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Baseline wander removal for bioelectrical signals by quadratic variation reduction

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A B S T R A C T

Baseline wander is a low-frequency additive noise affecting almost all bioelectrical signals, in particular the ECG. In this paper, we propose a novel approach to baseline wander estimation and removal for bioelectrical signals, based on the notion of *quadratic variation reduction*. The quadratic variation is meant as a measure of variability for vectors or sampled functions, and is a consistent measure in this regard. Baseline wander is estimated solving a constrained convex optimization problem where quadratic variation enters as a constraint. The solution depends on a single parameter whose value is not critical, as proven by a sensitivity analysis. Numerical results confirm the effectiveness of the approach, which outperforms state-of-the-art algorithms. The algorithm compares favorably also in terms of computational complexity, which is linear in the size of the vector to detrend. This makes it suitable for real-time applications as well as for applications on devices with reduced computing power, such as handheld devices.

1. Introduction

Bioelectrical signals are generated during spontaneous and evoked activity of human body. They are related to ionic processes arising from electrochemical activity of excitable cells, such as neurons and muscle cells, and reflect properties of the associated underlying biological systems [1]. Their analysis proves to be very helpful in explaining the function of the human body and identifying various pathological conditions [2]. Unfortunately, recorded signals are usually corrupted by different types of noise and interference, originating from external sources or from other physiological processes in the body [1,2]. In the worst cases, the useful signal may be dramatically masked by noise and its informative content can be revealed only after appropriate signal processing. This is the case, for example, of evoked potentials, which are part of brain signals, and late potentials, which are part of heart signals [1].

Baseline wander is a particular kind of noise affecting almost all bioelectrical signals, such as electroencephalogram (EEG) [3], magnetoencephalogram (MEG) [3], electrooculogram (EOG) [4,5], electromyogram (EMG) [6], and electrocardiogram (ECG) [1,7]. The sources of baseline wander may be different, but it always appears as a low-frequency artifact that introduces slow oscillations in the recorded signal.

In EEG and MEG registrations, baseline is due to brain activity, muscle tension, sweating, eye and head movements, electrode movement (in the case of EEG) or other noise sources [8,9]. In particular, baseline correction is a crucial task in the analysis of event-related activities measured in response to a time-locked stimulation [3]. This is the case of electric potentials recorded from the scalp with EEG, namely event-related potentials (ERPs), or magnetic fields measured close to the head through MEG, namely event-related fields (ERFs). Indeed, such a response is about 10-fold weaker than the spontaneous activity of the brain [1] and can be easily masked by noise. Moreover, stimuli are often presented at a relatively high rate so that the response to a previous stimulus has not extinguished at the moment of the current stimulus, resulting in an additional contribution to baseline [3]. Common approaches to

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baseline correction in ERP and ERF analyses are: (i) high-pass filtering [3]; (ii) ensemble averaging of several trials [1]; and (iii) subtraction of the average over a pre-stimulus interval [10]. The respective limits are: (i) baseline and ERPs, or ERFs, have overlapping spectra; (ii) a large number of records is needed and some information is unavoidably lost in the averaging operation; and (iii) trends more complex than the constant one cannot be removed.

The EOG is the measurement of electric potentials generated by voluntary or involuntary movements of the eyeballs within the conductive environment of the skull [4]. EOG analysis is frequently used in sleep and dream research and in the assessment of reading ability, visual fatigue, retinal dysfunction, and vestibular and balance dysfunction [4,11]. It is also used in EOG-based interfaces for assistive robots and electric wheelchairs [5]. The band of the EOG signal is in the range 0–30 Hz [4,12], partially overlapping the band of baseline wander. Baseline drift in EOG signals is mainly due to interfering background signals and electrode polarization [5,12]. Although baseline noise may be reduced by properly preparing skin and using suitable electrodes and electrode–gel combination, a preprocessing step for its removal is still required [5,12]. This is typically achieved by high-pass filtering with cut-off frequency of 0.1 Hz [12]. In [5] EOG detrending is achieved using a technique devised for ECG signals [13], which is based on wavelet decomposition.

