An Efficient Linear Phase High-pass Filter for ECG

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Abstract

Simple infinite impulse response (IIR) high-pass filters for ECG cause ST-segment distortion due to the overshoot in the impulse response unless the cutoff frequency is very low. Linear-phase filters solve the ST distortion problem but these filters are typically computationally expensive. Four 0.5 Hz linear-phase high-pass filters were compared. The reference high-pass filter was a single pole IIR filter run in the forward and backward direction (IIR). The other filters were a boxcar, a weighted average 9 boxcar filter to approximate a Blackman window (Multi-Boxcar), and a moving window median (Median). The filters were compared by average power spectrum on a 12-lead ECG database of prehospital ECGs containing significant baseline wander (n=5,368). The average power spectrum for the boxcar high-pass filters shows higher levels of low frequency attenuation. The multi-boxcar filter shows a lower passband ripple than the boxcar. The maximum (mean) absolute deviation from the raw signal power spectrum in the 1.0 to 10 Hz range was 0.86 (0.09), 1.6 (0.34), 0.27 (0.05) and 0.19 (0.04) dB for the IIR, boxcar, multi-Boxcar and median filters, respectively. The multi-boxcar filter improves the passband ripple compared to a simple boxcar high-pass while retaining an efficient design. The trade-off is a delay on the order of one second.

1. Introduction

The issue of ST-segment distortion in ECG due overshoot in the impulse response of infinite impulse response (IIR) high-pass filters is a well understood problem [1]. Changing the filter type to a linear phase high-pass filter solves the overshoot problem. Although the overshoot problem is solved by linear phase filters, the design trade-offs are problematic.

A commonly used form of linear phase filter for ECG high pass filtering is a simple IIR filter. The IIR filter has the overshoot problem, but the filter is made linear phase solving the overshoot problem by running the filter in both forward time and reverse time [1]. An example of baseline wander attenuation and corresponding false ST-segment elevation can be seen in Figure 1. In the forward-backward IIR case, the design trade-off is that the filter may not be real-time. It can only be applied to the entire signal in batch mode after recording stops.

Another generic solution is an IIR filter designed in sections. One section provides the low frequency attenuation (high-pass function), while the other all-pass section provides the phase correction to make the two sections applied in serial a linear phase filter [2]. In general, the filter coefficients must be precise for proper phase correction, therefore expensive floating-point calculations are necessary.

Finite impulse response (FIR) filters are easily designed to be linear phase by symmetry in the impulse response. For FIR filters, the output is a weighted average of the input. The filter coefficients provide the weights. For ECG however, the cutoff frequency is very different from the sample rate, typically a cutoff of 0.5 or 0.67Hz versus sample rates of 500 or 1000 samples per second. When the cut off frequency differs from the sample rate by orders of magnitude, the impulse response becomes very long, the number of filter weights is large and therefore computationally intensive. For each output sample, there is

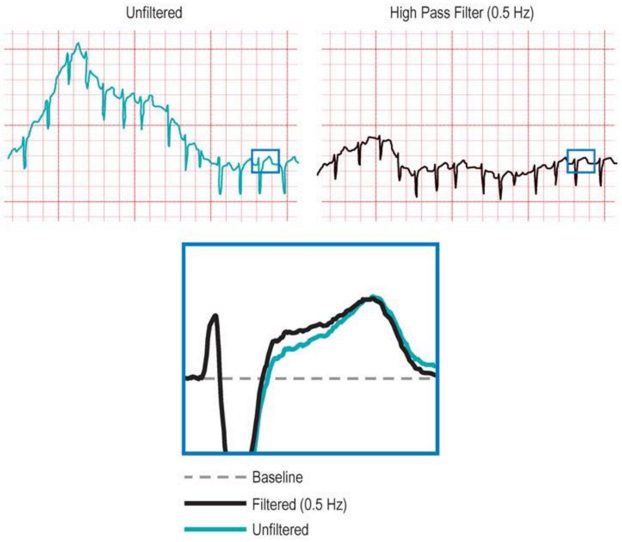

Figure 1. Example of ST-segment overshoot, false ST elevation, due to 0.5 Hz IIR high-pass filter.

a multiply accumulate operation for each filter weight. In ECG, a 0.5Hz high-pass filter would have an impulse response and therefore a number of weights on the order of the sample rate. The efficiency can be improved by a factor of two by making the filter weights symmetric.

