [26], [27].

The reference tool used in medicine to study a patient's cardiac activity is the electrocardiograph. This device captures and studies the electrical signals related to the cardiac muscle. However, an electrocardiogram is a one-time test or a one-day test and not continuous in time, whereas cardiovascular events can occur at any time. The placement of electrodes on the patient's skin can also be problematic. Indeed, some skins cannot be in contact with these patches because of their nature, let us think about the skin of burn victims or people with very thin and fragile skin. In summary, the electrocardiogram is an examination that is difficult to be continuous over time and can only be realized by a trained medical staff member.

This article proposes a complementary tool to this cardiac monitoring tool that does not necessarily require a medical specialist to perform it and, above all, is noninvasive. These two important features would, if this new tool were available to the public, minimize the discomfort and stress of a medical examination while taking some of the workload off of specialists in the field.

A number of studies have been realized in this field of interest and have shown that radio frequency (RF) radars provide a solution to this problem. Several articles present work done with millimeter-wave radars on different frequency ranges from 2.4 to 120 GHz and of different modulations, such as continuous-wave (CW), frequency-modulated CW (FMCW), and pulse.

Those frequency bands are standardized for consumer applications and studied by the scientific community, a lot of works use them. Several works are focused on the detection and estimation of the subject's heartbeat and breathing by a comparison between a radar emitting a signal with a beginning frequency set to 120 GHz and a connected watch [7]. Alizadeh et al. [19] worked with frequencies close to 77 GHz and a Hexoskin garment with integrated heart sensors to validate its heart rate (HR) and breathing rate (BR) estimates. Gupta et al. [22] also studied the output signals of such radars with a video study of the scene to compare his results. Wang et al. [18] compared and also detected HR and BR and concluded that CW radars are less reliable than FMCW radars for studying fine movements.

Yu et al. [8], Dai et al. [20], and Wang et al. [21] worked with several radars at 2.4 and 5.8 GHz surrounding the subject to remove random body motion (RBM). Thanks to this, it is possible to clearly identify the HR of the breathing by abstraction of the parasitic movements of the capturing environment. Zhao et al. [6] focused mostly on heartbeat to detect the subject's emotions thanks to the HR evolution. All of this work allow the heart and BRs of a subject in front of their device to be extracted by signal processing. Dong et al. [16] have taken the study a step further by detecting the compression and relaxation movements of the heart using a CW radar emitting a signal close to 24 GHz.

Another technique used for the detection and study of cardiac motion is the use of neural networks [23], [28]. Chen et al. [23] used these neural networks to identify the contraction and relaxation of this muscle.

The study achieved and presented in this article aims to detect and show this cardiac movement, i.e., to highlight the motion of the chest induced by the heart during a beat and study its evolution over time during the capture. Furthermore, the goal of this research is to go beyond beat detection and study the cardiac movement recorded in a noncontact process. The reproducibility of these patterns will also be highlighted. Thus, a comparative study and a correlation between mechanical data collected contactless via a millimeter-wave radar versus electrical data recorded by an electrocardiogram acquisition board with skin contact will be presented in this article and some key points will be defined in relation to the PQRST complex. In the context of the presented study, the subjects were previously asked to hold their breath for a few seconds and minimize their movements in order to avoid the RBM issue and highlight points of interest. Finally, this article proposes improvements over the studies cited by adding a study of movement in addition to the study of HR.

The article is structured as follows. First, the architecture and the methodology of the data acquisition will be presented. This will be followed by the description of signal processing methodology. Finally, the exploitation of the collected data by extraction of the usefull information and perspectives they provide will conclude this article.

II. METHODOLOGY

In order to study the correlation between the electrical and mechanical signals of the heart, a measuring campaign on several different subjects will be carried out. The results of the studies presented in this article are based on the acquisition on 20 people, distributed as follows: 9 women, 11 men, aged between 20 and 55 years. Thus, the theoretical mechanics of the heart will be presented first. Then, the optimal radar and ECG parameters will be defined to detect both components of a heartbeat: the mechanical one and the electrical one. Then, the captures will be realized on several people of different ages and genders. Finally, the collected data will be exploited through signal processing functions in order to be able to compare them with the electrical signal of the ECG.

Theoretical Mechanics of the Heart: To properly interpret the electrical and mechanical signals of the heart studied in this article, it is necessary to know the main characteristics of the heart and the main mechanisms of its functioning.

