Comparison of Time and Frequency Domain Methods for the Feedback on Chest Compression Rate

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Abstract

During cardiopulmonary resuscitation feedback systems can help rescuers to achieve optimal chest compression rates. In this paper we describe and compare two methods to provide chest compression rate feedback based only on the thoracic impedance signal, available in automatic external defibrillators. The first method (time domain) identified the relative maxima of the impedance and characterized each fluctuation by features of amplitude and duration to classify them as compression or non-compression. Then it reported the chest compression rate as the median of the rates of the previous compressions. The frequency domain method computed the Fast Fourier Transform for short windows of the impedance and identified the highest peak in a frequency band. If its amplitude exceeded a dynamic threshold, its frequency was reported as the compression rate. Both methods provided global root mean square errors of the estimated rate below $3.2\,min^{-1}$ *when evaluated with out of hospital cardiac arrest records.*

1. Introduction

Treatment for cardiac arrest involves early cardiopulmonary resuscitation (CPR) and early defibrillation. Current resuscitation guidelines emphasize the importance of providing high quality chest compressions (CC) to increase the chances of survival of the patient [1]. Real time CPR feedback systems have proved effective to improve CC quality [2,3]. Some of these systems require additional signals such as the acceleration [4–6] that can be acquired from external devices. Using the acceleration signal, feedback can be given on CC rate and depth.

However, in basic life support simplicity of the devices is key, as most rescuers are minimally trained. In this scenario automatic external defibrillators (AEDs) are used for the defibrillation of the patient. These devices analyze the ECG recorded through the defibrillation pads, decide if an electrical shock is recommended, and instruct the rescuer to provide it, if necessary. The thoracic impedance (TI) signal, which is also recorded through the defibrillation pads, suffers fluctuations with the ventilations of the patient and with each CC. These fluctuations have been successfully used to mark the instants of CCs [7, 8], although they cannot be used to estimate CC depth [9].

In this study we describe two methods to calculate the frequency of the chest compressions in the time and the frequency domains using exclusively the TI signal, and we compare their performances using a database of out of hospital cardiac arrest records.

2. Materials and Methods

2.1. Database

We used a subset of a large cardiac arrest registry that contains 623 OHCA episodes acquired by the Tualatin Valley Fire & Rescue Service (Tigard, Oregon, USA). The episodes were collected between 2006 and 2009 using the Philips HeartStart MRx monitor/defibrillator. In addition to the ECG and the TI signal acquired by the defibrillator, the chest compression acceleration and the compression depth (CD) were recorded using a CPR assist pad. The CD signal was used to annotate the position of the CCs (gold standard).

We selected 15 records for which the TI and the CD signals were available along the whole episode, with a minimum duration of 30 minutes. The mean duration of the selected episodes was $2348 \pm 335\,s$, with a mean of 1861 ± 1207 CC per episode.

2.2. Time Domain Method

CCs and ventilations produce identifiable variations in the TI. Fig. 1 shows a segment of a record that contains intervals with and without CCs. During compressions, the chest of the patient suffered a displacement (first

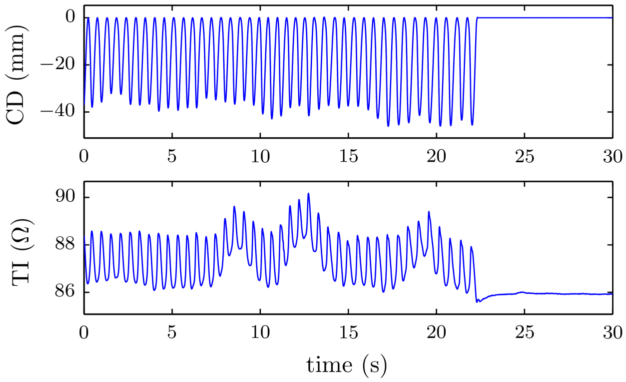

Figure 1. Segment of a record of the database. During CC, fluctuations are induced in the TI signal (second panel). These fluctuations stop when the CC are interrupted. Ventilations induce slower fluctuations that may be overlapped to the fluctuations induced by CC.

panel), and fast fluctuations were induced on the TI (second panel). In this case, the patient was ventilated around seconds 8, 12 and 19, and slow fluctuations appeared in the TI overlapped with the fluctuations induced by CCs.

The time domain CC rate feedback method analyzes short time windows (2 s) of the TI signal and for each of them provides a CC rate value. For each window, it preprocesses the TI signal, identifies fluctuations, characterizes them by features of amplitude and duration, and classifies them as compression or non-compression. Then, using the position of the last identified compressions that conform a block (i.e., that are not isolated), it calculates the CC rate value. The next subsections describe each of these steps in depth.

2.2.1. Preprocessing of the TI

The TI is preprocessed with a 3rd order Chebychev low pass filter, with $f_c = 2\,\text{Hz}$ and a maximum ripple in the band pass of 0.1 dB. This emphasizes the fundamental frequency of the fluctuations induced by CC and suppresses harmonic frequencies.