In this study, we show the filter performance of a novel efficient high-pass filter, the multi-boxcar filter, compared to other commonly used filter types.

2. Methods

Three commonly used 0.5Hz high-pass filters were compared to the multi-boxcar highpass, the reference forward-backward IIR filter, a sliding window median filter, and a standard boxcar filter. Only the IIR filter was realized directly as a high-pass filter. The other filters accomplished a high-pass filter function by subtracting the output of a lowpass filter from the original signal while accounting for the lowpass filter delay.

The forward-backward (FB) IIR filter was a single pole Butterworth high pass design with a 0.322 Hz cutoff frequency to ensure a 0.5 Hz overall cutoff when the forward and backward operations were combined in series. The boxcar filter was designed to have a 0.5 Hz cutoff by setting the length of the filter. A boxcar filter is implemented in an efficient way with a first-in-first-out (FIFO) memory. On initialization, the FIFO is loaded with ECG samples and all the samples are summed. Each new sample is added to the sum while the delayed sample at the end of the FIFO is subtracted as a way to efficiently calculate a running sum over the window. The filter impulse response has the shape of a train boxcar, thus the name. Since the filter delay is half the length of the window, the running sum is subtracted from the point halfway down the first-in-first-out (FIFO) to implement the high pass filter function.

The median high pass filter was implemented by subtracting the running median from a point halfway down the FIFO memory. The median operation is a smoothing operation like taking the mean, but the median is not sensitive to outliers. The length of the median filter FIFO was chosen empirically to obtain the desired 0.5 Hz cutoff frequency.

The efficient multi-boxcar high pass filter is implemented as the weighted sum of a set of boxcar filters, each with a different length and time offset from the base circular buffer. The filter design is summarized in Figure 2. The impulse response of each boxcar filter is stacked to result in an approximation of the desired impulse response. To more closely approximate the desired shape, each boxcar filter has a different gain or to put it a different way, the final output is the weighted sum of all the boxcar filters. The final design tested here used 9 boxcar filters to approximate a Blackman window which has the property of a deep even stopband. A close up of the impulse response is given in Figure 3. The frequency response can be seen in Figure 3 for implementations using 5, 9, 13, 17 and 21 boxcar filters to approximate the Blackman window. It is clear from the frequency response plots that the more boxcar filter elements used, the lower passband ripple.

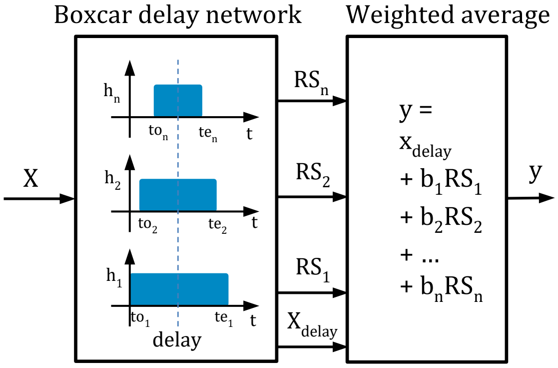

Figure 2. Block diagram of the multi-boxcar high-pass filter comprised of two elements, the running sum (RS) for each box car low-pass and the weighted average to generate the final output (y).

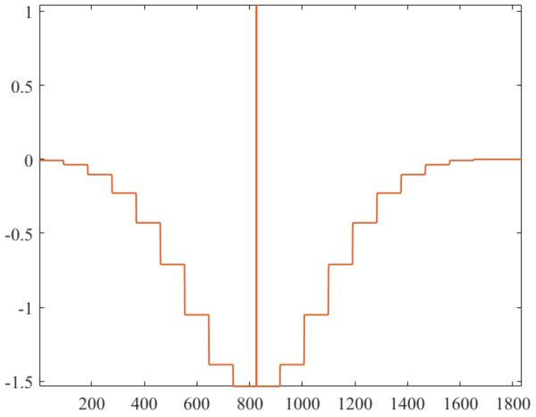

Figure 3. Close up view of the 9-boxcar high-pass impulse response. Note that the amplitude is 1000 at sample 1000, also the filter delay.

