Nonlinear filters for preprocessing Heart rate variability signals

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Abstract
Heart rate variability analysis requires normal sinus rhythm to accurately acquire heart rate variability measures in the time and frequency domain. Ectopic beats, missed QRS complexes and noisy beats hinder this analysis and introduce ambiguity in the variability measures. For this reason, it is necessary to design a specific filter to remove the ectopic beats and other noisy beats from HRV signal. In this paper a nonlinear adaptive threshold based Rank Order Filter (AROF) is proposed for denoising HRV signal. The filter has adaptability in rank, window size and threshold conditions based on the noise level. The quality of the restored signal is measured by the standard time and frequency domain measures of HRV signal and general statistical measures such as peak signal to noise ratio (PSNR) and root mean square error (RMSE) of restored signal. The performance of adaptive threshold based AROF is compared with wavelet based filter, median filter and an adaptive median filter. The performance of adaptive threshold based Rank Order Filter is superior not only in the PSNR value but also in the quality of the restored signal.

Index Terms
Adaptive rank order filter, Adaptive median filter, Ectopic beats, Heart rate variability, Median filter.

1. Introduction

Over the past 20 years there has been widespread interest in the study of variations in the beat-to-beat timing of heart known as heart rate variability (HRV) or RR interval variations. HRV has been used as a measure of mortality primarily with patient undergone cardiac surgery. Clinical depression strongly associated with mortality with such patients may be seen through a decrease in HRV [1]. HRV is a non invasive measure of autonomic nervous system balance.

Heart rate is influenced by both sympathetic and parasympathetic (vagal) activities of ANS. The influence of both branches of the autonomic nervous system (ANS) is known as sympathovagal balance reflected in the RR interval changes. A low frequency (LF) component provides a measure of sympathetic effect on heart and generally occurs in a band between 0.04 Hz and 0.15 Hz. A measurement can be made on the high frequency band (HF) defined between 0.15 and 0.4 Hz which is also known as respiratory sinus arrhythmia (RSA), and is a measure of cardiac parasympathetic activity. The ratio of power in the LF and HF bands (LF/HF) provides the measure of cardiac sympathovagal balance. The frequency domain measures are greatly hindered by the presence of ectopic beats and other noisy beats [2-3].

There are two main arguments for the removal of ectopic beats and missed QRS complexes and other noises from the HRV signal prior to the calculation of HRV metrics. First, heart rate modulatory signals involving the brain and cardio-vascular systems act upon the sinoatrial (SA) node of the heart influencing sinus rhythm. Assessments of autonomic function reflect the ability of the system to stimulate the SA node. Ectopic beats originate from secondary and tertiary pacemakers and this type of locally aberrant beat will temporarily disrupt normal neurocardiac modulation. Second, an ectopic beat will often appear late or early with respect to the timing of a sinus beat. This creates a sharp spike in the RR interval variations which are likely to add a significant power in the high frequency band. Many of the commonly used standard time domain HRV measures involves Euclidean distance computations and therefore just one outlier can significantly alter the value of a metric. There exist algorithm that detect and classify noisy beats [3], but for HRV analysis these beats must be removed either by editing [4], or some means of interpolation and filtering. In this paper a nonlinear Adaptive Rank Order Filter (AROF) with an adaptive threshold is proposed for denoising HRV signal. The performance of wavelet based filter (WF), median filter (MF) and adaptive median filter (AMF) are compared with proposed AROF in removing noisy beats present in the HRV signal.

2. Nonlinear Filtering

A popular scheme to deal with the noisy image is the median filter. Ioannis Pitas and Anastasios N. Venetsanopoules [5] presented an approach for median filtering to remove noise from images. The advantages of this median filter are low computational complexity and good results in cases of low noise density. Performance of the filter deteriorates as the noise density increases. D.R.K.Brownrigg [6] presented different approaches for weighted median filter which is extension of the median filter. It gives more weight to some values within the window. However, when the noise density increases, some details of the original

