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An ECG Signal Processing Algorithm Based on Removal of Wave Deflections in Time Domain

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Abstract— **This paper introduces a new approach to process biomedical signals by surgically removing wave deflections in time domain. The method first determines the epochs of high frequency deflections, cuts out them from the signal, and then connects the two disconnected points. To determine the epoch of a deflection to be removed, four slope trace waves are used to isolate the deflection based on signal characteristics of amplitude, slope, duration, and distance from neighboring deflections. The method has been applied to simulated data and MIT-BIH arrhythmia database to show its practical efficacy in the case of baseline wandering removal. It is found that the method has the capability to identify and remove high frequency deflections appropriately, leaving low frequency deflection such as baseline drifting.**

I. INTRODUCTION

ELECTORCARDIOGRAPHY(ECG) carries information on cardiac events of both normal and pathological processes. The signal usually requires preprocessing to remove different types of noise from various sources such as 50/60Hz power line interference, motion artifacts, muscle activities, or poor contact and polarization of the electrodes, for easier information extraction and reliable analysis. One of the main signal contaminations of ECG that has to be removed in the preprocessing stage is baseline drift, which makes the detection of QRS complex difficult or the analysis of isoelectricity of the ST segment difficult even after conventional signal filtering [1]-[2].

Conventional techniques for noise suppression are band-pass filtering, which distorts the ST segment as well as the QRS complex significantly [3]. Adaptive filtering techniques have been developed and applied for ECG signals. However, in some cases, these techniques show the difficulty in obtaining a suitable reference signal, limiting the wide application of the method [4]-[6]. Wavelet transform has been an interesting solution to ECG signal preprocessing [7]-[9]. Although this method is promising, the scale and the thresholds for non-stationary baseline drift removals and noise depression cannot be chosen adaptively.

Morphological operators have been widely applied in extracting shape information in the one dimensional or image signals because of its simplicity and robust performance [10]–[12]. However, their morphological filtering (MF) algorithm distorts the characteristic points in ECG signal, making it difficult to detect the significant ECG components or intervals reliably.

In this paper, we introduce a new approach to process biomedical signals by surgically removing wave deflections in time domain. The method first determines the epochs of high frequency deflections, cuts them out from the signal, and then connects the two disconnected points. To determine the epoch of a deflection to be removed, four slope trace waves are used to select and isolate the deflection using signal characteristics of amplitude, slope, duration, and distance from neighboring deflections. The method first removes the higher frequency deflections such as QRS complex or noise, leaving lower frequency deflections such as P-waves, T-waves, or baseline wandering in the signal. The removal procedure is repeated to remove the next higher frequency deflections.

The method has been applied to simulated data and MIT-BIH arrhythmia database to show its practical efficacy. It is found that the method has practical efficacy in removing waveform deflections, showing a kind of morphology based filtering characteristic without causing significant waveform distortion.

II. SLOPE TRACE WAVE AND DEFLECTION ALGORITHM

A. Slope Trace Waves

In order to determine an epoch of particular event of interest effectively, two slope trace waves, the descending slope trace wave (DSTW) and the ascending slope trace wave (ASTW), are proposed as shown in Fig. 1 and 2, respectively.

In Fig. 1, the DSTW (thick line) follows the original signal (thin line) in the ascending interval (a-p interval) and traces the signal with a delay and average slope that are updated continuously using several previously sampled data during time interval t_H in the descending interval (p-x interval).

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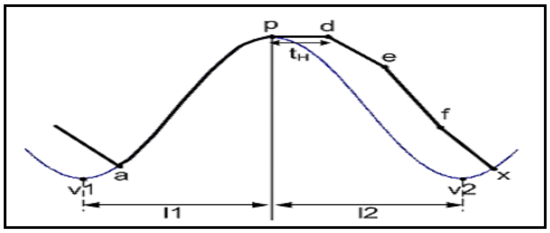


Fig. 1. The behavior of descending slope trace wave (thick line) trace sinusoidal wave (thin line).