The human heart is a complex muscular organ. This muscle located in the chest cavity works like a pump: it contracts and relaxes continuously. The human heart has four chambers: the right and the left atria, and the right and the left ventricles. These chambers have a specific role at each moment of a heartbeat. The heart rhythm consists of two phases: an electrical component followed by a mechanical component. Both are presented on Fig. 1. The mechanical phase of the cardiac cycle on the upper part of the figure is a succession of contraction phases called systoles ejecting blood out of the left ventricle and relaxation phases called diastole allowing the filling of the heart chamber. The electrical component on the lower part of the figure is directly responsible for the mechanical phase. Both components are perfectly synchronized and ECG is also used to study the physical characteristics of the heart, such as the healthy functioning of its ventricles [11].

The work presented in this article will correlate these two components using an ECG capture for the electrical part and an mmwave radar capture for the mechanical part. In

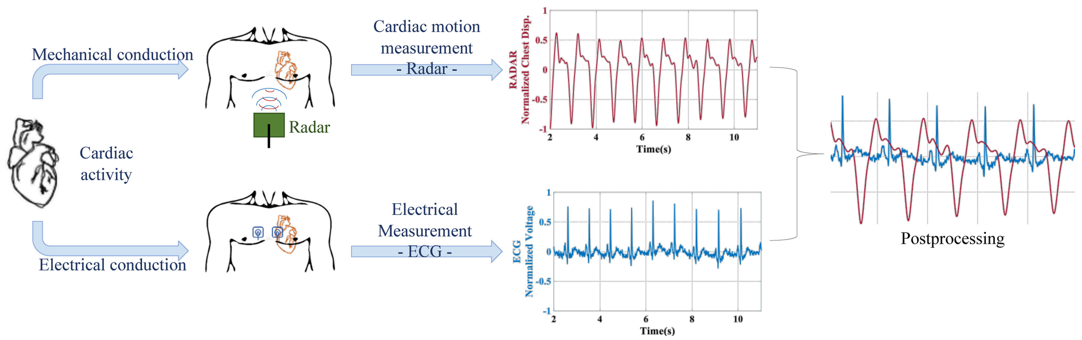

FIGURE 1. Schematic of the capture performed on the subject lying down and holding his breath.

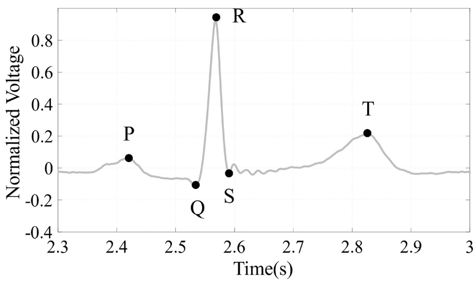

FIGURE 2. PQRST complex on an ECG pattern measured.

the literature, some concordances are already known such as the PQRST complex of the ECG shown in Fig. 2 and its mechanical meaning [3]. The P wave corresponds to the depolarization of the atria which leads to their contraction, the so-called QRS complex corresponds to the contraction of the ventricles and the T wave reflects the repolarization, the return to the resting phase of the ventricles. The contraction of the atria and the ventricles is so powerful that they induce a movement of the thoracic cage, and therefore of the person's chest, when they are activated. This movement will be studied and presented next. According to [17], the movement induced by the heartbeat is a displacement of the chest between 0.2 and 0.5 mm, whereas breathing has a greater impact on the position of the chest, creating a displacement of up to 12 mm.

Being able to detect and study the different stages of cardiac movement on a subject's chest would allow us to monitor this person's heart health in the same way as when they perform an ECG, but noninvasively.

Radar and ECG Board Settings: These two components, presented in the previous paragraph, although of different natures, are closely linked. The electrical component of the heart will be recorded using an ECG acquisition card and the mechanical movement of the chest induced by the signature of the heart during a beat will be recorded with a millimeter-wave radar.

In order to record the electrical activity of the subject's heart, the ADAS1000 from Analog Device will be used as an ECG acquisition board. This board will be connected on the one hand by patches and electrodes placed on the subject under test (SUT) and on the other hand to a computer in order to record the data over time. The acquisition frequency of the ADAS1000 will be set at 2 kHz, the maximum acquisition frequency proposed by the manufacturer.

Concerning the detection of the mechanical activity of the chest induced by the heartbeat, it is necessary to use a device with a high resolution for weak movements of the order of those stated at the end of the previous paragraph. Dong et al. [16] have shown that with a Doppler Radar System transmitting at around 24 GHz, it is possible to detect the contraction and relaxation of the heart during a beat. The frequencies used in the study presented in this article are almost three times higher (77–81 GHz), so they theoretically allow a greater sensitivity to the movement detection. Work has already been done in the same frequency band, but only the detection of a heartbeat has come out of papers. Thus, the work developed in this article will present the detection of the mechanical component of the heart with the help of an FMCW Doppler Radar System transmitting between 77 and 81 GHz.

In addition, Wu et al. [5] provided information that these waves can easily penetrate all types of clothing whereas they can hardly penetrate or be absorbed by human skin.

