# Contactless Measurement of Human Systolic Time Intervals Based on Doppler Cardiograms in Clinical Environment

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***Abstract*—As the most important organ of human body, heart has many measures and indicators to assess the cardiac function in clinic. Ventricular systolic time intervals (STIs) are of major relevance in providing crucial information regarding cardiovascular state. However, the existing measurement technologies are costly, complicated to operate, and also require contact sensors. Based on the human cardiovascular model and principle of Doppler cardiogram (DCG), the differential DCG (D-DCG) and quadratic D-DCG (QD-DCG) carry the aortic pressure (AP) information by which the STIs can be calculated. A 24-GHz digital dc-tuning Doppler radar sensor (DRS) has been implemented to detect the accurate DCGs. To assess the feasibility of contactless measurement of the STIs by DRS, clinical experiments and evaluations are carried out in the operation theater (OT). The preejection period (PEP) and the left ventricular ejection time (LVET) estimation results reached 95.23% and 93.12% accuracy, respectively, which indicates that the proposed method has great potential to be used for STIs estimation and could be convenient for patient home monitoring.**

***Index Terms*—Differential Doppler cardiogram (D-DCG), Doppler radar sensor (DRS), quadratic D-DCG (QD-DCG), systolic time intervals (STIs).**

## I. Introduction

FOR human health monitoring, heart activity detection is always the most important research topic for medical and related researchers. Measurement of the rhythmic time intervals of cardiac cycle offers a quantifiable method to assess cardiac function. Among them, the estimation of heart systolic time intervals (STIs) attracted the most interest due to its clinical value [1].

The STIs represent the duration of total electromechanical systole with two commonly used time intervals, i.e., preejection period (PEP) and left ventricular ejection time (LVET) [1]. The determination of STIs offers an efficient method to study the changes in left ventricular performance and the effects of therapeutic interventions or diseases on myocardial performance [1]. PEP and LVET have been known to be useful for evaluation of cardiac function. Specifically, the PEP/LVET ratio has been shown to be the most sensitive index of ventricular function [2]. In addition, the PEP can be used to improve blood pressure estimation based on pulse arrival time [2].

In the past decade, STIs were traditionally assessed by simultaneous recording of an electrocardiogram (ECG), phonocardiogram (PCG), and carotid pulse tracing using a multichannel photographic recording system [2], the operation is complex. Several technologies reported recently use Doppler echocardiograpy or impedance cardiography (ICG) to measure STIs [1]. All these methods require multiple contact sensors, making it unsuitable for daily healthcare and burn victims, and also increase the complexity of doctors operations in the clinical environment such as operation theater (OT).

Due to the noncontact advantage of Doppler radar sensor (DRS), recently, the Doppler signal, which induced by the heart mechanical motions conducted to the skin on the chest, can be detected by remotely measuring via DRS and offers a temporal characteristic point (CP) that is corresponding to the P wave, QRS wave, and R wave of ECG. Such signal was named “Doppler cardiogram (DCG)” in [4].

In this work, based on the analysis of human heart model, it is found that the differential DCG (D-DCG) and quadratic D-DCG (QD-DCG) carry aortic blood flow timing information corresponding to the time of aortic valve opening, which can be used to calculate STIs. To assess the feasibility of these DCGs to measure STIs, a $K$-band 24-GHz dc-coupled DRS was designed first for accurate detection of DCGs, and then, an adaptive signal extraction algorithm is proposed to obtain the DCGs in the presence of normal breath. Finally, the clinical experiment is conducted in OT, the ECG and aortic blood pressure are recorded by multiparameters life monitor simultaneously as a reference. Aiming at a noncontact, flexible measurement method, an agile DRS is implemented, including signal assessment and the feasibility of measuring the STIs. The experimental results showed that the detected DCGs are aligned very well with the reference signals. Also, the calculated STIs by contactless DRS have high accuracy with reference to ground truth.

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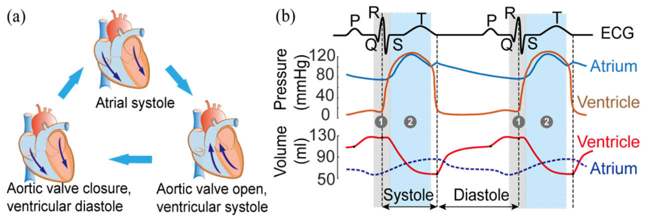


Fig. 1. (a) Cardiac cycle phases. (b) Modified Wiggers diagram with gray zone indicating 1 (PEP) and blue zone indicating 2 (LEVT) [2].

