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Segmented beat modulation method for electrocardiogram estimation from noisy recordings

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ABSTRACT

Clinical utility of an electrocardiogram (ECG) affected by too high levels of noise such as baseline wanders, electrode motion artifacts, muscular artifacts and power-line interference may be jeopardized if not opportunely processed. Template-based techniques have been proposed for ECG estimation from noisy recordings, but usually they do not reproduce physiological ECG variability, which, however, provides clinically useful information on the patient's health. Thus, this study proposes the Segmented-Beat Modulation Method (SBMM) as a new template-based filtering procedure able to reproduce ECG variability, and assesses SBMM robustness to the aforementioned noises in comparison to a standard template method (STM). SBMM performs a unique ECG segmentation into QRS segment and TUP segment, and successively modulates/demodulates (by stretching or compressing) the former segments in order to adaptively adjust each estimated beat to its original morphology and duration. Consequently, SBMM estimates ECG with significantly lower estimation errors than STM when applied to recordings affected by various levels of the considered noises (SBMM: 176–232 µV and 79–499 µV; STM: 215–496 µV and 93–1056 µV, for QRS and TUP segments, respectively). Thus, SBMM is able to reproduce ECG variability and is more robust to noise than STM.

1. Introduction

Electrocardiography is a simple, cheap, noninvasive test widely used to assess cardiac electrical functionality. The electrocardiogram (ECG) is acquired by placing electrodes on the patient's body surface and represents a spatio-temporal integration of the electrical activity of all cardiac cells. During each heartbeat, an orderly progression of depolarization goes through the heart; it normally starts in pacemaker cells in the sinoatrial node, spreads out through the atria (causing atrial contraction), passes through the atrioventricular node and eventually spreads throughout the ventricles (causing ventricles contraction). This orderly pattern of depolarization gives rise to a typical sequence of ECG waveforms (Fig. 1): the P wave, which reflects atrial depolarization; the QRS complex, which is the highest amplitude complex, reflects ventricular repolarization and hides atrial repolarization; the T-wave and eventually the U-wave, which reflect ventricular repolarization. Ideally, ECG can be thought of as a periodic signal obtained by repetition of such waveforms representing, as a whole, a single heartbeat. However, in real conditions, ECG is pseudo-periodic since no ECG beat is perfectly identical to another; rather, it may vary in terms of both morphology and duration. This physiological variability is mainly due to the autonomic nervous system that constantly and unconsciously controls the cardiac activity in order to optimize blood circulation to the current physiological and emotional conditions of the subject. Other causes of ECG variability include respiration, involuntary movements and non-physiological sources of noise.

The presence of too high levels of noise affecting ECG may jeopardize its clinical utility if not opportunely processed [1–6]. Among the most common sources of noise are: baseline wander (BW), which can be caused by respiration and perspiration [7,8]; electrode motion artifact (EMA), which results from unexpected motion of the electrodes [9]; muscular artifact (MA), which is caused by the random contraction of muscles as well as by sudden body movement [10]; and power-line interference (PI) at 50 Hz [6,11]. Sometimes BW, EMA and MA are all seen baseline-related noise

Abbreviations: BW, baseline wander; CC, cardiac cycle; ECG, electrocardiogram; EMA, electrode motion artifact; HR, heart rate; HRV, heart-rate variability; mCC, median cardiac cycle; mRR, median RR; MA, muscular artifact; PI, powerline interference; BMM, segmented beat modulation method; STM, standard template method.

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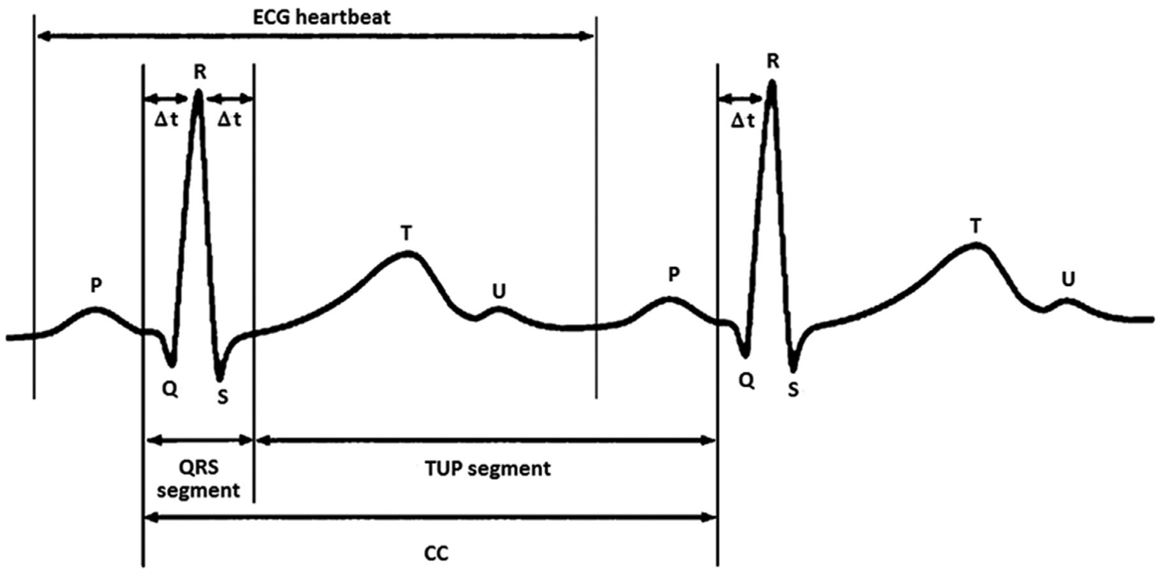