EMG signals are used in the assessment of muscles activity, acquired either on skin surface (surface EMG, or sEMG) or with a needle electrode inserted into the muscle (needle EMG, or nEMG) [14]. Regardless of the acquisition method, EMG signals are affected by baseline fluctuations primarily due to electrical drifts in the acquisition equipment [1,14–16]. Additionally, baseline drift is also caused by skin–electrode interface in sEMG [9,15], and by movements of the recording needle relative to the muscle and variation of skin potential induced by the needle in nEMG [16]. However, the main source of baseline fluctuations in EMG recordings is interference of adjacent muscle units different from the one under investigation [1,16]. The common approach to baseline fluctuation removal from EMG recordings is high-pass filtering [1,17,18]. Nevertheless, baseline drift and EMG signal have overlapping bands in the low-frequency region of the spectrum [16,18,19]. Moreover, the spectral content of baseline fluctuations is highly variable, depending on the muscle whose activity is recorded, the degree of muscle contraction, and the position of the needle electrode [16]. This translates into a difficulty in selecting the appropriate cut-off frequency of the filter [15]. In this regard, several recommendations have been issued, but they all suggest the use of different cut-off frequencies [6,15,19,20]. To overcome these limitations, several approaches have been proposed in the literature [16,18].

As regards ECG signals, the main cause of baseline wander is respiration. Indeed, both the resistivity and position of the lungs change during respiration [21]. Moreover, the orientation and location of the heart change during the respiratory cycle, and certain cyclic changes occur in the measured electric heart vector as a consequence of the respiration [21,22]. Additional causes of baseline wander in ECG signals are perspiration, patient's body movements, skin–electrode interface, and varying impedance between electrodes and skin due to poor electrode contact [1,7,9]. Baseline wander is *ubiquitous* in all electrocardiographic devices and its removal is an unavoidable step in any processing of ECG signals [1,7,23–25].

Baseline wander in ECG is modeled as a low-frequency additive noise with band in the range 0–0.8 Hz, which can extend up to 1 Hz, or even more, during stress tests [1,7]. As a consequence, baseline wander and ECG have overlapping bands in the low-frequency region of the spectrum [26]. Unfortunately, distortion in this band negatively affects the shape of the ST segment, which is the portion connecting the QRS complex with the T-wave. The ST segment has strong clinical relevance, since deviations from its physiological level reflect an undergoing acute coronary syndrome, which is one of the most severe forms of heart disease and the main cause of mortality in developed countries [25]. Furthermore, the low-frequency region of ECG spectrum proved to be useful in detecting nightly events of obstructive sleep apnea [27]. The in-band nature of baseline wander makes its removal difficult without affecting the ECG, when traditional techniques are used, thus spoiling relevant clinical information [28].

Given the critical role of baseline wander removal for ECG signals, several solutions have been proposed to tackle this problem [7,29–34]. Moreover, other bioelectrical signals are in general detrended using the techniques developed for ECG signals [1].

In this paper, we propose a novel approach to baseline wander estimation and removal for bioelectrical signals, which is based on the notion of *quadratic variation reduction*. Preliminary results were presented in [35]. We introduce the quadratic variation as a measure of variability for vectors or sampled functions, and prove that it is a consistent measure in this regard. The problem of baseline wander estimation is recast as a constrained convex optimization problem where the quadratic variation enters as a constraint. Baseline is estimated searching for the signal closest to the observed one, but exhibiting *reduced quadratic variation*. The solution depends on a single parameter whose value is not critical, as demonstrated by a sensitivity analysis. Numerical results on bioelectrical signals of different types confirm the effectiveness of the approach.

The paper is organized as follows. The rationale behind the proposed approach is described in Section 2. The baseline wander estimator is derived in Section 3. In Section 4 numerical results on ECG, EMG, and EEG signals are reported, with a comparison with the state-of-the-art in the case of ECG. Section 5 follows with conclusions. Finally, proofs of some results exploited in Section 3 are reported in the Appendix.

2. The quadratic variation

As highlighted in the previous section, baseline wander noise is an additive low[1] "variability" noise affecting the measured signal, which can be any of the bioelectrical

[1] Low with respect to the "variability" of the bioelectrical signal under consideration.