Extracting a Clean ECG from a Noisy Recording: a New Method based on Segmented-Beat Modulation

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Abstract

Electrocardiogram (ECG) testing is a common non-invasive diagnostic tool to identify heart diseases. Generally, an ECG recording is corrupted by different types of noise which may jeopardize clinical evaluation. Thus, aim of the present study is to introduce the new segmented-beat modulation method (SBMM) for extracting a clean ECG from a noisy recording. Each cardiac cycle (CC) is segmented into the QRS segment and the TUP segment, respectively independent and proportional to preceding RR interval. TUP-segment modulation is initially used to force all CC to have the same duration, in order to allow a template-beat computation as the median beat. Then, a clean ECG is obtained by concatenating the template-beat after TUP-segment demodulation in order to obtain reconstructed beats whose duration matches that of the corresponding beats in the original noisy recording. Optimization procedures are performed to compensate for small inter-beat morphological ECG variations independent from actual heart rate. SBMM was tested in two applications respectively involving an ECG corrupted by motion artifacts and an abdominal recording from a woman in labor. Results clearly demonstrate the SBMM ability to provide a clean, and thus clinically useful, ECG tracing from a noisy recording.

1. Introduction

Electrocardiogram (ECG) reports the electrical activity of the heart recorded by skin electrodes. By its nature, it is a pseudo-periodical signal constituted by a sequence of typical waveforms, each one representing a specific phase of the cardiac cycle: the P wave, representing the atria depolarization; the QRS complex, representing the ventricular depolarization, also hiding atria repolarization; and the T-wave, sometimes followed by the U wave, representing ventricular repolarization.

ECG analysis represents a non-invasive diagnostic tool that allows identification of the heart diseases [1]. Indeed, the latter alter the typical ECG waves morphology and period.

Generally, the recorded ECG signal is corrupted by different types of noise and artifacts (including power line interference, baseline drifts, motion artifacts, muscle contractions, electrode contact noise, electronic noise and electrical interferences) [1,2] which may change its morphological characteristics. Hence, to extract useful information from the ECG, this needs to be filtered in order to get rid of the noise without distorting the signal of interest [2,3]. Noisy components often fall within the ECG frequency band. Consequently, simple linear filtering (typically a band-pass filtering between 0.5-45 Hz) may not provide satisfactory results, and contextual filtering may be required [3-5].

Aim of the present paper is to introduce a new method, based on beat modulation, for extracting a clean ECG signal from a noisy recording. Two different applications were eventually proposed to practically demonstrate the procedure ability to provide a clean, and thus clinically useful, ECG: extraction of an ECG tracing from a recording hardly corrupted by motion artifacts; and estimation of maternal ECG tracing from an abdominal recording from a pregnant woman.

2. Segmented-beat modulation method

The segmented-beat modulation method (SBMM) is finalized to extract a clean ECG signal from a noisy recording under the assumption of knowing the R-peaks position. The algorithm is based on the practical observation that, in first approximation, the QRS-complex duration is independent on heart rate (HR), whereas duration of all other waves linearly varies with it. More specifically, if the duration of the QRS complex is independent from the preceding R-R interval, the duration of the other waves is proportional to it. Consequently each cardiac beat is divided in two segments: the QRS segment and the TUP segment, as represented in Fig. 1.

Considering the beginning of the cardiac cycle (CC) in the PQ segment (i.e. between the P-wave offset end and Q-wave onset) rather than at the beginning of the P wave

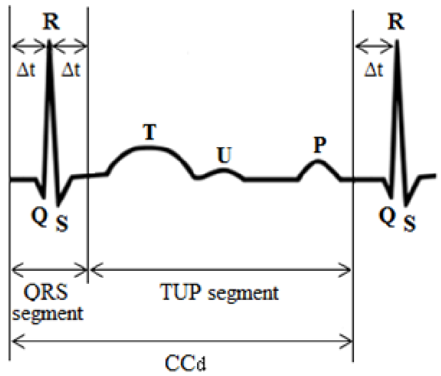

Figure 1. Segmentation of the cardiac cycle in two segments: QRS and TUP (CCd: CC duration

as usually done, the QRS segment is identified ± Δt ms (for example Δt=40 ms) around the R peak, while the TUP segment is identified within the time interval that begins Δt ms after the R peak and ends Δt ms before of the subsequent R peak. Then, the CC is the portion of ECG included between Δt ms before the R peak and Δt ms before the subsequent R peak. Consequently, each CC included in the ECG is characterized by its own duration (CCd), which may vary due to HR variability. However, the duration of all QRS segments is the same in all CC and equal to 2·Δt, whereas the duration of the TUP segments is beat-dependent and equal to CCd-2·Δt.