Fig. 1. Typical ECG waveforms from which are identifiable the usual heartbeat, starting and ending at the beginning of the P wave, and a specific CC, starting and ending at the beginning of the Q wave, segmented in QRS and TUP segments.

with different bandwidths [8,12–14]. To get rid of the noise, ECG is typically pre-filtered, often by application of linear techniques. Such pre-filtering, however, does not eliminate the noise frequency components within the ECG frequency band. If too heavily present, in-band components may prevent a correct ECG analysis, unless further processing is applied [7–9]. In common situations in which ECG is corrupted by noise surviving pre-filtering but the R peaks are still detectable, template-based techniques [2] are often used to estimate ECG from the noisy recording. Essentially, such techniques identify all heartbeats, overlap them after R-peak alignment, and average them to reduce noise and get a clean template of the heartbeat. Eventually, copies of such template are concatenated to get a clean ECG tracing that estimates ECG of interest. The major limit of most template-based techniques consists of not being able to reproduce physiological ECG variability, which provides clinically useful information on the patient's health. Thus, the aims of the present study were: to propose the Segmented-Beat Modulation Method (SBMM) [15–17] as a template-based filtering procedure able to overcome this limit by adaptively adjusting each reconstructed beat to the original beat morphology and duration; and to assess SBMM robustness to noise in comparison to another common template-based technique present in the literature.

2. Methods and data

2.1. ECG estimation methods

Two methods for the estimation of a clean ECG from a noisy recording will be presented, namely the standard template method (STM) and SBMM. Both techniques work under the hypothesis of knowing the R-peak positions and consider ECG as constituted by the repetition of N cardiac cycles (CC), which may differ in terms of amplitude and duration. If the heartbeat is known to begin with the P wave, CC is more general and may begin anywhere within ECG. Thus, the heartbeat is a specific case of CC. In this study, to compare SBMM against STM, the CC onset is identified in the PQ segment (i.e. between the P-wave offset end and Q-wave onset) Δt ms (for example $\Delta t = 40$ ms) before the R peak (Fig. 1). Eventually, both techniques perform modulation/demodulation processes to adapt CC duration.

B.M.E.D. (Bio-Medical Engineering Development, SRL, Ancona, Italy {1}) Matlab implementations of STM and SBMM algorithms (see below) have been used in the present study.

2.1.1. Standard template method

The STM algorithm is depicted in Fig. 2. It represents an adaptation of the method described in the literature [2] to the aims of this study. The R-peak sequence containing the location (samples) of the R peaks within the noisy ECG is used to identify all CCs and to compute the median RR interval (mRR). Each CC is modulated to force its duration to be exactly mRR by prolonging or truncating the baseline between the T wave and the following P wave. The modulated CCs are then used to compute the median CC (mCC), which provides a clean (thanks to the median operation) template of all CCs in the noisy ECG. The clean ECG at the output of the STM procedure is eventually obtained by N-fold repetition of mCCs, after having demodulated (by truncation or prolongation, i.e. by performing an opposite operation with respect to the previous modulation procedure) it in order to have its duration match the duration of the corresponding CC in the noisy ECG.

2.1.2. Segmented beat modulation method

The SBMM algorithm [15–17] is depicted in Fig. 3. The algorithm is based on the practical observation that, in first approximation, the QRS complex duration is independent of the heart rate (HR), whereas the duration of all other ECG waves linearly varies with it [18]. Specifically, the QRS duration is independent of the preceding RR interval, but the duration of the other waves is proportional to it. Under this assumption, each CC can be divided into two segments, the QRS and the TUP (Fig. 1). The QRS segment is identified $\pm\ \Delta t$ ms around the R peak, while the TUP segment is identified within Δt ms after the R peak and Δt ms before the subsequent R peak. Each CC is characterized by its own amplitude and duration. However, the duration of all QRS segments is the same in all CCs (twice Δt), whereas the duration of the TUP segments is CC-dependent (difference between CC duration and QRS duration).

According to SBMM procedure, the R-peak sequence containing the location of the R peaks within the noisy ECG is used to identify all CCs and to compute the median RR interval (mRR). Before computing mCC, all CCs are modulated in order to have their