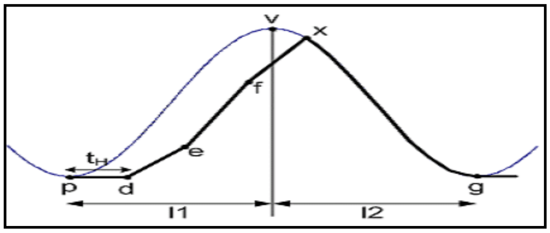


Fig. 2. The behavior of ascending slope trace wave (thick line) trace sinusoidal wave (thin line).

The DSTW is determined as following:

$$\textit{If } DSTW[n\text{-}1] < x[n]$$

$$DSTW[n] = x[n] \tag{1}$$

$$\textit{else } (\textit{that is}, DSTW[n-1] \geq x[n])$$

$$DSTW[n] = DSTW[n-1], \ \textit{for N sample after peak detection} \tag{2}$$

$$DSTW[n] = DSTW[n-1] - [Avg\_S], \ \textit{elsewhere} \tag{3}$$

$$\textit{here}, \ \left|Avg\_S\right| = \left|\sum_{i=n-N+1}^{n} \left(x[i] - x[i-1]\right) \Big/ N\right| \tag{4}$$

where x[n] represents the signal amplitude sampled at n, and |Avg_S| is the average slope of signal during time interval t_H that includes N samples. The boundary of an epoch is determined when DSTW becomes lower than the signal amplitude or ASTW become higher than the signal amplitude. After DSTW crosses the original signal at x, the algorithm selects the lowest amplitude between signal peak (p) and x, determining v2 as the right side boundary as shown in Fig. 1. The detailed explanation of the behavior of the slope tracing waves is given in the accompanying paper [13].

In Fig. 2, the ASTW (thick line) traces the original signal with a delay and average slope that are updated continuously using several previously sampled data during time interval t_H in the ascending interval (p-x interval) and follows the signal in the descending interval (x-g interval).

The ASTW is determined as following:

$$\textit{If } ASTW[n\text{-}1] > x[n]$$

$$ASTW[n] = x[n] \tag{5}$$

$$\textit{else } (\textit{that is}, ASTW[n-1] \leq x[n])$$

$$ASTW[n] = ASTW[n-1], \ \textit{for N sample after valley detection} \tag{6}$$

$$ASTW[n] = ASTW[n-1] - [Avg\_S], \ \textit{elsewhere} \tag{7}$$

$$\textit{here}, \ \left|Avg\_S\right| = \left|\sum_{i=n-N+1}^{n} \left(x[i] - x[i-1]\right) \Big/ N\right| \tag{8}$$

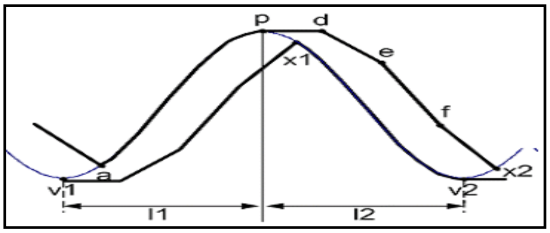


Fig. 3. Determination of deflection epoch by using both DSTW and ASTW.

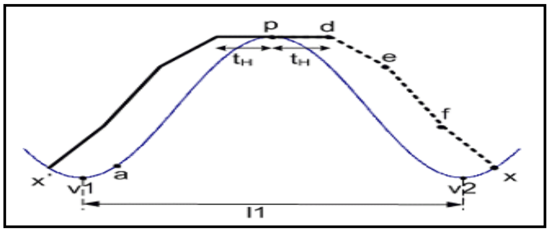


Fig. 4. Determination of deflection epoch by using DSTW in the forward and backward direction.