After having segmented all the N beats of the ECG tracing, the median duration of the CC (mCCd) is computed. The computation of the median CC (mCC; Fig.2) requires all beats to have the same length. Thus, all CC are modulated (stretched or compressed) in order to have their length to match mCCd. Since all QRS segments have the same duration, the modulation interests only the TUP segments (Fig. 2). Eventually, the mCC is obtained as the median of all CC constructed using the original QRS segments and the modulated TUP segments. For the median operator properties, the noise level affecting mCC is drastically reduced (Fig.3).

The mCC represents the basic beat from which to derive the clean ECG. Initially, an ECG tracing is obtained by an N-fold repetition of mCC to make it to contain the same number of beats of the original one. Each mCC constituting this tracing is then segmented and the median TUP segment is demodulated (compressed or stretched) to match the length of the TUP segment of the corresponding beat in the original ECG (Fig.4). All beats are then reconstructed using the median QRS and the demodulated median TUP. Optimization processes, involving cross-correlation maximization and error minimization between the reconstructed beat and the corresponding one in the noisy ECG, in order to compensate for possible small inter-beat, HR-independent variations of CC waveforms. Eventually all reconstructed

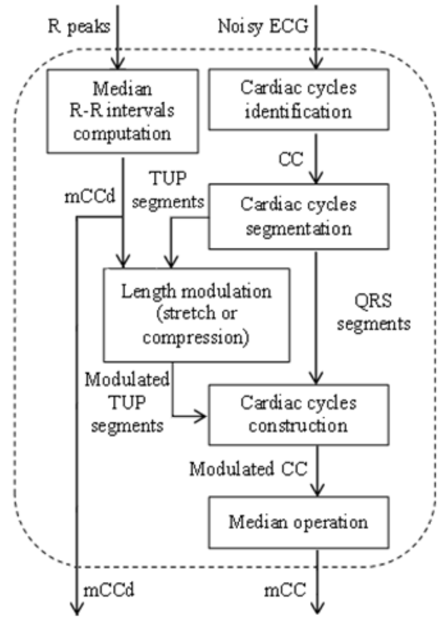

Figure 2. Block diagram related to median cardiac cycle (mCC) computation.

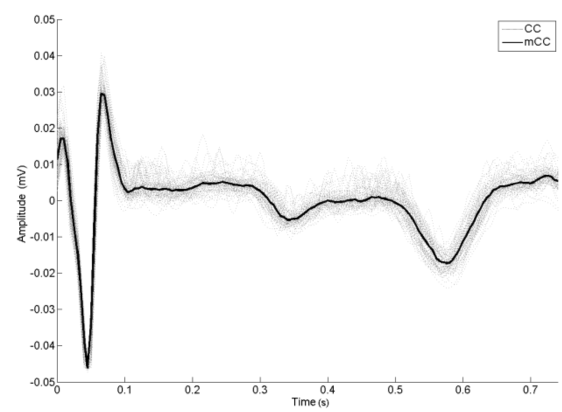

Figure 3. Example of a median cardiac cycle (mCC) computation from all modulated cardiac cycles (CC).

beats are concatenated to get the output clean ECG (Fig.4).

3. Clinical applications

To show the goodness of the SBMM in extracting clean ECG from noisy recording, two clinical applications are presented. The first one is more generic, and regards filtering of an ECG recording affected by motion artifacts. Instead, the second one is more specific and is about estimating the maternal ECG from an

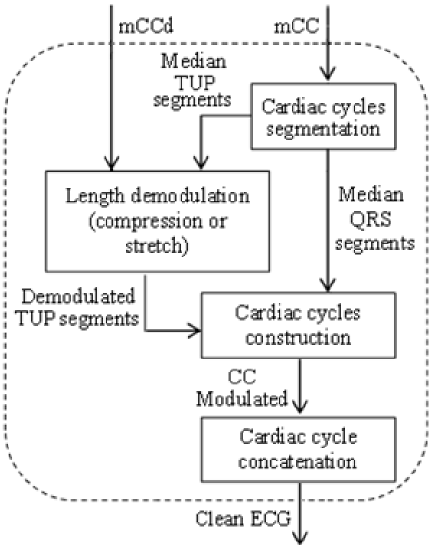

Figure 4. Block diagram related to clean ECG extraction.

abdominal recording of a woman in labor. In both applications, the original noisy ECG was preliminary processed with band-pass (0.5-45 Hz) digital filter to remove out-of-band components of power-line noise, respiration and baseline drifts.

