Chapter 22

Noise Cancellation in ECG Signals with an Unbiased Adaptive Filter

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ABSTRACT

The electrocardiographic (ECG) signal is a transthoracic manifestation of the electrical activity of the heart and is widely used in clinical applications. This chapter describes an unbiased linear adaptive filter (ULAF) to attenuate high-frequency random noise present in ECG signals. The ULAF does not contain a bias in its summation unit and the filter coefficients are normalized. During the adaptation process, the normalized coefficients are updated with the steepest-descent algorithm to achieve efficient filtering of noisy ECG signals. A total of 16 ECG signals were tested in the adaptive filtering experiments with the ULAF, the least-mean-square (LMS), and the recursive-least-squares (RLS) adaptive filters. The filtering performance was quantified in terms of the root-mean-squared error (RMSE), normalized correlation coefficient (NCC), and filtered noise entropy (FNE). A template derived from each ECG signal was used as the reference to compute the measures of filtering performance. The results indicated that the ULAF was able to provide noise-free ECG signals with an average RMSE of 0.0287, which was lower than the second-best RMSE obtained with the LMS filter. With respect to waveform fidelity, the ULAF provided the highest average NCC (0.9964) among the three filters studied. In addition, the ULAF effectively removed more noise, measured by FNE, in comparison with the LMS and RLS filters in most of the ECG signals tested. The issues of adaptive filter setting for noise reduction in ECG signals are discussed at the end of this chapter.

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INTRODUCTION

The electrocardiographic (ECG) signal is the electrical manifestation of the contractile activity of the heart. Computerized ECG analysis is widely used as a reliable technique for the diagnosis of cardiovascular diseases, and the ECG signal is the most commonly used biomedical signal in clinical practice (Rangayyan, 2002; Tompkins, 1993). However, a surface recording of the ECG signal (with the frequency range of 0.05-250 Hz), obtained by placing electrodes on the subject's chest, is inevitably contaminated by several different types of artifacts. The dominant artifacts in an ambulatory ECG recording include (Rangayyan, 2002; Wu & Rangayyan, 2009):

- **Baseline wander:** Drift of the baseline is a type of low-frequency (lower than 0.5 Hz) artifact and usually caused by respiration or movement of the subject.
- **Physiological artifacts:** This type of artifact is mainly induced by muscular contractions. Electrode-motion artifact has a wide frequency range (from 1 to 5,000 Hz) and is generally considered to be the most troublesome, because it can mimic the appearance of ectopic beats and cannot be removed easily by simple filters.
- **Random noise:** Random noise could be the result of the thermal effect in the instrumentation amplifiers, the recording system, and pickup of ambient electromagnetic signals by the cables used (Rangayyan, 2002). Random noise usually appears with high frequency; its frequency range depends on the specific source. In real-time clinical monitoring systems used during surgery, electrosurgical noise is a significant obstacle to be overcome.
- **External interference:** Examples of environmental interference are those caused by 50 or 60 Hz power-supply lines, radiation from lights, and radio-frequency emissions from nearby medical devices.

The removal of artifacts is crucial for ECG monitoring, and is an essential procedure prior to further diagnostic analysis in many clinical applications, e.g., classification of ectopic beats (Afonso, Tompkins, Nguyen, & Luo, 1999; Hu, Palreddy, & Tompkins, 1997), detection of QRS complexes (Meyer, Gavela, & Harris, 2006; Hu, Tompkins, Urrusti, & Afonso, 1993), analysis of asymptomatic arrhythmia (Thakor & Zhu, 1991), extraction of the fetal ECG signal from the maternal abdominal ECG (Kanjilal, Palit, & Saha, 1997; Khamene & Negahdaripour, 2000; Zarzoso & Nandi, 2001), classification of myocardial ischemia (Silipo & Marchesi, 1998), diagnosis of atrial fibrillation (Yang, Devine, & Macfarlane, 1994), ECG-based sleep apnea detection (Mita, 2007), and ECG signal data compression (Zigel, Cohen, & Katz, 2000; Hamilton, Thomson, & Sandham, 1995). The extraction of high-resolution ECG signal from noise-contaminated recordings is an important part of the artifact removal procedure (Clifford, Azuaje, & McSharry, 2006). The goal of noise reduction in the ECG signal is to separate the valid signal components from the undesired noise, so as to present an ECG that facilitates easy and accurate interpretation (Afonso, Tompkins, Nguyen, Michler, & Luo, 1996).

Widrow *et al.* (Widrow et al., 1975) reported that an adaptive filter has the ability to adjust automatically the tap-weights to produce the desired impulse response, according to the time-varying characteristics of the input signal. Recent literature indicates that a number of adaptive filtering methods have been applied in several different clinical applications. Thakor and Zhu (Thakor & Zhu, 1991) designed a type of adaptive recurrent filter to detect normal QRS complexes in ambulatory ECG recordings, and then applied it for the analysis of arrhythmia. Xue *et al.* (Xue, Hu, & Tompkins, 1992) developed adaptive whitening and matched filters based on artificial neural networks for the detection of QRS complexes. Hamilton (Hamilton, 1996) compared the effectiveness of power-line interference removal