After assimilating all the characteristics necessary for the device needed to collect vital signal data and in view of the works previously presented it has been decided to work with the Texas Instruments IWR1642BOOST radar. It will be connected to the DCA1000 board also from Texas Instruments in order to retrieve the raw data of each experiment which will be the next step proposed by [10].

When the radar will be mentioned throughout this article, it is referring to the combination of the IWR1642BOOST radar and the DCA1000 board.

Amplitude, reproducibility, and periodicity of cardiac patterns are all criteria that may be of interest to a cardiologist and may indicate good health or, more importantly, pathology [3], [11]. Thus, the motion resolution of the radar and therefore its parameterization must meet these criteria.

Table 1 summarizes the main parameters used in the experiment to meet these criteria.

A chirp is a signal emitted by the radar whose frequency evolves over time. The bandwidth used in this experiment

TABLE 1. Radar setting tab.

Parameter	Value
Bandwith	77-81 GHz
Nbpointsperchirp	64
Nbchirpperframe	16
Frameperiodicity	1.6 ms
Transmitterantenna	1
Receiverantenna	4

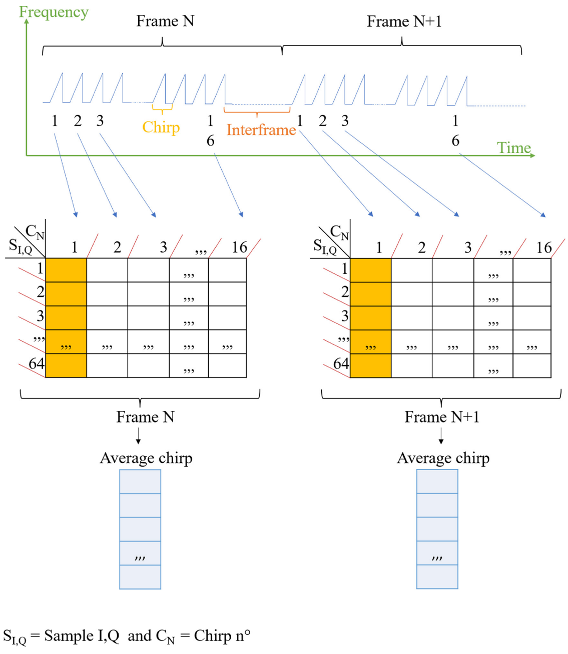

FIGURE 3. Description of the composition of the useful signal matrix.

will be fixed at 4 GHz (from 77 to 81 GHz), the maximum bandwidth allowed by the radar in order to increase the distance resolution of this device as much as possible. The transmitted signals are reflected by the subject's chest placed in front of the radar [5] and received by the four receiving antennas. The difference in frequency between the reflected wave and the one being transmitted, called the intermediate frequency, will allow us to define the time taken for the wave to make the round trip to the target and then the distance of the target from the transmission/reception source. Studying the temporal evolution at this distance will reveal the movement of the subject at this position during the capture. In the receiver architecture, there is an I/Q demodulator as explained in the book [2]. These two channels are sampled to provide two output matrices, one for each channel as shown in Fig. 3. Thus, for each chirp, two tables of 64 points each is recorded on the computer, one for the I data and the other one for the Q ones.

The radar transmits via the transmitting antenna a frame consisting of 16 successive chirps followed by an interframe time without any transmission before starting to transmit the next 16 chirps as shown in Fig. 3. The period of a frame is fixed at 1.6 ms, which corresponds to 625 frames/s. This high number of frames per second was set to record as much information as it could be get during a heartbeat within the capabilities of the radar without deteriorating the other parameters. Only one average chirp per frame will be kept in order to have a periodic reading throughout the capture. The heart of a healthy adult human being beats on average at 70 beats per minute (BPM). When this person makes a physical effort, his HR increases. Thus, considering a high HR of 200 BPM or about 3.33 beats per second, the chosen parameters will allow us to obtain 187.5 points during a beat. The frames period is thus at least 187 times shorter than the occurrence of the useful signals, which allows the study of the movement of the heart and its different stages.

The output radar raw data are recorded as a matrix per frame and per antenna as shown in Fig. 3, and the processing of those data will be discussed in the data processing section.

Once these parameters were validated, a measurement campaign has been set up as presented in the next section.

Data Recording: The measurements realized during the campaign are recordings of about 30 s each. During the measurement, the subject is lying on his back at rest and is asked not to move, within reason, from the moment, the capture starts to its end. The start and end of each capture are indicated to the SUT with a countdown and a given signal. He or she is connected to the 6-lead ECG acquisition board via electrodes placed on the wrists, ankles, and chest. The radar is positioned 0.5 m above the subject laterally centered on the chest, that corresponding to the optimal target-radar distance for the motion study with the chosen parameters.