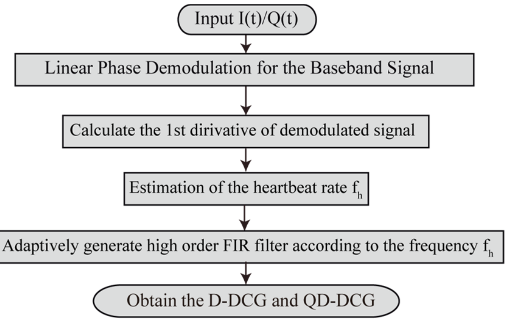


Fig. 2. Flowchart of the proposed adaptive D-DCG extraction algorithm.

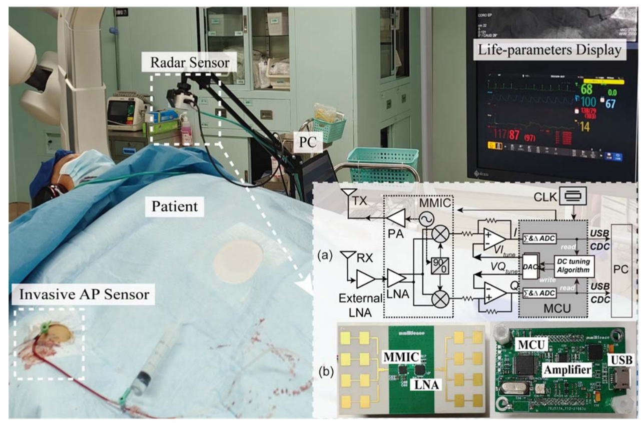


Fig. 3. Experimental setup in OT. (a) System block diagram of the 24-GHz radar sensor. (b) Implementation of 24-GHz radar sensor.

## II. Theory

### A. Principle

In cardiology, the cardiac cycle contains a complete contraction and relaxation of both the atria and ventricles that take place in an ordered sequence. In Fig. 1(a), the different phases of the cardiac cycle are represented. Fig. 1(b) shows the modified Wiggers diagram, which provides a comprehensive view of relationships between the phases and components of cardiac cycle. As illustrated in the diagram, according to the widely used STIs' definition, PEP is the time interval between the Q point of the ECG and the opening of the aortic valve, corresponding to the point at which rising begins of aortic pressure (AP) waveform. Also, LVET is the time interval between the opening of the aortic valve and its subsequent closure [1], corresponding to the interval from rising beginning to the notch in the AP waveform.

The Teichholz model is a widely used heart model in medicine, and it describes the human heart as a biplane, long-axis ellipsoid. The temporal volume $V(t)$ can be modeled as

$$V(t) = 7D^3(t)/(D(t) + 2.4) \tag{1}$$

where $D(t)$ is the temporal length change of the model's short axes [3]. According to the heart position in human body, the length change $D(t)$ will cause the human chest displacements via tissues, which is named DCG in [4]. Thus, the volume change $V(t)$ can be obtained by this model. Subsequently, the Windkessel model reveals the relationship between blood pressure $P(t)$ and blood flow in the aorta. The flow of blood $i(t)$ from the heart is given as [5]

$$\left(1 + \frac{r}{R}\right) i(t) + CR_1 \frac{\mathrm{d}i(t)}{\mathrm{d}t} = \frac{P(t)}{R} + C\frac{\mathrm{d}P(t)}{\mathrm{d}t} \tag{2}$$

where $P(t)$ is the blood pressure in the aorta, $C$ is the arterial compliance, $R$ is the peripheral resistance of the arterial system, $r$ is the resistance to flow, and $R_1$ is the characteristic aortic impedance.

In physiology, the left ventricular, which has the biggest volume of the heart's four chambers, its contraction forces oxygenated blood through the aortic valve to be distributed to the entire body [5]. The ventricular volume change $V(t)$ results in the blood flow to the aorta, and its first derivative result should have a correlation with the blood flow to aorta [5]

$$i(t) \propto V'(t) \quad \text{and} \quad \frac{\mathrm{d}i(t)}{\mathrm{d}t} \propto V''(t). \tag{3}$$

Therefore, the DCGs (D-DCG and QD-DCG) should have correspondence with aortic blood pressure from which can acquire the timing information of aortic valve activity.

