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Automatic Detection of Characteristic Points in Impedance Cardiogram

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Abstract

Estimation of stroke volume and several other cardiovascular indices using impedance cardiography requires error-free detection of the characteristic points in the impedance cardiogram. A technique for automatic detection of B, C, and X points, using R peaks in the simultaneously acquired ECG as reference, is presented. It does not require estimation of the baseline and selection of processing parameters. Use of the technique on pre-exercise and post-exercise recordings from healthy subjects and cardiac patients showed a very low detection error.

1. Introduction

Impedance cardiography is a noninvasive technique, based on monitoring of the thoracic impedance, for estimating the stroke volume (SV) and some other indices related to cardiac activity [1-5]. It involves applying a low level current (< 5 mA) of 20 − 100 kHz across the thorax through a pair of spot or band electrodes placed on the thoracic segment and sensing the voltage developed across the same or another inner pair of electrodes. Envelope of the voltage is related to the time-varying impedance of the thorax and the negative of its derivative is known as the impedance cardiogram (ICG).

Impedance cardiography has also been used for diagnosing atrial and ventricular dysfunctions, valve disorders, aortic stenosis, and vascular diseases [4,6,7]. Bour and Kellett [8] reported its use in determining the ventricular dyssynchrony in cardiac resynchronization therapy. The technique may be used in the emergency departments for finding the cause and severity of heart attack [6,9]. In sports medicine, it may be used for examining the effects of different physical exercises, sleep, and drugs on cardiovascular system [10]. It may be useful in detecting ischemia (a localized vasoconstriction) during exercise [6]. It has been used to monitor the resuscitation in a patient in intensive care unit [11], for examining the effect of different diseases on autonomic nervous system [12], for blood flow monitoring during anesthesia [13], and for monitoring of the cardiac hemodynamics during the cesarean delivery under spinal anesthesia [14]. The time interval between the Q wave of ECG and the C point of ICG has been shown to be related to the systolic blood pressure and thus it may be used for monitoring the blood pressure without using a cuff [15].

Almost all the applications of impedance cardiography require determination of some of the characteristic points of the ICG waveform. A time-domain technique for automatic detection of B, C, and X points in the ICG signal is presented. It does not require estimation of the baseline and selection of processing parameters. It is evaluated on recordings taken under rest as well as in the post-exercise relaxation condition with large respiratory artefact and high variability in cardiac activity.

2. Signal processing

The ICG waveform has a set of characteristic points [1,16] known as A, B, C, X, and O, as shown in Figure 1. These points are related to distinct physiological events in the cardiac cycle. The A point follows the P wave of the ECG signal and is related to the atrial contraction. The B point is associated with the aortic valve opening and it coincides with the first heart sound in the phonocardiogram (PCG). The C point is considered to be associated with the ventricular contraction [2]. The X point is below the baseline, and it is associated with the aortic valve closure [2,16]. It coincides with the second heart sound in PCG, as shown in Figure 1. Thus the time interval between the B point and the X point is the left ventricular ejection time. The O point is associated with the wide opening of the mitral valve.

The ICG peak is taken as the C point and the lowest point after it is taken as the X point. Initially, the zero-crossing before the C point was taken as the B point. Later it was determined as the point corresponding to 15% of the ICG peak, as shown in the figure [2]. However it has been reported that the B point may occur at any point on the ascending portion of the signal before the C point [17].

The sensed ICG signal is generally contaminated with artifacts related to motion and respiration [1,5,18,19]. The spectra of the cardiac related components, respiratory artifact, and motion artifact in the sensed ICG have a significant overlap. The artifacts may have much larger amplitudes than the cardiac related signal, severely affecting the detection of the characteristic points of ICG and introducing errors in the estimation of SV and other cardiovascular indices. Ensemble averaging of the sensed