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information are smeared by this filter. To eliminate this problem H.Hwang and R.A.Haddad [7] presented an Adaptive median filter. Adaptive filters changes its characteristics based on statistical characteristics of the data. The performance of the adaptive filters is usually superior to non adaptive counterparts. Expansion of window size in the Adaptive median filter is determined by the criterion if the median is noisy or not. This criterion is not appropriate when the noise density is moderate or high. The elements processed by this filter are reused again and again. This may degrade the quality of the restored information.
To avoid the problems in the Adaptive Median Filter, an Adaptive Rank Order Filter is proposed for denoising images [8]. This filter expands the window if all the elements (not only the median) within the window are noisy. In this work an adaptive threshold based AROF filter is used for denoising the complex HRV signal. This adaptive threshold based AROF algorithm addresses three problems: blurring of signal for large window size, poor noise removal for smaller window size and an adaptive threshold which are encountered in other methods [5-8]. This filter effectively removes the noise from the HRV signal even when the noise density is high.

3. Adaptive Rank Order Filters

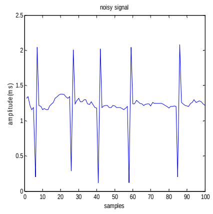
The adaptive rank order filter is the extension of the rank order filter. Three types of adaptation incorporated into the rank order filter to form an adaptive threshold based AROF; 1:An adaptive filtering output, 2: An adaptive window size and 3: An adaptive threshold condition to remove the noise. In the aspect of adaptive filtering output, the output may be a noise-free median or a noise-free non-median which is then used to replace the center element in the window. As for the adaptive window size, a window expansion scheme is adopted where the criterion to expand window is all elements within the current window are noisy. For an adaptive threshold, the threshold condition is based on the median value of the previous window. These adaptabilities improve the quality of the restored signal with moderate and high noise density.

3.1 Steps involved in AROF algorithm

Given a noisy signal A and initial window size 3, the adaptive threshold based AROF is implemented as follows:

Step 1: Duplicate the noisy input signal to output signal B.
Step 2: Check the center element in the window is noisy or not. If yes then go to step 3. Otherwise, move the center of the window to next element and redo step 2.
Step 3: Sort all the elements within the window in the ascending order and find the median fmed.
Step 4: Determine if fmed is noisy or not using the threshold conditions (within + or - of 20% of previous window fmed value) based on the signal characteristics. If it holds fmed is not a noisy element then go to step 5. Otherwise, fmed is noisy and go to step 6.
Step 5: Replace the corresponding center element in the output B with fmed and go to step 6.
Step 6: Check if all other elements within the window are noisy or not. If yes, then expand the window size and go back to step 3. Otherwise, go to step 7.
Step 7: Replace the corresponding center element in output B with the noise free element which is the closest one to the median.
Step 8: Reset window size and move the center of the window to next element.
Step 9: Repeat the steps until all the elements are processed.

The following example explains how the ectopic beats suppress the HRV variations (Fig 3.1) and the effect of adaptive threshold AROF filter shown in Fig 3.2.



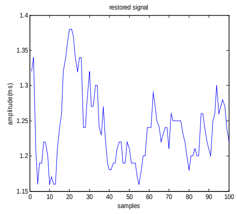


Fig 3.1 Noisy beats Fig 3.2 AROF filtered signal

4. Results and Discussion

Performance of proposed filter is studied and compared with the performance of 1: Wavelet based filtering method, 2: Median filter and 3: Adaptive median filter.

4.1 Filtering of HRV signal corrupted by 40% noise

Real time HRV signal shown in Fig.4.1 (a) is downloaded from physionet web site [10] and 40% noise is added in random as shown in Fig.4.1 (b). Then the noisy signal is filtered using wavelet based filter using db4 wavelet in Fig.4.1(c), Median filter in Fig.4.1(d), Adaptive median filter in Fig.4.1(e) and an adaptive threshold based Adaptive rank order filter in Fig.4.1(f) are shown. The figures show the AMF and AROF filters restore the fluctuations better than wavelet based filter and median filter.

