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New real-time heartbeat detection method using the angle of a single-lead electrocardiogram

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ABSTRACT

This study presents a new real-time heartbeat detection algorithm using the geometric angle between two consecutive samples of single-lead electrocardiogram (ECG) signals. The angle was adopted as a new index representing the slope of ECG signal. The method consists of three steps: elimination of high-frequency noise, calculation of the angle of ECG signal, and detection of R-waves using a simple adaptive thresholding technique. The MIT-BIH arrhythmia database, QT database, European ST-T database, T-wave alternans database and synthesized ECG signals were used to evaluate the performance of the proposed algorithm and compare with the results of other methods suggested in literature. The proposed method shows a high detection rate—99.95% of the sensitivity, 99.95% of the positive predictivity, and 0.10% of the fail detection rate on the four databases. The result shows that the proposed method can yield better or comparable performance than other literature despite the relatively simple process. The proposed algorithm needs only a single-lead ECG, and involves a simple and quick calculation. Moreover, it does not require post-processing to enhance the detection. Thus, it can be effectively applied to various real-time healthcare and medical devices.

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1. Introduction

The electrocardiogram (ECG) is the recording of the electrical activity of the heart which is non-invasively measured. The ECG is important in the diagnosis of cardiovascular disease because it provides critical information about ischemic heart diseases, arrhythmia, coronary artery disease, angina pectoris, myocardial infarction, atherosclerosis [1]. The system that automatically analyzes the ECG firstly requires accurate heartbeat detection prior to identify the diagnosis parameters of the cardiovascular disease [2–6].

Numerous heartbeat detection algorithms that can be applied to automatic diagnosis systems have been proposed. Existing methods have used derivative-based algorithms [2,5,7,8], wavelet transforms [3,6,9,10], filter bank [11], Hilbert transform [12,13], matched filters [14,15], artificial neural networks [14,16–18], and hidden Markov models [17,19,20]. Using a different concept, phasor transform was also applied for automatic delineation of fiducial points of single-lead ECG [21]. Most of the previous methods have produced excellent results in heartbeat detection.

However, these methods have complex pre- and/or post-processing procedure, and they need too many parameters for calculation [4,15]. In addition, some methods require multi-lead ECG signals [22], or additional training or a reference signal in order to enhance the detection performance [14,17]. Increasing of the computational complexity and cost in algorithm is hindered real-time implementation. Furthermore, their performance is seriously affected by various noises, such as baseline wandering, and high frequency noise [2,5].

This study presents a computationally efficient and accurate method for the heartbeat (actually R-peak) detection based on the geometric angle between two consecutive samples of single-lead ECG signal. It is a new approach for detecting the heartbeat that uses the angle between two consecutive samples without the amplitude or morphology of the ECG. Its primary advantage is that it can accurately emphasize the QRS complex without being influenced by variations in amplitude, width, or the morphology of the QRS complex. Moreover, it yields high detection rates despite the relatively simple process. Therefore, the proposed method is suitable for the real-time automated diagnosis, the various real-time healthcare and medical devices.

2. Methods

2.1. Angle of ECG signal

Prior to calculating the angle of ECG signal, as a preprocessing stage, a 64th order low-pass finite impulse response (FIR) filter

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with a cut-off frequency of 25 Hz was used to eliminate high-frequency noise. The cut-off frequency and the order of the filter were chosen within a range that does not affect the morphology of the QRS complex. After the preprocessing, the angle of ECG signal was calculated. In this study, the geometric angle, $y(n)$ in degree, between two consecutive samples of ECG signal is defined as

$$y(n) = \tan^{-1}\left(\frac{a}{b}\right) = \tan^{-1}\left(\frac{c \times |x(n) - x(n-1)|}{360/fs}\right) \quad (1)$$

where $x(n)$ is a n^{th} sample of digitized ECG signal, a is a scaled version of absolute value of amplitude difference between the two samples, and b is a scaled time interval between the two samples, and f_s is the sampling rate of the signal. The absolute value of amplitude difference is multiplied by a scale factor, c. The initial value of c is 512, but when a/b is smaller than 58 (about 89.01 degree) during two seconds, the value is changed to 1024. After that, the value of c is changed to 512 again when a/b is larger than 120 (about 89.5 degree). This helps to detect the beat which is inherently small or getting smaller. Actually, b is a constant value according to the sampling rate in digitized signal. In case of digitized signal with 360 samples per second, b is set to 1, and we can easily calculate the angle in degrees, $y(n)$, using an arctangent operation of scaled absolute value of amplitude difference between the two samples as described in the right term of Eq. (1). Fig. 1 shows the filtered ECG signals (f_s=360 Hz) and corresponding angles obtained by Eq. (1). As shown in this figure, the angles of QRS complex of typical Lead II fall within a range of 80 to 90 degrees. Also, despite the beat-to-beat change in morphology and amplitude of QRS complex, the angles are still maintained within a range of 80 to 90 degrees.