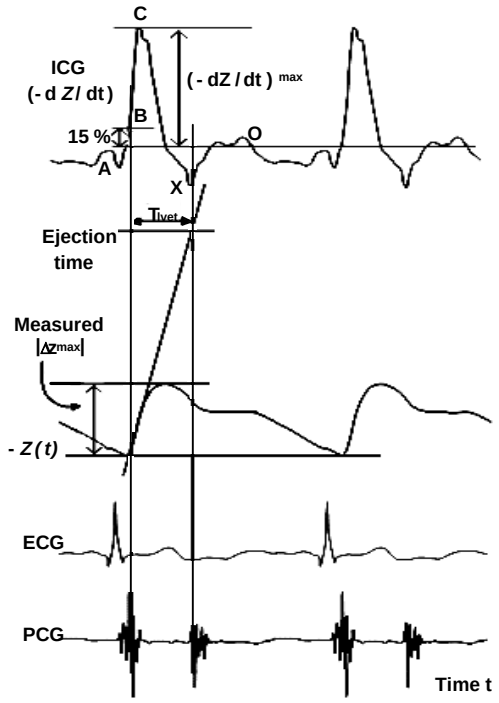

Figure 1. ICG and other related signals, adapted from [1]

ICG with respect to the ECG-R peaks [19] is the most commonly used method for artifact suppression, but it may introduce smearing in the characteristic points due to the beat-to-beat variation in the cardiac events, and it cannot be used for continuously monitoring the cardiovascular indices. Digital filtering techniques are not very effective in suppressing the artifacts because of their spectral overlap with the cardiac related signal. Several signal processing techniques based on adaptive filtering, wavelet-based denoising, etc. have been developed to suppress the artifacts [20-22]. As these denoising techniques suppress the artifacts only to a certain extent, we need techniques for automated detection of the characteristic points without significant errors even in the presence of artifacts.

In one of the techniques for improving the estimation of the left ventricular ejection time, PCG signal was used as the reference [23]. Several wavelet-based techniques have been reported for detecting the characteristic points without using waveforms from another sensor [8,24,25]. These techniques require manual selection of the threshold values and are not very effective in detecting the less prominent B and X points in the artifact contaminated signals.

A technique is proposed and investigated for detecting the B, C, and X points, the characteristic points most commonly used for estimating SV and several other cardiovascular indices. It is a time-domain technique and it has been developed after an examination of a large number of artifact-free and artifact-contaminated recordings. It does not require estimation of the baseline and selection of the processing parameters. Unlike the wavelet based techniques, it can be used on shorter record lengths.

The cycle identification in the ICG signal may be prone to event misdetection. Hence R-peak in the simultaneously recorded ECG is taken as a reference for cycle identification. The R peak detection may be carried out by Pan-Tompkins algorithm [26]. As correct identification of cardiac cycles is critical for detecting the characteristic points in ICG, artifact suppression may be applied on the ECG signal before R- peak detection.

In each cardiac cycle, the C point is detected as the highest point within the ICG segment starting at the ECG R peak and of length equal to one-fifth of the R-R interval. The B and X points are determined with reference to the C point. The first minimum preceding the C point is taken as the B point. The lowest point in the ICG segment starting at the C point and of length equal to one-third of the C-C interval is taken as the X point. These definitions for identifying the B and X points result in a consistent estimation of B-X time interval to be used as the left ventricular ejection time.

3. Method of evaluation

The technique was tested on ICG recordings from nine healthy subjects and five cardiac patients. The ICG signals were recorded at a sampling rate of 500 Hz, using an ICG instrument developed in our lab [21] and the ICG instrument model 'HIC-2000' (from Bio-impedance Technology, Chapel Hill, NC). For processing of ICG waveforms, a wavelet-based denoising, using scale-dependent thresholding [27] was used. This denoising technique gives about 23 dB improvement in the signal-to-artifact ratio for signals highly corrupted by respiratory artifact. Detection of characteristic points was carried out on both the unprocessed ICG as well as the denoised ICG.

A visual examination of the results of the automated detection of the characteristic points was carried out by using a program which marked the detected points on the waveform itself. For a quantitative evaluation of the technique, locations of the automatically detected points were compared with the points visually located in accordance with definitions as given earlier in the second section and shown in Figure 1. Failure to detect a true point was counted as a failed detection (FD), and detection of a false point was counted as misdetection (MD). With TP as the total number of true points detected, the following performance indices, similar to those used in [28], were calculated.

$$\text{Sensitivity} = TP / (TP+FD) \quad (1)$$

Positive predictivity = TP / (TP+MD) (2)

Detection error = (FD +MD) / (TP+FD) (3)