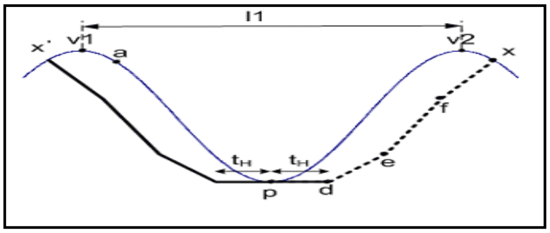


Fig. 5. Determination of deflection epoch by using ASTW in the forward and backward direction.

The ASTW also behaves the similar way with the DSTW except it starts slope tracing from the valley rather than peak as shown in Fig. 2.

B. *Epoch Determination*

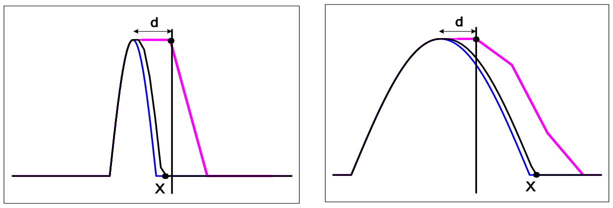
In Fig. 1 and 2, the algorithm uses single slope trace wave, DSTW or ASTW. However, the algorithm can use the two slope trace waves simultaneously in the forward direction, determining the both side of the epoch between v1 and v2 as shown in Fig.3.

The left side of the epoch can be obtained using a single slope trace wave applied in the forward direction and then in the backward direction. In this method, the left side of the epoch is determined after the algorithm reaches the end of delay period (point d in Fig.4 or 5), where the algorithm chooses the peak amplitude as a temporary DSTW (or the valley amplitude as a temporary ASTW), and follows the same procedure explained above but in the backward direction, assuming enough number of previously sampled data is stored. When the temporary DSTW in the backward direction becomes lower than signal amplitude (or the temporary ASTW in the backward direction becomes higher than signal amplitude), the algorithm determines the left side of the epoch (point x').

In Fig. 1-3, the algorithm divides the deflection into two interval l_1 and l_2, from valley to peak and from peak to next valley, respectively, while in Fig.4 and 5, two intervals are represented as one. How to divide the intervals may depend on the signal characteristic or the purpose of signal epoch determination.

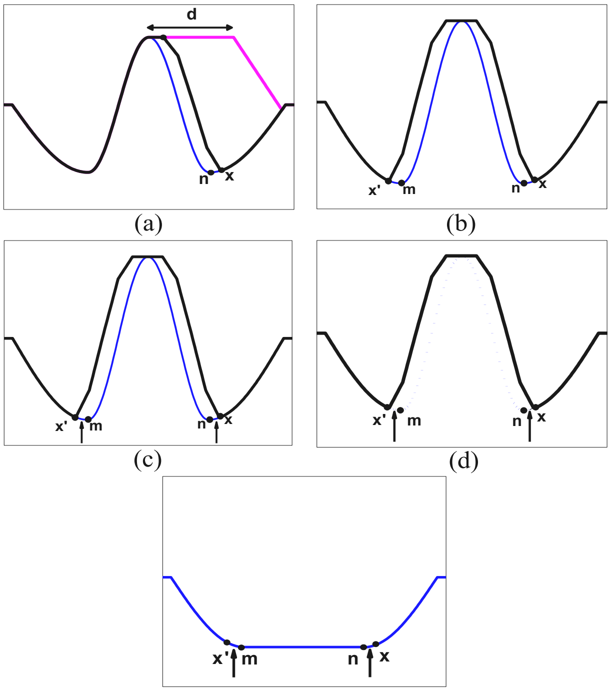
C. Deflection Removal Algorithm using DSTW/ASTW

In this section, we illustrate the method to remove higher frequency deflections from ECG, showing the surgical waveform filtering capability of DSTW and ASTW. To determine the epoch of deflection to remove, two DSTW and two ASTW with different delays are applied. In Fig.6, two sinusoidal wave deflections (15 *Hz* and 60 *Hz*) are shown with two DSTWs of different delay intervals applied simultaneously. The same DSTWs with different delays trace the two deflections differently because of their slope difference. In Fig. 6(a), the DSTW with a shorter delay (DSTW_S) crosses the signal at x which is still inside the delay interval of DSTW with a longer delay (DSTW_L), whereas in (b), the DSTW_S crosses the signal at x which is outside the delay interval of DSTW_L. By choosing the delay intervals appropriately, the algorithm can distinguish a wave deflection of particular characteristic and determines its epoch.