3.1. Application 1: cleaning ECG from motion artifacts

ECG testing is often performed under exercise conditions, so that the recording may include not only the signal of interest (i.e. the ECG) but also electromyography noise and motion artifacts, which can jeopardized a correct ECG interpretation. In cases like this, our SBMM can be a useful tool for cleaning the ECG from the undesired components. As an example, an ECG tracing corrupted by electrode motion artifacts was considered (upper panel of Fig. 5). The recording was obtained from a physically active volunteer by applying the electrodes on the limbs (available at the “MIT-BIH Noise Stress Test Database” of Physionet, www.physionet.org; signal to noise ratio=12). Application of the SBMM to this tracing allowed extraction of a clean ECG signal (lower panel of Fig. 5), from which typical waveforms are more easily identified.

3.2. Application 2: extracting maternal ECG from an abdominal recording of a pregnant woman

Fetal ECG monitoring are sometimes noninvasively performed using abdominal recordings obtained positioning electrodes on the abdomen of a pregnant woman. The main component of an abdominal recording,

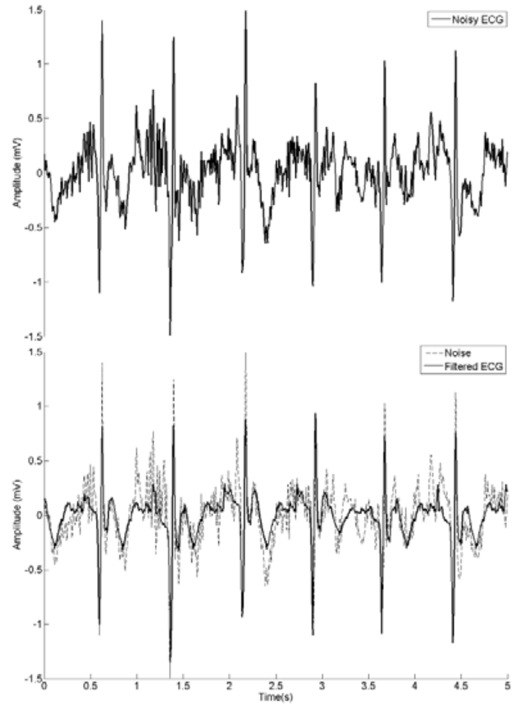

Figure 5. ECG extraction from a recording corrupted by electrode motion artifacts.

however, is the maternal ECG, typically much higher in amplitude than the fetal ECG (i.e. the signal of interest). Consequently, the maternal ECG has to be accurately estimated to be then subtracted from the abdominal recording in order to get the fetal ECG. Maternal ECG signal can be obtained by applying the SBMM to an abdominal recording, as shown in the example application reported here. The abdominal recording (upper panel of Fig. 6), obtained from a woman in labor (available at the “Abdominal and Direct Fetal Electrocardiogram Database” of Physionet), clearly shows the maternal ECG and fetal ECG overlapping. Application of the SBMM to this abdominal recording allowed accurate maternal ECG extraction (lower panel of Fig. 6).

4. Discussion

This study proposes the new SBMM as a useful tool to extract a clean ECG from a noisy recording. As several other methods before, such technique is based on the construction of a template-beat [6], which is then concatenated to obtain the filtered ECG. However, only this technique involves CC segmentation into two segments, the QRS segment and the TUP segment, respectively independent and proportional to preceding RR interval. TUP-segment modulation (compression or stretch) is initially used to force all CC to have the same duration. Such condition is indeed required for computing