About apnea, breathing has a big impact on the thoracic movement, up to six times more important than the heartbeat [13], [17]. This induced movement is so impacting that even after filtering out the usual frequencies corresponding to breathing, there is still residual respiratory movement in the chest displacement. In order to clean up the signal as much as possible and to avoid spurious movements, the captures of this study were therefore carried out in apnea, asking SUT to hold his breath with full lungs and with empty lungs.

In fact, with only a few seconds of signal, it is possible to determine the movement of the chest induced by the heart. The 30-s recording time is requested in order to maximize the data during a capture, but only the period of the capture during which the person is actually holding their breath is retained and processed. It would be perfectly possible to use only 10 or 15 s or even less to the study, but the longer the capture, the more it enabled to study the repeatability of the cardiac pattern. Furthermore, a few seconds of breath holding are frequently requested during breathing and relaxation exercises [31].

Fig. 1 summarizes a schematic of the capture performed on the subject lying down.

The electrical and mechanical signals of the heart are thus collected and saved simultaneously throughout the capture.

Once the measurements were collected, raw data were prepared to highlight vital signs information.

Data Preprocessing: The overall data processing on radar raw data and the ECG data is presented in Fig. 4.

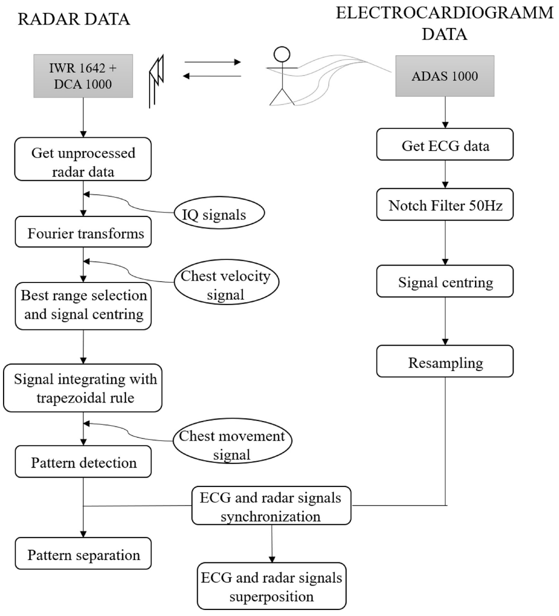

FIGURE 4. Overall data processing on radar raw data and the ECG data.

Concerning the ECG Data: Once the data from the ADAS1000 board were recorded, a matrix containing the evolution of each lead recorded over time is available. In the graphical representations of the electrocardiogram in this article, only Lead II is represented. In order to reduce the powerline frequency noise impacting the signal, an infinite impulse response (IIR) notch filter at 50 Hz has been applied. This type of filter, which is easy to implement and operate, is used because it is very powerful and particularly suitable thanks to its ability to cut the unwanted part of the signal by 99%. It allows to keep a maximum of frequency detail while removing the 50-Hz band. In order to compare the ECG signal to the radar signature, the signal has been centered and then resampled in order to get a curve with the same sampling frequency, or the same number of points, than the one representing the mechanical movement of the heart.

Concerning the Radar Raw Data: They are stored on the computer in the format stated in the section *Radar and ECG board settings*. First, a fast Fourier transform (FFT) was applied along each chirp in order to determine the distance of each range by using the modulus of this FFT. Subsequently, only the index of the range with the highest average modulus over the whole capture will be retained. This means that there is a lot of information to process on this range. Furthermore, taking into account that the capture is operated in apnea and with a minimum of parasitic movement in the radar's scope of study, only the chest movement provides real information in these recordings and therefore has a very high average modulus. By way of confirmation, the selected range can be reduced to a distance using the formula $d = f.(c.r/2B)$ with f the intermediate frequency associated to this range in Hz, c the celerity of light in m.s^{-1}, r the ramp time in *second*, and B the frequency bandwidth in *Hz*. The pointed range corresponds to a distance around 50 cm, which is the distance used for manipulation with a zero angle of incidence. A short-time Fourier transform (STFT) is then applied in the second dimension of the matrix, i.e., at a range fixed throughout the capture. This processing allows us to study the variation in frequency at this distance and thus trace the chest movement induced by the heartbeat. The output of this step is a usable signal containing the temporal evolution of the velocity of the SUT chest at a known distance from the radar.

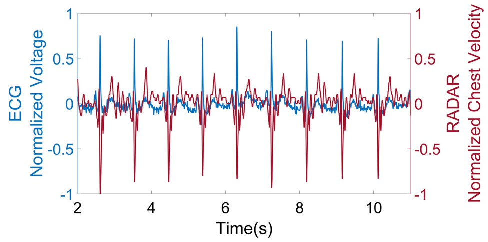

FIGURE 5. Chest velocity curve of the SUT holding his breath and the ECG signal recorded over the same period.