### B. Algorithm

For a zero-IF DRS, the mixer outputs $I(t)$ and $Q(t)$ signals can be expressed as follows:

$$I(t) = A_I \cdot \cos[4\pi x(t)/\lambda + \varphi_0 + \Delta\varphi] + \mathrm{dc}_I \tag{4}$$
$$Q(t) = A_Q \cdot \sin[4\pi x(t)/\lambda + \varphi_0 + \Delta\varphi] + \mathrm{dc}_Q \tag{5}$$

where $A_I$ and $A_Q$ are the amplitudes of the quadrature $I/Q$ signals, respectively, $\mathrm{dc}_I/\mathrm{dc}_Q$ are the dc offsets, $\varphi_0$ is the initial phase of the radar system, $x(t)$ is the target motion, $\lambda$ is the wavelength of the radar carrier, and $\Delta\varphi$ is the residual phase noise.

Aiming to linearly recover the target motion $x(t)$ with no distortion, (4) and (5) have to be calibrated to remove the dc offsets by fitting the $I/Q$ signals on the unit circle using compensation techniques [6]. Then, the heart motion $x(t)$ can be reconstructed by applying the modified differentiation and cross-multiply (MDACM) algorithm [8].

During the detection of human vital sign, the recovered target motion $x(t)$ usually contains human cardiac and respiration components. In the normal breath scenario, the respiration waveform is generally very smooth, its fundamental frequency is between 0.2 and 0.4 Hz and does not contain many higher harmonics [7]. Therefore, using a suitable high-pass filter can filter out most of the respiratory signals.

In this letter, an adaptive digital finite impulse response (FIR) high-pass filter is designed to remove the respiration. The cutoff frequency $f_c$ of FIR filter is adaptively determined by differential signal spectrum estimation of demodulated human motion. Then, $f_c$ is selected to be $(f_h - 0.1)$ Hz. The transition band of the designed filter is 0.1 Hz, and

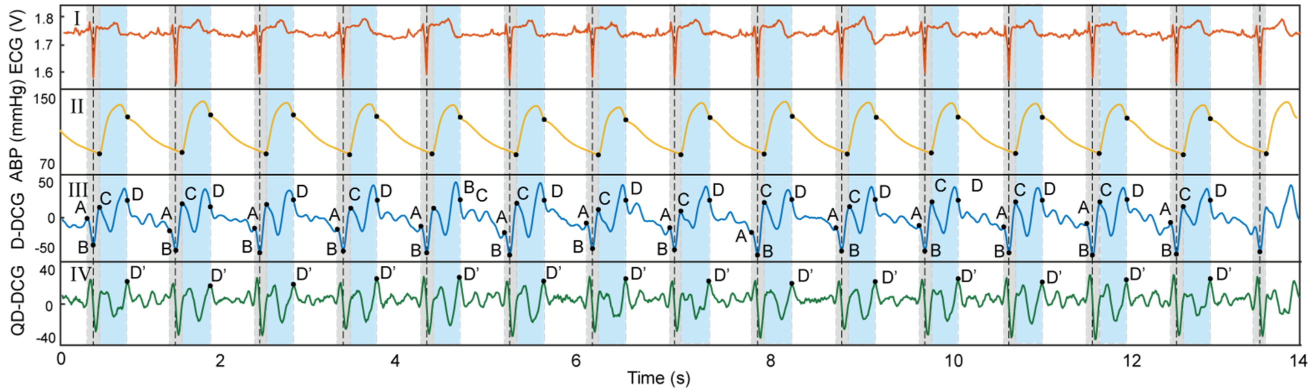


Fig. 4. Comparison between the measured D-DCG and the reference signals measured by multiparameters life monitor in OT.

the stopband attenuation is 80 dB. By leveraging the FIR equiripple method, the desired FIR filter can be constructed with advantageous computational efficiency. After the filtering process, the D-DCG signal can be fully retrieved in the presence of human respiration. Also, if needed, the DCG signal can be obtained by integrating the D-DCG signal. The flowchart of the proposed adaptive D-DCG extraction algorithm is shown in Fig. 2.

