Detection of End of T-wave in Fetal ECG Using Recurrence Plots
Namareq Widatalla, Ahsan Khandoker, Yoshiyuki Kasahara and Yoshitaka Kimura

Abstract— Automatic detection of fetal ECG features can assist in diagnosis of fetal cardiac complications and may reduce the time required for diagnosis. Detection of the end of the repolarization period wave in ECG has been proven challenging due to its low amplitude and low frequency range. The prolongation of end of T-wave is associated with sudden cardiac death, thus, methods that can accurately pinpoint it is highly desirable for early diagnosis of cardiac diseases. In this paper, a technique based on recurrence plots is developed for the detection of end of T-wave. The developed technique was tested on maternal ECG (mECG), fetal scalp ECG (fsECG) and non-invasive fetal ECG (nfECG) records. The technique was able to detect end of T-waves in all of the mECG beats, 75% of the non-invasive fECG beats (verified by simultaneously captured doppler ultrasound signals) and 78% of the fsECG beats. Detection of fECG signals were more challenging than mECG signals due to the noise and their low amplitude T-waves.

I. INTRODUCTION

Electrocardiogram (ECG) signals provide information about the electrical activity of the heart and proper interpretation of them convey vital information about the health and function of the heart [1]. ECG as a tool to measure heart activity is effective, however, the real challenge lies in the accurate detection and interpretation of their features. The increased and high mortality rate that result from improper monitoring for cardiac health indicate that there is a need for reliable techniques to detect abnormalities within the heart in general. Thus, automatic techniques that can identify cardiac irregularities in ECG can facilitate early detection of cardiac irregularities and remote health monitoring [2, 3].

Interpretation of ECG signals depends highly on detecting ECG features which are P, QRS, T and U waves [1]. So far, several techniques have been developed for automatic ECG analyses. Nevertheless, such techniques rely mainly on detection of R peaks only. Therefore, detection techniques that rely on recognition of other ECG features, like T waves, can help in diagnosis of cardiac diseases. T-waves are associated with several diseases and accurate detection of them and their ends can contribute to early diagnosis of cardiac complications. Detection of the T-waves in fetal ECG (fECG) is considered very challenging due to their low amplitudes compared to the R peaks. Furthermore, T peaks lie within the low frequency range which make them prone to high frequency noise [3].

Signal processing of fetal ECG (fECG) is considered more challenging compared to adult ECG due to the additional source of noise that originates from the mother and fetus brain activity. The high noise impeded within fECG makes it challenging to properly diagnose fetal heart. Therefore, detection methods that can successfully pinpoint irregularities within fECGs are favored for diagnosis of heart diseases [4]. In this study a technique based on recurrence plots is used to detect end of T-waves in maternal and fetal ECG. Recurrence plots are powerful for the analyses of dynamic systems and they can be used to quantify the recurrences of states of systems [5]. Since ECG peaks, P, R and T repeat overtime, they can be detected by recurrence plots. In this paper recurrence plots were used to identify the location of T-waves to detect the end of T-wave points.

II. METHODS

A. Data Collection

Simultaneous maternal ECG (mECG), Doppler Ultrasound (DUS), fetal scalp ECG (fsECG) and non-invasive (nfECG) recordings were collected from 4 healthy pregnant women during labor at gestational age of 38-41 weeks. The subjects had an age range of 27-43. The data were collected from Tohoku University Hospital after getting approval from Tohoku University Institutional Review Board and after getting written informed consent from the subjects. Simultaneous recording was performed in order to compare the results of analyses of nfECG records with the results of the more accurate records, fsECG and DUS. The ECG signals were collected at a sampling rate of 1,000 Hz and DUS data were collected at 1.15 MHz from Ultrasound Transducer. mECG and nfECG signals were recorded by attaching 12-lead on the abdomen of the mother. After that, a method that involves cancelation of mECG and blind source separation with reference (BSSR), explained in [6], was used to extract nfECG. fsECG was collected by attaching an electrode to the scalp of the fetus.

B. Signal Processing

The domain of ECG frequency lies between 0.05 Hz and 100 Hz and each feature of ECG dominates within a certain range [1]. The T-wave frequency is below 10 Hz which is also common for baseline noise [3]. Presence of baseline noise can affect the detection of end of T-waves. Thus, in this study, signals with high baseline noise were filtered using wavelet transform. In order to filter the baseline noise, the signals were decomposed into 10 levels using the db4 wavelet. The decomposed levels showed that the baseline noise was dominant in the seventh level which was then removed from the signals. Most of the fECG signals had high frequency noise which was filtered through wavelet transform; high frequency noise was mostly dominant at levels 1-4. The
analyzed signals were 15 s in length and a total of 77 mECG and 274 fECG beats were analyzed. All of the beats in the 15 s of mECG records were analyzed. Due to the high noise in some of the fECG records, not all of the beats within the 15 s period were analyzed. mECG records had around 17-21 beats per 15 s and fECGs had 32-40 beats per 15 s.