The following figure exposes an extract of the capture carried out in apnea with full lungs on an adult male.

Fig. 5 shows an extract of the velocity signal of the SUT chest as exposed in Fig. 4, the radar data are represented by the red curve and the ECG signal recorded over the same period by the blue one.

Looking at the curves in this graph, it could be noticed a significant peak with an identical period to the ECG one and recorded at the same time. However, the only information of the velocity does not allow us to get close to a data known by the specialists in the medical field. Looking at the mechanics of the movement of a heartbeat, it is reasonable to consider that the largest movement induced and therefore detected on the chest of a person is the activity of the most important part of the heart: the movement of the ventricles. In order to get closer to this correlation, studying the proper motion of the chest is necessary, which means getting this motion signal from the available data, the velocity curve.

The integration of the velocity signal will provide the displacement signal of the studied object. To get this information, two types of integration have been tried, such as rectangular integration and trapezoidal integration. After comparing these two techniques, the trapezoidal integration curve was chosen to best represent the signal as it more accurately fits the area under the curve being studied. The following graph represents an extract of the evolution of the subject's chest movement induced by his heartbeats in apnea during a capture.

Fig. 6 shows an extract of the displacement of the SUT chest detected by the radar as presented in Fig. 4 superimposed on the ECG signal. The presence of a periodic pattern with the same period as the pattern of the electrical signal with a slight temporal shift can be noticed. As with the velocity curve, this time shift between the two curves can be explained by the causal relationship between the electrical component of the heart and the mechanical component of this muscle.

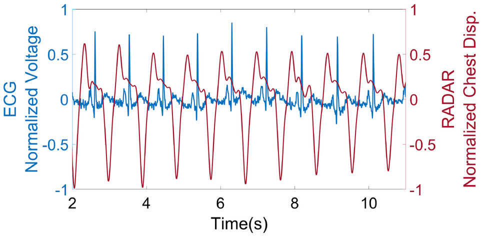

FIGURE 6. Chest displacement curve of the SUT holding his breath and the ECG signal recorded over the same period.

Data Processing: In order to study the reproducibility of the experiment, recordings were performed on different subjects who had consented to undergo the experiment. None of the subjects were aware of having any cardiac pathology. On each of these people, four apnea recordings as presented in the *data recording* subchapter have been accomplished, two full lung measurements and two empty lung measurements in order to rule out any nonreproducible hypothesis which would be unfounded by nature. These recordings were then studied over time.

By studying the signals recorded during the measurements, a representative shape of the periodic signal was significantly detected. These extracts of signals will be called "cardiac patterns" in the following. In order to study the period and the reproducibility of these patterns, a function has been developed to split the ECG signal and the radar signature into cardiac patterns.

For this study, all local minima of the radar signature were automatically detected in order to determine the maximum period between two successive minima.

Thus, the maximum period value corresponding to the maximum detected duration of a pattern is recovered. Using this value, the recorded signal is then split into patterns of length of this maximum period value by centering each pattern on the center of the signal between two successive minima. A 2-D array as large as the maximum period value and with as many lines as the number of detected patterns is thus recorded. Finally, the patterns are windowed just before being superimposed in order to have the temporal evolution of the latter. All this processing was automated. For the ECG signal, the same work was done based on the detection of R-peaks, the biggest peaks of ECG patterns exposed in Fig. 2. The figures presenting this data processing are shown in Section III.

III. RESULTS

Figs. 7 and 8 represent the accumulation of the different centered patterns detected during the recording of the mechanical signal via the radar and those of the electrical signal of the ECG. The black lines on these two graphs represent the respective median of the matrix presented in both figures. The low scatter of the represented data indicates a high reproducibility of this pattern over time during a full capture of about 30 s.

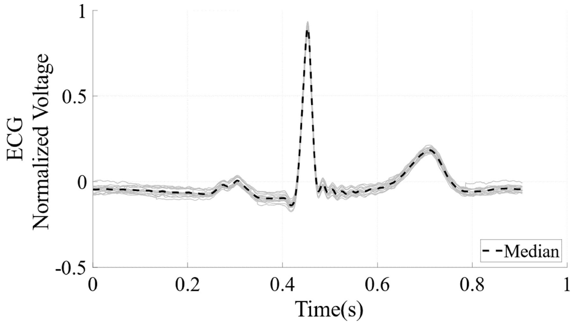

FIGURE 7. Peak centered cumulative measurement of the ECG signal.