## III. Experiments and Discussion

Fig. 3(a) shows the detailed block diagram of the DRS developed for measuring the DCG based on a 24-GHz front-end silicon–germanium millimeter-wave integrated circuit (MMIC), SGR SPK1101A. Also, an additional $K$-band low noise amplifier silicon radar LNA_024_005 is employed to improve the noise figure performance of the receiver. The $I/Q$ signals sampled by the embedded 16-bit sigma–delta analog-to-digital converters (SDADCs) inside the microcontroller unit (MCU) STM32F373CCT6 can be transmitted to a computer with full-speed universal serial bus (USB) interface.

In addition, a low-complexity dc tuning algorithm running in MCU is proposed, as shown in the gray zone in Fig. 3(a), to make full use of the sampling range of the analog to digital converters (ADCs) with no need to add any hardware. In Fig. 3(b), the photograph shows the implemented board-integrated radar system according to the block diagram in Fig. 3(a).

The experiment was conducted at the bedside in a hybrid OT on a 45-year-old female patient. The scheme of the clinical experiment setup is shown in Fig. 3. A patient multiparameters life monitor, Philips MP2 M8102A, is used for patient in this OT. This monitor can simultaneously record the ECG, invasive arterial blood pressure (ABP), and other life parameters. The patient has just finished the angiography operation and is in the postoperative observation period, at which time the life-parameters monitoring was still working and the invasive AP sensor was not removed. The DCGs measurement was conducted from the front of patient with supine posture without requirement for patient movement. The ECG, AP, and radar signal recording were simultaneously made for comparison purpose, while the patient is in supine position with normal breath, so that the STIs measured by DCGs can be convincingly verified. The written informed consent was obtained from the patient.

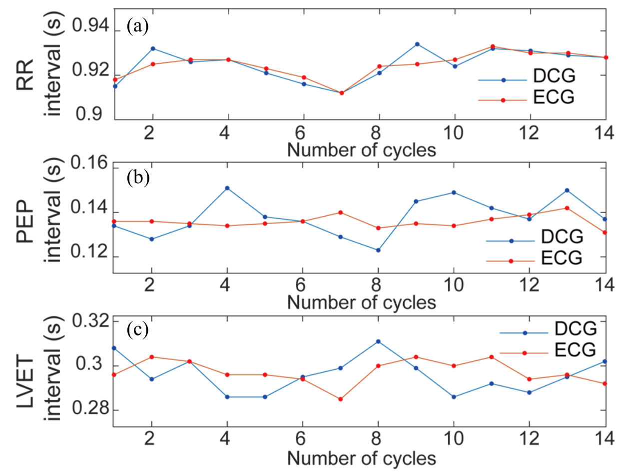


Fig. 5. Comparison between the time intervals retrieved from the D-DCG/QD-DCG and reference signals: (a) RR, (b) PEP, and (c) LVET.

Fig. 4 shows the 14-s record of the experiment. The R peak denoted by the vertical dashed line of ECG corresponds to the minimum point of D-DCG, which means the maximum blood flow velocity. PEP and LVET are annotated in blue and gray zone, respectively. The CPs A to D/D′ are denoted in panels III and IV of Fig. 4. It is noted that point D’ located on a peak of QD-DCG is needed to determine point D that corresponds to the closure of aortic valve. Other points A–C indicate the time information of ECG Q-wave, the ECG R-peak, and the opening of the aortic valve, respectively.

Fig. 5 shows the comparison between the STIs retrieved from the DCGs and reference signals. The root-mean-square error (RMSE) and the mean absolute percentage error (MAPE) of PEP and LVET are 8.6 ms/6.35% and 9.5 ms/3.2%, respectively. Besides, to compare the accuracy of the detected DCGs with respect to ECG, the R-R intervals detection error is also calculated, which is 3.5 ms/0.38%.

## IV. Conclusion

In this work, the feasibility of contactless measurement of STIs using DCGs is demonstrated in the clinical scenario. A $K$-band board-integrated dc-coupled DRS and multiparameters life monitor in OT were simultaneously employed to verify the arguments. The experimental results show that the designed radar system and the proposed algorithm have a promising potential to be used for STIs estimation.

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