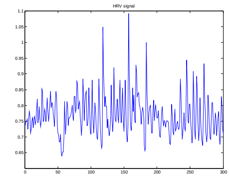


Fig 4.1 a) HRV signal

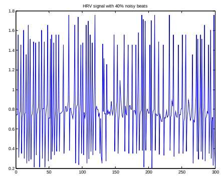


Fig 4.1 b) signal With 40% noise

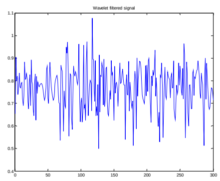


Fig 4.1 c) Wavelet Filter

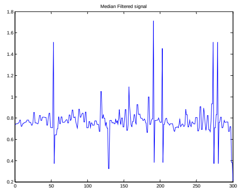


Fig. 4.1 d) Median Filter

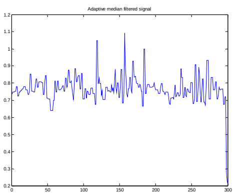


Fig 4.1 e) AMF

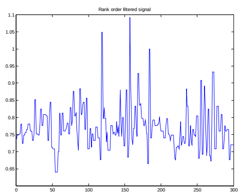


Fig 4.1 f) AROF signal

4.2 Histogram plots of HRV signal corrupted by 40% noise

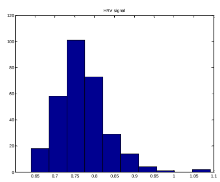


Fig 4.2 a) Original signal

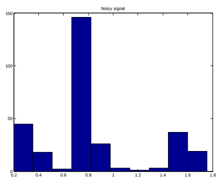


Fig 4.2 b) 40% noisy HRV signal

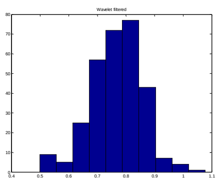


Fig 4.2 c) Wavelet Filter

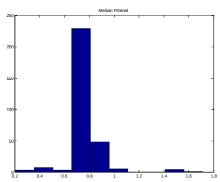


Fig 4.2 d) Median Filter

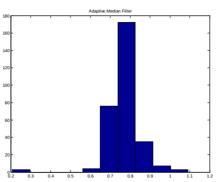


Fig 4.2 e) AMF

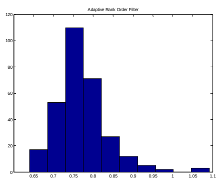


Fig 4.2 f) AROF

Histogram plots of filtered signal at 40% noise level are shown in figures 4.2 (a-f). The figure shows the adaptive threshold based AROF preserves the signal distribution compared to AMF, median filter and wavelet based filter. The median filter does not remove the noise completely.

4.3 Root mean square error (RMSE) comparison of filters at various noise levels.

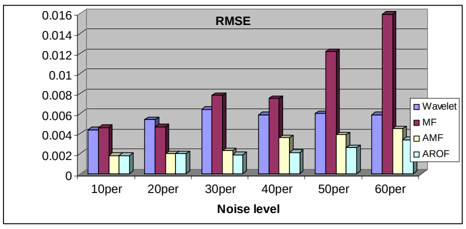


Fig.4.3 RMSE comparison of filters

The RMSE value of MF increases with increasing noise level. The RMSE value of adaptive threshold based AROF is the lowest among all filters.

4.4 Peak signal to noise ratio (PSNR) comparison of filters at various noise levels.

The PSNR value of AROF is the highest among all filters at various noise level.

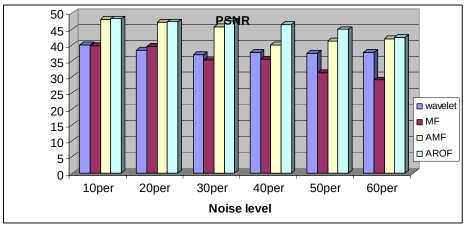


Fig.4.4 PSNR comparison of filters

The quality of the restored signal at 40% noise level is measured by the standard time domain and frequency domain measures using the HRV analysis free software [9]. The time domain measures 1: mean RR interval (mean RR), 2: RR interval standard deviation (STD (RR)), 3: mean heart rate (mean HR), 4: heart rate standard deviation (STD (HR)) and 5: root mean square successive differences (RMSSD) are given in Table-1. The Welch's periodogram method [9] is used for standard frequency domain measures. The very low (VLF), low (LF) and high (HF) frequency measures and its absolute powers of adaptive threshold based AROF signal are given in Table-2. The measures of adaptive threshold based AROF signal are much closer to original signal measures compared to WF, MF and AMF signals.