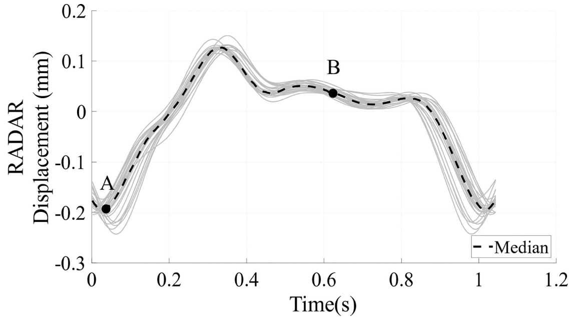

FIGURE 8. Peak centered cumulative measurement of the radar signal.

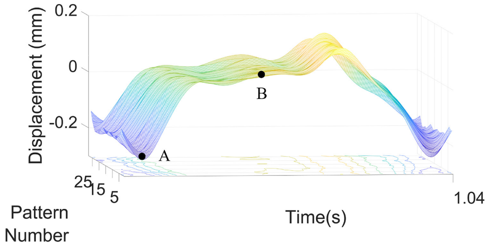

FIGURE 9. 3-D diagram of the time evolution of the centered pattern detected during the recording of the mechanical signal by the radar of a breath-holding subject.

Both Figs. 7 and 8 give then an overall idea of the reproducibility of the patterns during a recording. This high reproducibility could be characterized by calculating the standard deviation at two points already present on the curves. The result is 1.8% and 0.8% for points A and B, respectively. However, these representations do not provide the full information about the temporal evolution of these beats. By paying attention to the 3-D representation of the matrix of patterns extracted from the cardiac signature of the radar exposed on Fig. 9, the totality of the temporal dimensions is represented. This representation methodology allows us to observe the evolution of the chest movements induced by the heartbeats during a full capture.

Focusing on the evolution over the time, it can be noticed once again the constance of all patterns for captures of about 30 s.

The work presented in this article demonstrates the detection of much more than just heartbeats allowing to determine a subject's HR. It also gives access to the contraction and relaxation movements of the heart muscle: systole and diastole.

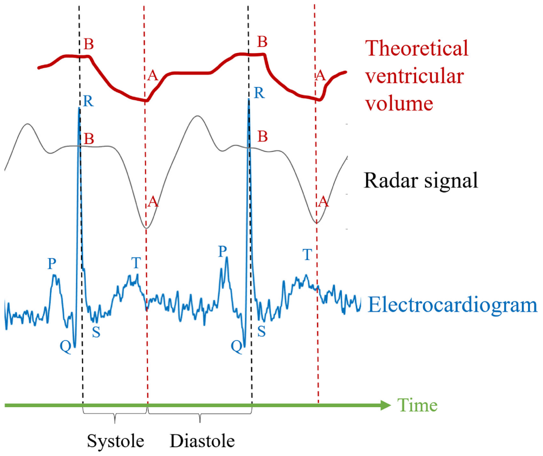

FIGURE 10. **Superposition of the theoretical evolution of the ventricular volume extracted from the Wieggers diagram and the cardiac signature of the chest induced by the heart and the ECG signal during two beats measured on an SUT.**

Two significant points A and B can be noticed and positioned, respectively, at the beginning of the upward slope of the displacement and just before the downward slope of the signal at the end of the pattern. These two key points are, respectively, the beginning of diastole, the phase during which the heart contracts and ejects blood into the arteries, and the beginning of systole, the phase during which the heart relaxes and fills with blood.

These two points are also easily observed on the curve representing the evolution of the ventricular volume over time on Fig. 10. Due to that the largest movement of the heart during a beat is that of the left ventricle [3], it is reasonable to consider the approximation of the radar output curve with the ventricular volume one.

IV. DISCUSSION

In this article, methodologies for data acquisition, interpretation, and visualization were presented. They led to the conclusion that it was possible to trace the different parts of the cardiac movement during a beat with a millimeter-wave FMCW radar: systole and diastole.

In comparison with the work performed in the world of research, highlighting cardiac movement goes beyond detecting beats to extract an HR as was done in [7], [14], [19], and [22]. Dong et al. [16] exposed the detection of the compression and relaxation movements of the heart using a CW radar when Wang et al. [18] concluded that FMCW radars could be more efficient to get heart movements than CW. Then, the research work presented here shows up heart movements recorded using an FMCW radar and pointed the reproducibility of them, adding two key points on the signal.

The separation of the patterns from the output signal radar highlighted the reproducibility and periodicity of the movements detected by the radar. Superimposing these extracts confirms the constancy of these beats at regular intervals with an ascending movement as important as the descending part. The heartbeat was found via the radar and confirmed by superimposing the electrical signals of the heart recorded by the ECG acquisition board.