2.2.2. Chest Compression Identification

In this step the fluctuations of the preprocessed TI are analyzed to identify those generated by CC. First the maxima and minima of the filtered signal are identified. A maximum and its two adjacent minima conform a fluctuation. Then, for each fluctuation the following parameters are computed:
- Δt_c: duration of the compression. Distance between the two minima of the fluctuation.
- ΔZ_1: amplitude change between the first minimum and the maximum.
- ΔZ_2: amplitude change between the maximum and the second minimum.
- ΔZ: mean of ΔZ_1 and ΔZ_2.

Finally, based on these parameters, each fluctuation is classified as compression or non-compression. The requirements to be considered a compression are the following:
- $\Delta t_{\text{min}} < \Delta t_c < \Delta t_{\text{max}}$, where Δt_{min} and Δt_{max} are two fixed thresholds.
- $\Delta Z > \Delta Z_{\text{min}}$, where ΔZ_{min} is a dynamic threshold.

The dynamic threshold ΔZ_{min} starts with the initial value ΔZ_{min0} and then is updated for each analysis window as the weighted average (weighting factor α) of the amplitude of the N previous compressions that belong to a block. A block of CC is defined as a group of CC that are not separated by more than 1 second.

The selected values for the fixed thresholds were $\Delta t_{\text{min}} = 0.19\,\text{s}$, $\Delta t_{\text{max}} = 0.95\,\text{s}$, and for the dynamic threshold $\Delta Z_{\text{min0}} = 0.1\,\Omega$, $N = 10$ and $\alpha = 0.25$. The dynamic threshold is limited between $0.14\,\Omega$ and $0.25\ \Omega$.

2.2.3. CC Rate Calculation

CC rate is computed from the position of the last detected compressions that belong to a block. If the block contains less than 3 compressions, no rate is reported. Otherwise, the rate is computed as the inverse of the median of the last intervals (distance between consecutive CCs) of the block. If the block contains more than 8 compressions, only the last 7 intervals are used.

2.3. Frequency Domain Method

The frequency domain method first preprocesses the TI and applies a 2-second Hamming window to the filtered signal. Then its Fast Fourier Transform (FFT) is computed with 256 points and escalated. The highest peak in a band of interest is identified, and if this peak is higher than a dynamic threshold, its amplitude is reported as the CC frequency. These steps are described in more detail in the following subsections.

2.3.1. Preprocessing of the TI

The TI signal is filtered with a low pass 4rd order Chebychev filter, with a maximum ripple in the pass band of 0.1 dB and $f_c = 2\,\text{Hz}$. Then, the filtered signal is resampled from 200 to 20 samples per second. Finally, the signal is high pass filtered with a 5th order Chebychev filter of $f_c = 0.44\,\text{Hz}$ to suppress low frequency fluctuations.

2.3.2. Spectral analysis

A 2-second Hamming window is applied to select the analysis interval. Then the FFT is computed with 256 points, and the spectrum is escalated dividing by the number of samples of the Hamming window to convert the units to Ohms.

2.3.3. CC Rate Calculation

The highest peak of the spectrum between $f_1 = 1.1$ and $f_2 = 2.8\,\mathrm{Hz}$ is identified. If the amplitude of this peak is above a dynamic threshold, the frequency is identified as the CC frequency f_{cc}, and the CC rate is calculated as rate (cpm) $= 60 \cdot f_{cc}$. Otherwise no CC rate is reported. The dynamic threshold is updated for each analysis window as the mean of the previous 10 amplitudes multiplied by a weighting factor 0.25. This threshold is limited between $0.1\,\Omega$ and $0.25\,\Omega$.

2.4. Performance Evaluation

For each of the methods the percentage of false negatives (FN), this is, analysis windows for which no feedback was given when there were compressions, and false positives (FP), i.e., feedback given when no compressions were present, are reported. Additionally, for the true positives, the root mean square error (RMSE) of the CC rate feedback is computed.

3. Results

Table 1 shows the global RMSE, the percentage of FN and the percentage of FP for each of the methods. The RMSE errors were below $4.5\,\mathrm{min}^{-1}$ for all the records for the time domain method, and below $4.7\,\mathrm{min}^{-1}$ for the frequency domain.

Table 1. Summary of the results

	RMSE	FN	FP
Time domain	$3.2\ \mathrm{min}^{-1}$	1.7%	2.6%
Frequency domain	$3.1\ \mathrm{min}^{-1}$	1.9%	2.2%

Figure 2 shows a segment of a record in which the fluctuations induced by CC are clearly identifiable in the TI signal, even before preprocessing it. The 2-second analysis windows are depicted with red lines. In the top panel, the gold standard feedback is shown (feedback computed from the position of the CC annotated on the CD signal). In the lower panel, both the feedback obtained from the time domain method (upper part) and from the frequency domain method (lower part) are shown. In this case, the values provided are very similar.