(a) (b)

Fig. 6. Behavior of two DSTW. (a) DSTW_S crosses the signal within the delay period of DSTW_L. (b) DSTW_S crosses the signal outside the delay period of DSTW_L.



(a) (b) (c) (d) (e)

Fig. 7. Deflection removal procedure. (a) determination of deflection to remove, (b) determination of epoch of the deflection, (c) determination of refined epoch of the deflection, (d) removal of the deflection within the epoch, (e) deflection removed signal.

Fig. 7 shows how to surgically remove a deflection using the DSTWs. When the DSTW_S crosses the signal within the delay interval of the DSTW_L as shown in Fig. 7(a), the algorithm decides the deflection as the one to be removed and apply the temporary DSTW_S in the backward direction from the peak, determining the left side of epoch of the reflection (point x') as shown in Fig. 7(b). Then, it determines the minimum amplitude points (points m, n) in the interval between x and peak and in the interval between x' and peak. After that, the left side of the epoch is refined as a medium amplitude between x' and minimum (point m), and the right side of it as a medium amplitude between minimum (point n) and x, respectively, (Fig. 7(c)). The signal in the refined epoch is now removed as shown in Fig. 7(d). Finally, the algorithm connects the two cut points using least distance line or interpolation (Fig 7(e)). Two ASTW also follow the same procedure except for that they remove the downwarded deflection.

III. APPLICATION OF THE DEFLECTION REMOVAL ALGORITHM

In this section, we applied the deflection removal algorithm to remove baseline wandering to show its practical applicability. The algorithm was applied to simulated data and MIT-BIH ECG database.

Fig. 8 shows the algorithm performance on a simulated data obtained by adding two sinusoids of 1 Hz and 2 Hz to 101 MIT-BIH data. Fig. 8(a) is the original signal, Fig. 8(b) is the simulated signal, and Fig. 8(c) is the obtained baseline wandering by the deflection removal algorithm that eliminated QRS complexes, P-waves, and T-waves using least distance connection. Fig. 8(d) is the resulting ECG obtained by subtracting (c) from (b). Although the algorithm is simple, the baseline wandering is removed effectively without significant morphology distortion unlike the case of using filters.

Fig. 9 - 11 show the examples of algorithm performance applied to several MIT-BIH ECG records. In the ECG records, we had chosen the intervals of signal experiencing baseline wandering. As can be seen, the baseline wanderings are removed without causing noticeable signal distortion.

IV. DISCUSSION

The algorithm introduced in this paper may be unusual from the viewpoint of conventional signal processing, because the algorithm chooses the portion of a signal and remove it in time domain like performing a surgery. However, our intention on this approach is to analyze biomedical signals in the same way that a physician analyzes and understands the collected signals by his/her own eyes.

Because this approach can separate deflections according to their morphological characteristic, we expect that it can be used as a morphology based filter. As we have seen in Fig. 8-11, the algorithm has performed like both high-pass filter and low-pass filter depending on which result we choose. The bottom graphs can be considered as the high-pass filtered