C. Recurrence Plots

Recurrence plots are useful tools to visualize dynamical systems and analyze the recurrence of events or states in systems. Recurrence plots are obtained from calculating the number of trajectories of the phase space of a system. If two trajectories are very close, they are counted as similar and the degree to their closeness is determined by a threshold value. If the threshold value is very small, then many trajectories will be counted as similar. Similarly, if the threshold value is very large, there will be hardly any similar states. Therefore, the threshold value is a very important parameter that should be chosen properly based on the system [5].

Recurrence plots can be used to detect the location of peaks within the ECG signal. Since each peak has a unique amplitude, it can be pinpointed clearly in recurrence plots. MATLAB was used to obtain recurrence plots for the ECG signals and detailed explanations about the method are found in [7, 8]. Recurrence plots exhibit peaks with different amplitudes in different colors or intensities. As indicated in Fig. 1, which shows an example of recurrence plots of a 5 s of a mECG record, R and T waves are shown clearly in the colored recurrence plot. The p waves can also be seen; however, their amplitudes are very small compared to T and R peaks. R peaks had a range of intensity of 0.8-1 and T-peaks’ range of intensity was 0.3-0.6. Since T-waves had a least intensity of 0.3, the threshold value was set to 0.3 to obtain black and white recurrence plots. Black and white recurrence plots were obtained because they can be handled easily in MATLAB to calculate end of T-waves. As indicated in Fig. 2, the black and white recurrence plot shows T and R peaks clearly.

In order to pinpoint the exact locations of end of T-waves, ECG signals were segmented into intervals based on the locations of the R peaks. The intervals that lied between two R peaks were separated and their amplitudes were adjusted to facilitate the detection of T waves. Values between the RR intervals were recalculated using (1) in which \( x_o(t) \) is the new calculated signal and \( x(t) \) is the original signal.

\[
x_o(t) = 2 \times x(t) + \text{abs}(x(t)) \quad (1)
\]

Equation 1 was used in order to amplify T-waves relative to other presenting noisy peaks which is an important step to increase the sensitivity of recurrence plots detection. In order to distinguish T-waves from p-waves, the region that lied within 65% of length starting from the first R peak was amplified. A comparison between the recurrence plots of \( x(t) \) and the amplified \( x_o(t) \) of a mECG signal and a fECG are shown in Fig. 2 and Fig. 3 respectively.

The difference between the signal before and after applying (1) is clearer in the fetal case more than the mother case due to the excess presence of noise in the nfECG record. Before applying (1) on nfECG signals, the signals were filtered from high noise. The obtained recurrence plots could clearly detect
the locations of T-waves, however, they could not pinpoint the exact locations of their ends as indicated in Fig. 4. Thus, the end of a T-wave was determined by finding the minimum value that follows an end of T-wave of a recurrence plot within the next 0.05 s in the signal.

T-end points in nECG signals were compared with the aortic closing timing (Ac) in doppler signals [9]. The Ac was found somewhere in the interval 0.16 s - 0.22 s that lied after the first R peak within RR intervals. In order to test the degree of accuracy of the detection algorithm in the nECG signals, a comparison between the actual value and the detected value was done. Fig. 6 shows an example of detected ends of T-waves of a nECG record compared with a simultaneously recorded doppler signal. As illustrated in the figure, the detected ends of T-waves are very close to the actual values in the doppler signal.

Table 1 shows a summary of the results of the detection of the fECG records. The total number of the analyzed beats for fECG signals were 276, 138 of nECG and 138 of fsECG but a total of 12 beats were removed from fECG records due to the high noise in some of their beats. The detected end of T-wave points in nECG signals were considered valid if the difference between the value from the doppler record and the detected value from the algorithm is less than 0.03 s. Compared to nECG signals, the end of T-waves were easy to pinpoint in fsECG signals since the waves were distinguishable compared to the nECG signals. Thus, doppler signals were not needed to validate the detected points in fsECG signals. In a similar manner, the points detected by the algorithm were considered valid in fsECG signals if the difference between the actual T-end point and the detected one was less than 0.03 s.

Table 1

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>nECG</th>
<th>fsECG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean end point</td>
<td>0.18 s</td>
<td>0.17 s</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.03 s</td>
<td>0.02 s</td>
</tr>
</tbody>
</table>

Mean and standard deviation of QT intervals and QTc (Bazett’s formula) were calculated for the fECG signals for more validation of the results. Around 5 beats were removed from the nECG signals due to the difficulty in pinpointing QT. In the doppler signal the QT is equivalent to the Q-Ac [9].