Figures 3 and 4 show the feedback on CC rate provided by the time and the frequency domain, respectively, for a more challenging segment in which fluctuations on the TI are not so clear. In both figures the top panel shows the CD and the gold standard feedback, and the second

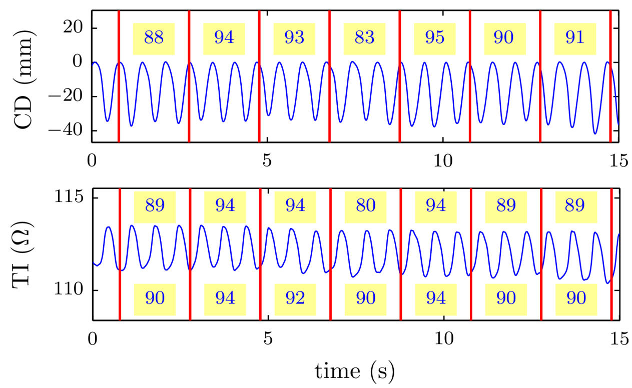

Figure 2. Example of the feedback provided for a segment of a record. Analysis windows are delimited by red lines. In the top panel (CD signal) the gold standard feedback is indicated for each analysis window in the upper part of the plot. In the lower panel (TI signal) the feedback provided by the time domain method is shown in the upper part of the plot, and the output of the frequency domain method in the lower part.

panel shows the recorded TI signal. For each figure, the third panel shows the preprocessed TI signal and the feedback provided by the corresponding method (time domain in Figure 3 and frequency domain in Figure 4). The time domain method provides CC rate feedback for all the analysis windows, although in some of them the error is above 4 cpm. The frequency domain method, however, has two false negatives. The fourth panel of Figure 4 shows the FFT of the third analysis window. The amplitude of the spectrum peak present in the band of interest is below the dynamic threshold, and thus no CC rate feedback is provided.

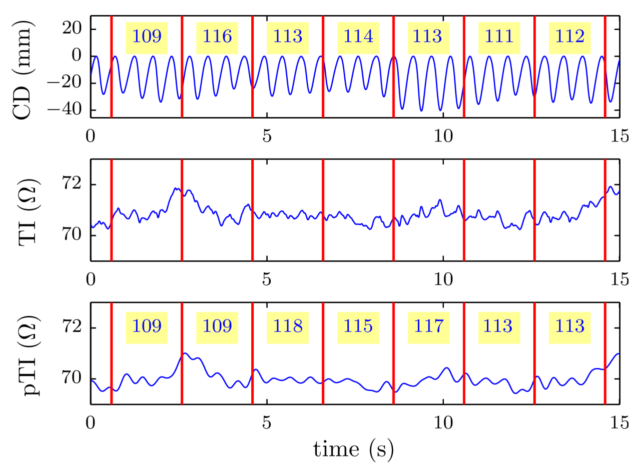

Figure 3. Example of the feedback provided by the time domain method for a segment of a record.

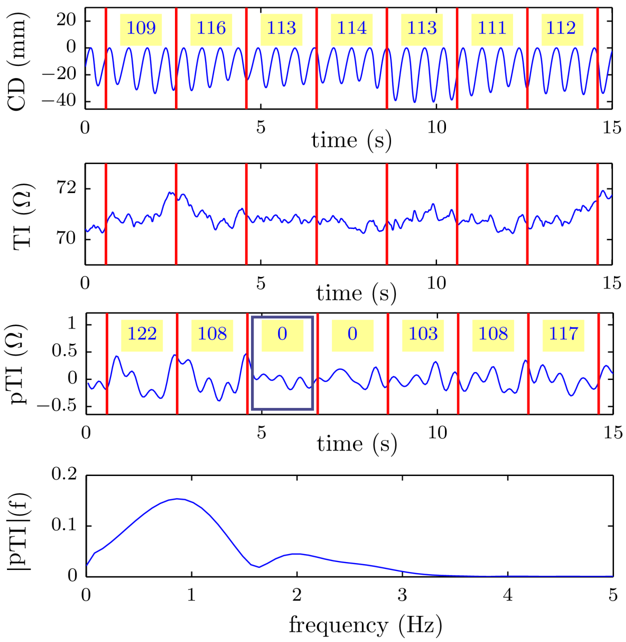

Figure 4. Example of the feedback provided by the frequency domain method for a segment of a record. Two of the analysis windows are false negatives.

4. Discussion and Conclusions

In this paper we described and compared the performance of two methods to provide feedback on CC rate based only on the TI signal, one on the time domain and the other in the frequency domain. Although both methods provide similar results, for some analysis windows one may perform better than the other, as shown in the examples depicted in Figures 3 and 4. In this case the frequency domain method fails to identify the frequency of the CC for two of the analysis windows, while the time domain method provides feedback.

In general, both methods provided a high accuracy (global RMSE below 3.2 min^{-1}) with a low FN and FP rate, and could be implemented in current AEDs without requiring additional devices. The only condition for the application of the methods is a high quality TI signal.

Acknowledgements

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