V. CONCLUSION

The research presented in this article allows to visualization of the chest displacement induced by the heart during beating recorded using an FMCW millimeter-wave radar. Two phases are clearly visible and explained by comparison with the corresponding ECG signals.

The detection work exposed here was carried out on captures of subjects holding their breath. To simplify the motion detected by the radar as much as possible, as it has been proven [13] and it has been also verified through tests, that breathing, even when filtered, has a significant impact on the signal of the subject's chest motion and thus interferes with the detection of the motion induced by the heartbeat. In order to measure the heartbeat, the captures were made in apnea. Perspectives for this research could be to work on the whole signal, i.e., allowing the SUT to breathe during the measurement. It is possible to reconstruct the breathing signal from the period of each heartbeat [13]. The objective is to refine the preprocessing of the radar output signal in order to highlight the motion induced by the heartbeat as clearly as during a breath-hold capture despite the subject's breathing. A new campaign of measurements is currently being acquired, still asking the patient not to move during the recording, but this time proposing to breathe normally during the 30 s.

Another possible angle of research would be the optimization of the signal processing functions in order to gain efficiency and speed of execution.

REFERENCES

[1] A. L. Goldberger, Z. D. Goldberger, and A. Shvilkin, *Clinical Electrocardiography: A Simplified Approach e-Book*. Philadelphia, PA, USA: Elsevier Health Sci., 2017.

[2] M. Jankiraman, *FMCW Radar Design*. Norwood, MA, USA: Artech, 2018.

[3] D. Dubin, *Rapid Interpretation of EKG's: An Interactive Course*, 6th ed. Tampa, FL, USA: Cover Publ. Co., 2000.

[4] E. Wilkins et al., *European Cardiovascular Disease Statistics 2017*, Eur. Heart Netw., Bruxelles, Belgium, 2017.

[5] T. Wu, T. S. Rappaport, and C. M. Collins, "The human body and millimeter-wave wireless communication systems: Interactions and implications," in *Proc. IEEE Int. Conf. Commun. (ICC)*, 2015, pp. 2423–2429.

[6] M. Zhao, F. Adib, and D. Katabi, "Emotion recognition using wireless signals," in *Proc. 22nd Annu. Int. Conf. Mobile Comput. Netw.*, 2016, pp. 95–108.

[7] T. Li, G. Wan, L. Liu, T. Zhu, and P. Wang, "ECG signal detection method based on millimeter wave radar," in *Proc. IEEE 2nd Int. Conf. Inf. Commun. Softw. Eng. (ICICSE)*, 2022, pp. 220–224.

[8] X. Yu, C. Li, and J. Lin, "Two-dimensional noncontact vital sign detection using Doppler radar array approach," in *IEEE MTT-S Int. Microw. Symp. Tech. Dig.*, 2011, pp. 1–4.

[9] C. Gu, G. Wang, T. Inoue, and C. Li, "Doppler radar vital sign detection with random body movement cancellation based on adaptive phase compensation," in *IEEE MTT-S Int. Microw. Symp. Dig. (MTT)*, 2013, pp. 1–3.

[10] M. Salman and Y. Noh, "Contactless vital signs tracking with mmWave RADAR in realtime," in *Proc. IEEE Int. Conf. Big Data Smart Comput., BigComp*, 2023, pp. 389–390, doi: 10.1109/BigComp57234.2023.00094.

[11] M. Galinier et al., “Holter EKG for the hypertensive Heart disease,” *Annales Cardiologie d’Angéiologie*, vol. 51, no. 6, pp. 336–340, 2002, doi: 10.1016/s0003-3928(02)00151-8.

[12] A. Tursz, M. Crost, P. Gerbouin-Rerolle, J. Beauté, and H. Romaro, *Quelles Données Recueillir Pour Améliorer Les Pratiques Professionnelles Face Aux Morts Suspectes de Nourrissons de Moins de 1 an?* Institut National de la Santé et de la Recherche Médicale (INSERM), Paris, France, 2005.

[13] F. Yasuma and J.-I. Hayano, “Respiratory sinus arrhythmia: Why does the heartbeat synchronize with respiratory rhythm?” *Chest*, vol. 125, no. 2, pp. 683–690, 2004, doi: 10.1378/chest.125.2.683.

[14] Y.-H. Lin, J.-H. Cheng, L.-C. Chang, W.-J. Lin, J.-H. Tsai, and T.-W. Huang, “A broadband MFCW agile radar concept for vital-sign detection under various thoracic movements,” *IEEE Trans. Microw. Theory Techn.*, vol. 70, no. 8, pp. 4056–4070, Aug. 2022, doi: 10.1109/TMTT.2022.3186014.