The study data for practical testing outside of the impulse and frequency response is a prehospital 12-lead ECG dataset from a regional EMS system serving multiple hospitals. This dataset is a good candidate for high-pass filter testing because prehospital ECG is known to be more prone to artifact and baseline wander due to the desire to record the ECG as quickly as possible because “time is tissue” in the 911 chest pain population. The goal is to minimize recording and treatment time on-site to also minimize the time to primary cutaneous intervention (PCI) for acute myocardial infarction. The dataset was collected from multiple EMS agencies over several years resulting in a set of 5,366 12-lead ECGs [3,4].

The high-pass filters were compared based on average

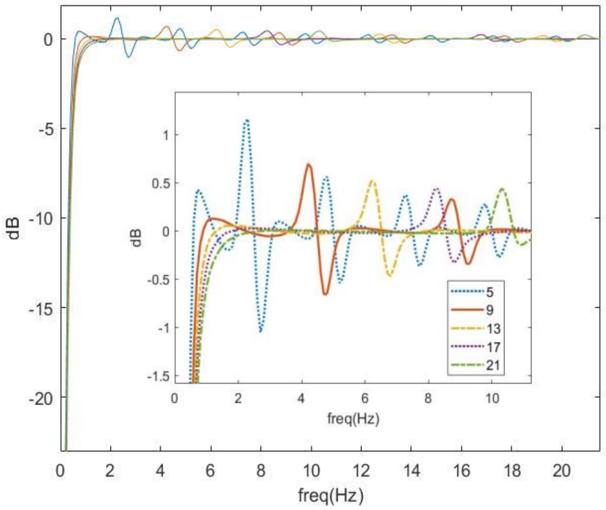

Figure 4. Frequency response of the 0.5 Hz multi-boxcar based family of high pass filters for various number of boxcar filters using in the approximation of the ideal impulse response.

power spectrum across the study data. The power spectrum for each lead of every ECG was added to the single averaged power spectrum. The comparison was analyzed by computing the difference, maximum and average, from the signal power spectrum without high-pass filtering. In addition, the power spectra were plotted for visual comparison of the 4 filters.

3. Results

The power spectra for all four filters and the raw signal can be seen in Figure 6. As expected for the difficult prehospital EMS environment, the low frequency content of the raw signal (blue) below 1.0 Hz is at least 10dB above the ECG signal content just above 1.0 Hz. The power spectrum of the median and multi-boxcar filtered signals closely tracks the raw signal power spectrum from 1.0 Hz and beyond. The boxcar accentuates around 1.0 Hz and the reference forward-backward IIR filter attenuates around 1.0 Hz. All filters but the median filter substantially attenuate low frequencies below 0.5 Hz. To quantify the difference between the filter's output and the raw signal power spectrum, Table 1 tabulates the maximum deviation and the average deviation over the 1.0 to 10.0 Hz passband frequency range. The filters are arranged in order of decreasing deviation. The median filter is both the best in terms of deviation above 1.0 Hz and the worst below 0.5 Hz. The multi-boxcar filter is a good compromise between stop band attenuation and passband ripple

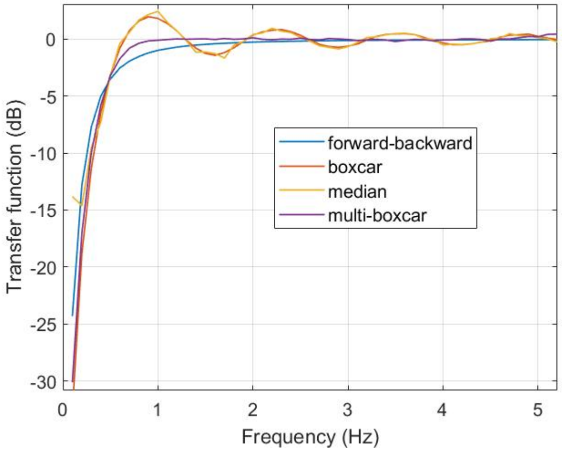

Figure 5. Comparison of highpass filter transfer functions.