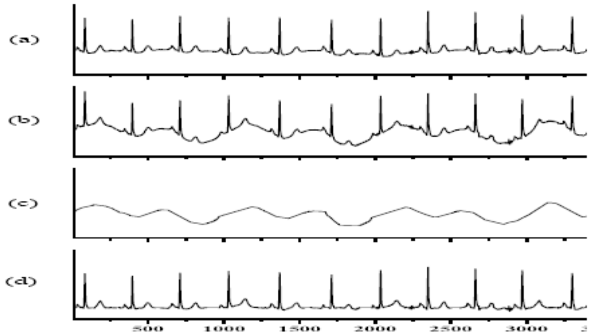


Fig. 8. The removal of baseline wandering by the deflection removal algorithm. (a) original signal (101 MIT-BIH), (b) simulated input signal, the sum of (a) and two sinusoidal waves, (c) baseline wandering obtained by the algorithm, (d) processed signal without baseline wandering.

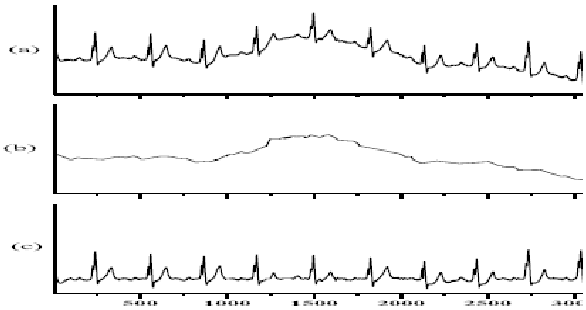


Fig 9. The removal of baseline wandering by the deflection removal algorithm. (a) original signal (111 MIT-BIH), (b) baseline wandering obtained by the algorithm, (c) processed signal without baseline wandering.

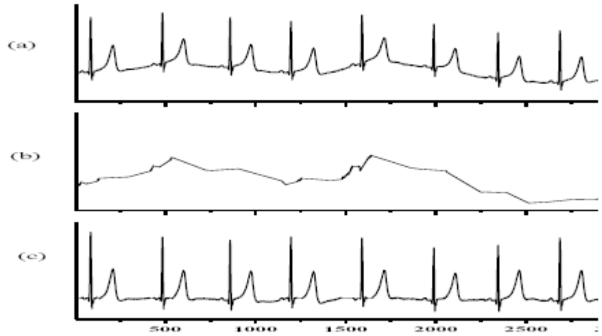


Fig 10. The removal of baseline wandering by the deflection removal algorithm. (a) original signal (113 MIT-BIH), (b) baseline wandering obtained by the algorithm, (c) processed signal without baseline wandering.

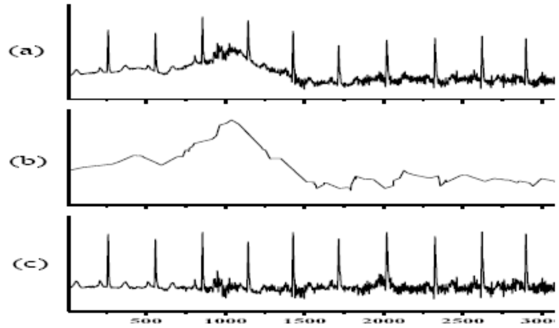


Fig 11. The removal of baseline wandering by the deflection removal algorithm. (a) original signal (101 MIT-BIH), (b) baseline wandering obtained by the algorithm, (c) processed signal without baseline wandering.

ones whereas the second graphs from the bottom can be considered as low-pass filtered one.

Although we obtained a satisfactory result in identifying and removing a waveform deflection, it is too early to discuss the advantage or value of the algorithm because there are many things we have to verify and to advance in the future. First, we have to investigate the optimal delay intervals for DSTW_S and DSTW_L for different deflections and a formal way to find proper values for them. By far, we have used heuristically obtained values in this paper. It has been observed that different combination of the delay intervals caused significant variations in the result. Second, we can add other parameters to the algorithm such as amplitude threshold, as discussed in the accompanying paper [13], to enhance the algorithm performance, particularly for finding deflection we want to remove. Third, we need to find a better interpolation method for connecting the eliminated portion of a signal, instead of using a least distance line we have used in this paper.

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