4. Results

Evaluation of the technique was carried out by applying it on a total of 545 cardiac cycles in the recordings from nine healthy subjects and five cardiac patients. Examples of the detection of the points are shown in Figure 2. A qualitative visual examination of the automatically detected points showed a very small number of errors, and most of the errors were related to errors in the detection of the R peaks. A quantitative evaluation was carried out by calculating the performance indices as given in Eq.1-3. The values of the indices for the detection of the B, C, and X points, using the unprocessed as well as the denoised waveforms, are given in Table 1. For detection of the C point, the technique showed excellent sensitivity (99.4 %) and very low detection error (1.8 %) in the unprocessed as well as the denoised signals. Somewhat higher errors were observed in the detection of relatively less distinct B and X points. The results for the unprocessed ICG and the denoised ICG were almost similar.

Table 1. Evaluation indices (%) for detection of characteristic points. Sens.: sensitivity, Pos. pred.: positive predictivity, Det. error: detection error.

ICG Point	Unprocessed ICG			Denoised ICG		
	Sens	Pos. pred.	Det. error	Sens	Pos. pred.	Det. error
B	93.4	93.0	13.6	94.4	93.9	11.7
C	99.4	98.7	1.8	99.4	98.7	1.8
X	97.4	96.9	5.6	97.0	96.5	6.5

5. Conclusion

A time-domain technique for automatic detection of B, C, and X points in the ICG waveform has been presented. It does not require estimation of the baseline and selection of the processing parameters. Use of the technique on pre-exercise and post-exercise recordings from healthy subjects and cardiac patients showed that the points were detected with a high sensitivity and a low detection error, with very similar results for the unprocessed and the denoised ICG waveforms. It needs to be further evaluated by applying it on recordings in a clinical setting for estimating the stroke volume and other cardiovascular indices.

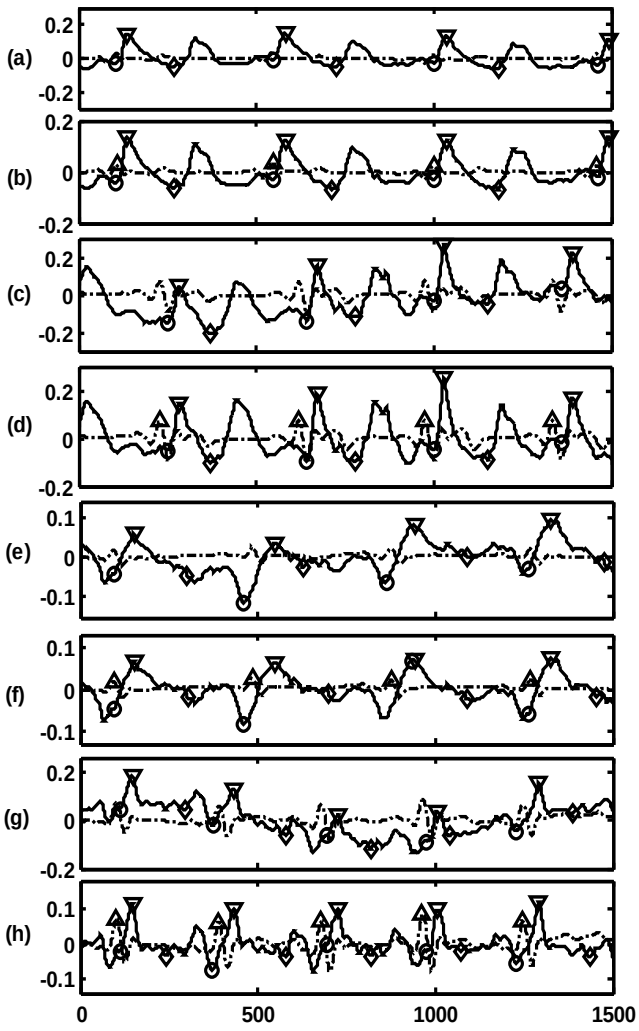

Figure 2. Detection of BCX points: (a) pre-execrcise recording from subject SH9, (b) recording in 'a' after denoising, (c) post-exercise recording from subject SH9, (d) recording in 'c' after denoising, (e) pre-exercise recording from subject PT1, (f) recording in 'e' after denoising, (g) post-exercise recording from subject PT1, (h) recording in 'g' after denoising. Solid: ICG, dotted: ECG, inverted triangle: C point, triangle: R peak, dimond: X point, circle: B point.

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