[15] C. Gouveia, D. F. Albuquerque, P. Pinho, and J. Vieira, “Bio-radar cardiac signal model used for HRV assessment and evaluation using adaptive filtering,” *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–10, 2022, doi: 10.1109.TIM.2022.3190035.

[16] S. Dong et al., “Doppler cardiogram: A remote detection of human heart activities,” *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 3, pp. 1132–1141, Mar. 2020, doi: 10.1109.TMTT.2019.2948844.

[17] W. Lv, W. He, X. Lin, and J. Miao, “Non-contact monitoring of human vital signs using FMCW millimeter wave radar in the 120 GHz band,” *Sensors*, vol. 21, no. 8, p. 2732, 2021, doi: 10.3390/s21082732.

[18] Y. Wang, W. Wang, M. Zhou, A. Ren, and Z. Tian, “Remote monitoring of human vital signs based on 77-GHz mm-Wave FMCW radar,” *Sensors*, vol. 20, no. 10, p. 2999, 2020, doi: 10.3390/s20102999.

[19] M. Alizadeh, G. Shaker, J. C. M. D. Almeida, P. P. Morita, and S. Safavi-Naeini, “Remote monitoring of human vital signs using mm-Wave FMCW radar,” *IEEE Access*, vol. 7, pp. 54958–54968, 2019, doi: 10.1109/ACCESS.2019.2912956.

[20] T. K. V. Dai, Y. Yu, P. Theilmann, A. E. Fathy, and O. Kilic, “Remote vital sign monitoring with reduced random body swaying motion using heartbeat template and wavelet transform based on constellation diagrams,” *IEEE J. Electromagn., RF, Microw. Med. Biol.*, vol. 6, no. 3, pp. 429–436, Sep. 2022, doi: 10.1109/JERM.2022.3140900.

[21] F.-K. Wang, T.-S. Horng, K.-C. Peng, J.-K. Jau, J.-Y. Li, and C.-C. Chen, “Single-antenna doppler radars using self and mutual injection locking for vital sign detection with random body movement cancellation,” *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 123, pp. 3577–3587, Dec. 2011, doi: 10.1109/TMTT.2011.2171712.

[22] K. Gupta, M. B. Srinivas, J. Soumya, O. J. Pandey, and L. R. Cenkeramaddi, “Automatic contact-less monitoring of breathing rate and heart rate utilizing the fusion of mmWave radar and camera steering system,” *IEEE Sensors J.*, vol. 22, no. 22, pp. 22179–22191, Nov. 2022, doi: 10.1109/JSEN.2022.3210256.

[23] J. Chen, D. Zhang, Z. Wu, F. Zhou, Q. Sun, and Y. Chen, “Contactless electrocardiogram monitoring with millimeter wave radar,” *IEEE Trans. Mobile Comput.*, early access, Oct. 14, 2022, doi: 10.1109/TMC.2022.3214721.

[24] A. Timmis et al., “European society of cardiology: Cardiovascular disease statistics 2021,” *Eur. Heart J.*, vol. 43, no. 8, pp. 716–799, 2022, doi: 10.1093/eurheartj/ehab892.

[25] G. A. Roth et al., “The burden of cardiovascular diseases among us states, 1990–2016,” *JAMA Cardiol.*, vol. 3, no. 5, pp. 375–389, 2018.

[26] Z. Xu et al., “Simultaneous monitoring of multiple people’s vital sign leveraging a single phased-MIMO radar,” *IEEE J. Electromagn., RF, Microw. Med. Biol.*, vol. 6, no. 3, pp. 311–320, Sep. 2022, doi: 10.1109/JERM.2022.3143431.

[27] F.-K. Wang, J.-X. Zhong, and J.-Y. Shih, “IQ signal demodulation for noncontact vital sign monitoring using a CW Doppler radar: A review,” *IEEE J. Electromagn., RF, Microw. Med. Biol.*, vol. 6, no. 4, pp. 449–460, Dec. 2022, doi: 10.1109/JERM.2022.3214753.

[28] V. Rajagopal, A.-K. Moadi, A. E. Fathy, and M. A. Abidi, “Portable real-time system for multi-subject localization and vital sign estimation,” in *Proc. IEEE Radio Wireless Symp.*, 2023, pp. 40–43, doi: 10.1109/RWS55624.2023.10046315.

[29] (WHO, Geneva, Switzerland). *Cardiovascular Diseases (CVDs)*. 2021. [Online]. Available: https://www.who.int/en/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds)

[30] “European cardiovascular disease statistics.” 2017. [Online]. Available: https://ehnheart.org/cvd-statistics.html

[31] “GARMIN—Sciences de la Santé.” GARMIN. 2023. [Online]. Available: https://www.garmin.com/fr-FR/garmin-technology/health-science/respiration-rate/