III. RESULTS

The technique developed in this paper was able to detect all of the end of T-waves in the nECG signals of the 4 subjects and Fig. 5 shows an example. Detection of T-waves in fECG signals was more challenging compared to the nECG signals due to their high noise and low T-wave amplitudes. Detection of T-waves in fsECG signals was easier than nECG signals due to their less noise. Also, it was easier to pinpoint the location of T-end points in fsECG signals without the need of doppler signals for validation. Due to the difficulty in recognizing the exact location of T-end points in nECG signals, fetal doppler signals were used to pinpoint them.
Table 1. Results of detection - fECG

<table>
<thead>
<tr>
<th>Feature</th>
<th>nfECG</th>
<th>fsECG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of beats</td>
<td>131</td>
<td>133</td>
</tr>
<tr>
<td>Detected</td>
<td>75%</td>
<td>78%</td>
</tr>
<tr>
<td>Not Detected</td>
<td>20%</td>
<td>19%</td>
</tr>
</tbody>
</table>

Table 2 shows the results and as the table shows, the mean of QT and QTc of nfECG and of doppler signals are almost the same. Furthermore, the mean of QT and QTc of fsECG are very close to the those of nfECG and doppler. The mean value obtained for Q-Ac is close but higher than the value, 0.225 s ± 0.013 s, mentioned in [9] and the difference between the two values could be due to the difference in gestational age which is 28-36 in [9]. The mean values of QT and QTc of nfECG are very close to the control values, 0.234 s ± 0.023 s and 0.37 s ± 0.04 s respectively, mentioned in [10].

Table 2. Results of QT and QTc interval calculations - fECG

<table>
<thead>
<tr>
<th>Feature</th>
<th>Doppler</th>
<th>nfECG</th>
<th>fsECG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of beats</td>
<td>126</td>
<td>126</td>
<td>133</td>
</tr>
<tr>
<td>QT (s)</td>
<td>0.238±0.027</td>
<td>0.237±0.030</td>
<td>0.238±0.026</td>
</tr>
<tr>
<td>QTc (s)</td>
<td>0.369±0.04</td>
<td>0.368±0.05</td>
<td>0.369±0.04</td>
</tr>
</tbody>
</table>

IV. DISCUSSION

In this study, recurrence plots proved to be powerful in pinpointing recurrent events in ECG signals. Recurrence plots could separate the peaks based on their amplitudes easily in mECG signals because each peak had a unique amplitude. Detection of T-waves was easier after segmenting the ECG signals into intervals and amplifying the regions that contained the T waves.

In this study, the technique has been proven to be accurate in detecting end of T-waves in mECG records. Furthermore, detection of most of the end of T-waves in fECG records was possible. The accuracy of the detected points in fECG was measured by comparing the actual values with the detected values. The actual values of T-end points in fECG were hard to pinpoint. Thus, the degree of accuracy of the detected points in fECG signals was measured by comparing them with the simultaneously recorded doppler signals. The comparison showed small differences in most beats between the actual values and the detected values by the algorithm. For further validation of the values obtained from the doppler signals, they were compared with the ones mentioned in [9]. The values of doppler signals obtained in this study and the ones mentioned in [9] were close proving their validation.

Mean and standard deviations of QT and QTc intervals were calculated for the fECG signals and doppler signals and the results are summarized in Table 2. As shown in the table, the values of QT and QTc for nfECG, doppler and fsECG signals are almost the same indicating further that the technique was able to detect most of the end of T-waves. The mean values of QT and QTc of nfECG were compared with the values in [10] and the comparison showed consistency between the two values.

Compared to mECG records, the algorithm could not detect T-end points within all of fECG records due to the high noise in the signals. The fact that fECG signals is more challenging to analyze due to the noise is consistent with what has been discussed in [4]. In addition, since recurrence plots separate features based on amplitudes, it was hard to detect T-waves in beats that had very low T-amplitudes, especially in the nfECG records. It was mentioned in [3] that detecting T-waves are challenging due to their low amplitudes which was also the case in this study in which it was difficult to distinguish T-waves from other noisy peaks.

The technique developed in this paper can be further developed to be used for automatic detection techniques for better monitoring of cardiac health. Although the results of the detection in this study showed promising results, the total number of subjects was low, therefore, more data should be collected and analyzed to validate and enhance the technique.

V. CONCLUSION

End of T-wave is associated with several cardiac irregularities and methods that can detect its irregularities can assist in reducing cardiac complications. This paper discussed a detection technique based on recurrence plots to pinpoint end of T-waves in maternal and fetal ECG signals. The technique could detect all of T-end points in mECG and most points in fECG signals. T-waves proved to be challenging to detect in fECG signals due to their low amplitude compared to the R peaks. Also, exact pinpointing of their ends was harder in cases that had high frequency noise in the signal.

REFERENCES