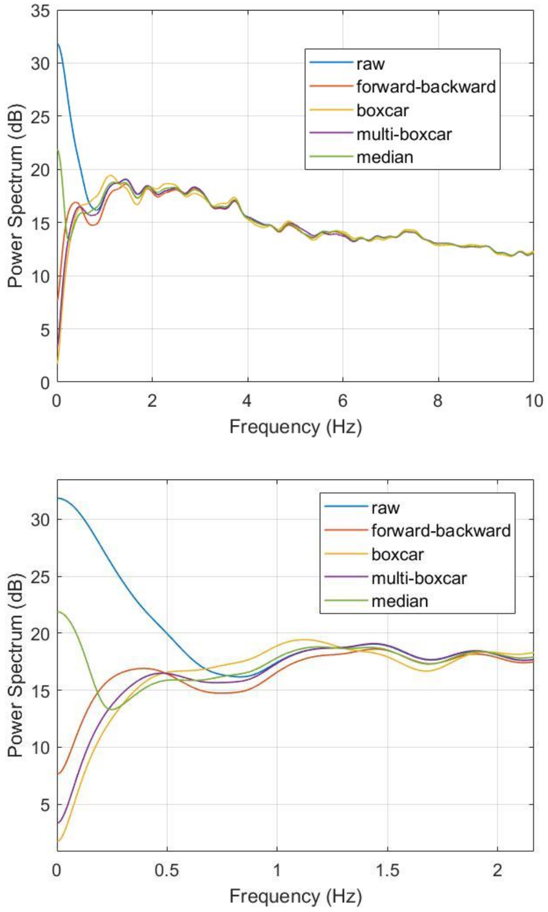

Figure 6. The upper panel shows the averaged power spectra of the raw signal (blue) from the study population and the four filters compared. The horizontal axis is frequency in Hertz while the vertical axis is power in decibels (dB). The lower panel zooms in on the cut off frequency to emphasize the local frequency differences.

Table 1. Deviation of preprocessing filter from the raw signal power spectrum in decibels (dB) from 1.0 to 10Hz.

Filter	Max deviation	Average deviation
Boxcar	1.4	0.26
FB IIR	0.86	0.09
Running median	0.40	0.08
Multi-boxcar	0.31	0.04

4. Discussion

Digital boxcar filters are used in many different applications including radiofrequency mapping of subsurface features of the earth like ground water. A related boxcar filter design was described by the authors of a paper on radiofrequency mapping. The goal was similar to that in ECG – attenuate very low frequency interference with an efficient filter design. Their filter used a boxcar filter, but with a cosine taper to the edges to reduce sidelobes in the filter stopband [5]. In our case sidelobe reduction of the lowpass element results in much improved passband ripple. This is the result of using a Blackman window lowpass instead of a boxcar lowpass. The cosine taper improves the frequency response of the boxcar but not nearly to the level of a Blackman window.

Only one application of the general design technique is described here, but the method is more flexible than presented. The design method outlined here can be used to efficiently approximate any long duration impulse response in a simple manner. A more conventional but more complicated design method would use a series of lowpass and down-sample steps, apply the desired lowpass filter at a lower sample rate for efficiency, and then up sampling (interpolate) to get back to the original sample rate. The method presented here is simple in comparison. The drawback of course is the pass band ripple introduced by the course approximation of the desired impulse response. We showed in this application that the pass band ripple was limited to under +/- 1 dB when using just 9 boxcar filters in the approximation in Figure 4.

The FIR based high pass filters presented here including the running median all have a long delay on the order of a second or two and therefore edge effects at the start of the signal and the end of the signal. When the signal is long compared to the end effects, the effect on measurements is negligible but when the duration of end effects approaches the total length of the signal, the end effects will affect the filter performance measures. The FIR filter advantages will be underestimated due to end effects because the baseline is estimated by a much smaller number of points than when running steady state outside of the signal start and end. The edge effects are expected to have minimal impact when the filter is used for the intended longer ECG signals.

5. Conclusion

As long as the target real-time ECG application can tolerate a two second delay, the multi-boxcar high pass filter presented here accomplishes not only good excellent band attenuation but also good pass band ripple with an efficient design.

Acknowledgments

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