2.2. Heartbeat detection

In order to detect the heartbeat, we applied an adaptive threshold method to the angle obtained from Eq. (1). The value of threshold is also expressed as an angle. First, by comparing the calculated $y(n)$ and the threshold, a time window to detect the R-peak was determined. Then, the R-peak was detected from the filtered ECG signal which is corresponding to the time window. In this procedure, the threshold is automatically adjusted to the each beat, since the characteristics of QRS complex, such as amplitude, width and shape or morphology vary depending on the subject and measuring environment. For this reason, an adaptive threshold method was adopted to respond properly to different conditions. The value of threshold, $w(n)$, can be updated according to the following condition:

$$w(n+1) = \begin{cases} y(n) - k1, & y(n) > w(n) + k1 \\ w(n), & w(n) < y(n) \le w(n) + k1, ct = 0 \\ w(n) - (k2 \times ct), & y(n) \le w(n), ct = ct + 1 \\ 80, & w(n) \le 80 \end{cases} \quad (2)$$

where $k1$ and $k2$ are 0.5 and 0.0001 degrees, respectively. The initial value of the threshold is zero degree. If $y(n)$ is greater than $w(n)+k1$, $w(n+1)$ is updated as $y(n)-k1$. If $y(n)$ is equal or less than $w(n)$, the decreasing constant, ct, increases by one, and $w(n+1)$ is reduced by the value of the ct multiplied by $k2$. Since the value of ct increases over time, $w(n+1)$ decreases rapidly. When this condition continues and the threshold reaches to 80 degrees, the threshold is not updated. If $y(n)$ is greater than $w(n)$ and less than or equal to $w(n)+k1$, ct is reset to zero, and $w(n+1)$ is equal to $w(n)$. This adjusting rule described in Eq. (2) has been devised to have larger threshold value at the time of occurrence of R-peak and to have lower value at the rest time. As can be seen from Eq. (2), the upper limit and reduction rate of threshold value are determined by $k1$ and $k2$. The higher the value of $k1$ and $k2$, the threshold is determined to smaller value and is reduced quickly. As a result, the false detection (false positive) increases by tall T-wave or noise. In the opposite case, the missed detection (false negative) increases. Therefore, it is important to select the proper value of $k1$ and $k2$. These two values were determined empirically to reduce the detection error.

After the R-peak occurs, the adjusting technique reduces the threshold value, and increases the value of ct over time. When a new R-peak occurs, the value of ct becomes zero. So, it can be considered that the R-peak exists only when the value of ct is small. Therefore, by observing the value of ct, we can determine the range of time

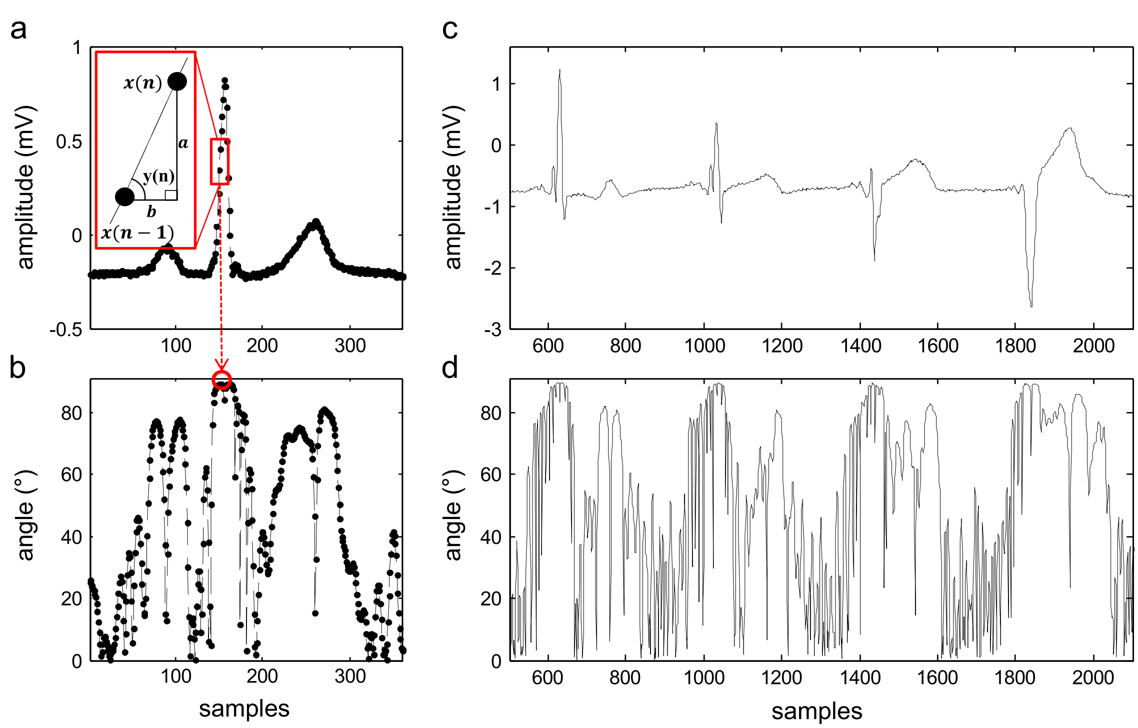

Fig. 1. Filtered ECG signals and corresponding angles. (a) Typical Lead II signal, (b) corresponding angle of (a) obtained by Eq. (1), (c) lead II signal with beat-to-beat changes in morphology of QRS complex (d) corresponding angle of (c).

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