The restored signals and histograms shows the adaptive threshold based AROF filter not only removes the noisy beats from the HRV signal it also retains the fluctuations, distribution and structure of the HRV signal. The performance of AMF is better than wavelet based filter and median filter. The median filter performance degrades when the noise level increase. The wavelet based filter performance is better than median filter performance when the noise level is moderate and high.

Table-1 Standard time domain measures of restored signals

HRV time domain Parmeters	***Original signal***	***Signal at 40% noise level***	***Wavelet Filtering***	***MF Filtering***	***AMF Filtering***	***AROF Filtering***
MeanRR(sec)	0.76907	0.832833	0.76941	0.772517	0.765693	0.770533
STD(RR) (sec)	0.060288	0.370958	0.089543	0.152623	0.196774	0.062581
Mean HR(1/min)	78.4952	94.9742	79.1695	80.1842	80.1107	78.37
STD(HR)(1/min)	5.8555	57.0037	10.2524	16.7099	17.6295	5.9716
RMSSD (ms)	67.2984	603.7019	113.9618	188.3813	119.3743	64.9987

Table-2 Standard frequency domain measures of restored signals

HRV frequency domain Parmeters	***Original signal***	***Signal at 40% noise level***	***Wavelet Filtering***	***MF Filtering***	***AMF Filtering***	***AROF Filtering***
VLF(Hz)	0.015625	0.027344	0.033203	0.033203	0.013672	0.014872
LF(Hz)	0.103516	0.058594	0.056641	0.146484	0.134766	0.108438
HF(Hz)	0.279297	0.175781	0.275391	0.207031	0.226563	0.246563
Abs.powers						
VLF(ms2)	33.5266	1444.041	45.7659	854.3024	84.1476	44.632
LF(ms2)	124.2505	4285.537	374.8241	1583.924	200.8468	134.8025
HF(ms2)	476.1469	53153.02	652.5885	6077.353	524.7049	501.0015

4.5 Performance of adaptive threshold based AROF at different noise level

Table-3 Standard time domain measures at various noise level

HRV time domain Parmeters	***Original signal***	***10% noise level***	***20% noise level***	***30% noise level***	***40% noise level***	***50% noise level***	***60% noise level***
MeanRR(sec)	0.76907	0.766783	0.767191	0.7698	0.770533	0.772789	0.780749
STD(RR) (sec)	0.060288	0.058974	0.059376	0.065764	0.062581	0.061869	0.062268
Mean HR(1/min)	78.4952	78.7133	78.6776	78.5005	78.37	78.1283	77.3583
STD(HR)(1/min)	5.8555	5.8105	5.8615	6.2795	5.9716	5.8189	5.6656
RMSSD (ms)	67.2984	63.6761	62.502	68.2783	64.9987	64.4121	57.5814

Table-4 Standard frequency domain measures at various noise level

HRV frequency domain Parmeters	***Original signal***	***10% noise level***	***20% noise level***	***30% noise level***	***40% noise level***	***50% noise level***	***60% noise level***
VLF(Hz)	0.015625	0.015605	0.015525	0.015225	0.014872	0.013672	0.013352
LF(Hz)	0.103516	0.105469	0.105469	0.106797	0.108438	0.109148	0.109997
HF(Hz)	0.279297	0.254141	0.244044	0.246163	0.246563	0.226563	0.212891
Abs.powers							
VLF(ms2)	33.5266	20.06	19.7316	44.1824	44.632	112.6619	139.9148
LF(ms2)	124.2505	107.477	113.6439	117.0906	134.8025	193.5023	261.0057
HF(ms2)	476.1469	479.5833	483.8357	484.8862	501.0015	515.1525	568.3105

The standard time and frequency domain measures at various noise levels are given in table-3 & 4. At 40% noise level and above the restored signal VLF and HF variations are reduced but LF variations are increased. The noise affects the HF variations of the HRV signal at all levels.

5. Conclusion

The adaptive threshold based AROF in this paper has adaptive threshold conditions in addition to adaptability to window size and non median values. Adaptive filters are first time used for the removal of noisy beats in HRV signal. The simulation results are compared with the median filter, adaptive median filter and wavelet filtering method. The performance of proposed adaptive rank order filter is superior not only in the PSNR value but also in the quality of the restored signal when the noisy beats presented percentage is moderate or high (30% to 60%) under considerations.

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