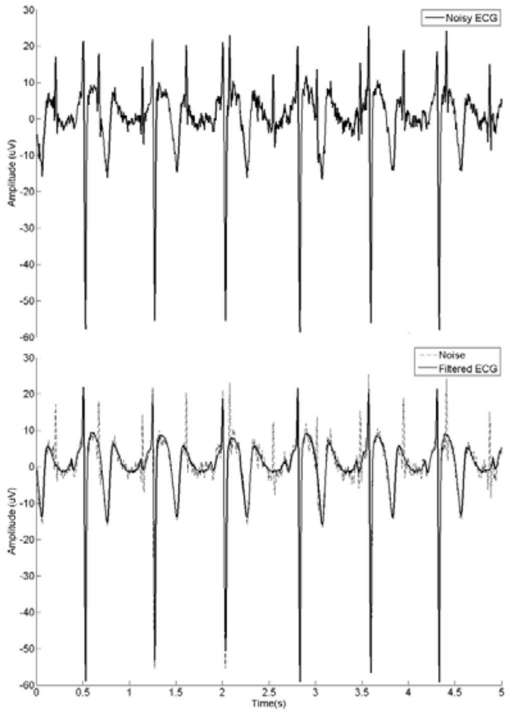

Figure 6. Maternal ECG extraction from an abdominal recording of a woman in labor.

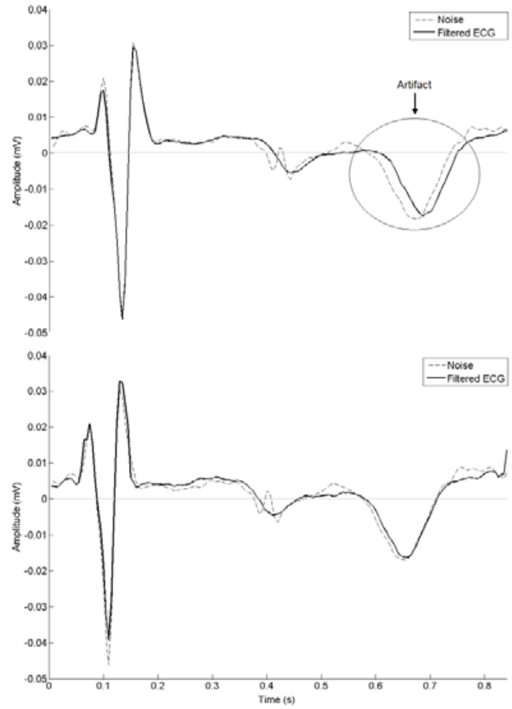

Figure 7. Maternal ECG extraction from an abdominal recording of a woman in labor.

the template-beat as the median beat. Then, filtered ECG is obtained by concatenating the template-beat after TUP-segment demodulation (stretch or compression) in order to obtain reconstructed beats whose duration matches that of the corresponding beats in the noisy recording. The modulation/demodulation procedure performed on the TUP segments strongly improves accuracy of the reconstructed clean ECG, as shown in Fig. 7, where is reported an example of an ECG extraction from a noisy recording performed without (upper panel) and with (lower panel) the modulation/demodulation process. The SBMM can be applied only if the R peaks relative to the ECG signal to be extracted are known. In most clinical cases, such condition is satisfied since the amplitude of the R peaks is higher than the noise, and specifically designed algorithms can be applied to localize the R peaks. In less frequent cases in which the R peaks are not directly derivable from the noisy recording to be filtered, the R peaks have to be indirectly obtained, for example using other ECG leads (for example in fetal application the R-peaks position can be derived using thoracic leads) or from other signals before the SBMM can be applied.

5. Conclusion

The new segmented-beat modulation method is a useful tool for extracting a clean ECG signal from a noisy recording.

References

[1] Verulkar NM, Zope PH, Suralkar SR. Filtering techniques for reduction of power line interference in electrocardiogram signals. IJERT 2012;1: 1-7.

[2] Nayak S, Soni MK, Bansal D. Filtering techniques for ECG signal processing. IJREAS 2012; 2: 671-9.

[3] Luo S, Johnston P. A review of electrocardiogram filtering. J Electrocardiol 2010;43:486-96.

[4] Ifeachor EC, Outram NJ, Henderson GT, Wimalaratna HSK, Hudson N, Sneyd R, Dong C, Bigan C. Nonlinear methods for biopattern analysis: role and challenges. Proc Ann Int Conf IEEE EMBS 2004;2:5400-6.

[5] Singh A, Mehra R. Adaptive filter for ECG noise Reduction using Rls Algorithm. IJERA 2013;3:1304-8.

[6] Kotas M, Jezewski J, Matonia A, Kupka T. Towards noise immune detection of fetal QRS complexes. Comput Meth Prog Bio 2012;57:383–94.

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