Efficacy of DWT denoising in the removal of power line interference and the effect on morphological distortion of underlying atrial fibrillatory waves in AF-ECG

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Abstract— **The objective of this study is to assess the efficacy of Discrete Wavelet Transform (DWT) in the removal of power line (50Hz) interference (PLI). Eighteen mains noise corrupted ECG signals were denoised using thirty two different DWT mother wavelets in order to assess which are the top performing for power line interference cancellation. For comparative purposes the signals were also denoised using a traditional notch filtering approach and the results assessed using three performance parameters: Signal to noise ratio (SNR), Mean Square Error (MSE) and Signal Correlation Value (SCV). 12 of the 32 wavelet functions utilized for mains interference denoising outperformed the traditional notch filtering approach, with the top four performing wavelets being Daubechies 'Db10', Biorthogonal 'Bior6.8', DMeyer 'Dmey' and Daubechies 'Db8', with Db10 producing SNR, MSE and CCV values of 32.50, 5.13x10^{-5} and 0.9995 respectively. This was considerably better than the notch filtering technique which produced comparable results of 25.67, 1.10x10^{-3} and 0.9952 respectively. The second phase of this study assessed the effect that DWT PLI attenuation had on underlying fibrillatory wave morphology. The results indicate that discrete wavelet processing has a negligible effect on underlying fibrillatory waves and is therefore a viable method for mains noise removal in ECG analysis of AF patients.**

Keywords— **DWT, AF, ECG, PLI, 50Hz Interference**

I. INTRODUCTION

Power line interference (PLI), 50/60 Hz, is a commonly encountered noise source in ECG signal processing, which corrupts the signal and affects the quality of body surface ECG. Over the years there have been a number of methods implemented to attenuate mains interference such as notch filtering [1], which targets a narrow frequency band around 50Hz or 60Hz frequencies, strongly attenuating any of these in order to denoise the signal. In recent times, the DWT has emerged as a promising tool for ECG signal denoising [2]. The purpose of this research is to assess the efficacy of a range of DWT mother wavelets (Daubechies, Symlet, Biorthogonal etc.) in the removal of PLI via the use of three performance parameters; Signal to Noise Ratio, Mean Square Error and Signal Correlation Value. In the particular case of ECG signals which are presenting atrial fibrillation (AF-ECG) it has been previously shown that a number of parameters can be ascertained from the underlying fibrillatory wave (f-wave) signal which can help to characterize and direct treatment methods for the arrhythmia [3]. Thus, the second phase of this study aims to assess the affect which DWT mains noise attenuation has on underlying f-wave components by assessing key parameters such as dominant frequency and total spectral power before and after wavelet processing.

II. METHODOLOGY

A. Study Population

Eighteen simulated body surface ECG recordings with a 1 kHz sampling frequency, which have been corrupted by a range of mains (50Hz) interference levels (-10dB to 10dB) have been included in this study. The second phase of this study required the use of real AF-ECG data acquired from patients undertaking internal cardioversion at Royal Victoria Hospital, Belfast. This data was acquired from patients with persistent AF, who would clinically benefit from cardioversion and had previously failed transthoracic cardioversion. Complete medical procedure and exclusion criteria for this study were previously described by Kodoth et al. [4].

B. Simulated ECG and Noise Interference

Eighteen twenty second segments of simulated 'clean' ECG signals were created in Matlab® version 2012a (The Mathworks Ins., Natick, MA, USA) using the ECGSYN programme from Physionet, developed by McSharry et al. [5]. Each clean ECG signal was then corrupted by a mains (50Hz) noise signal simulated in Matlab® using a sine wave function, of 50 Hz frequency, where the amplitude of such signal could be manipulated in order to represent a range of noise intensities (-10dB to 10dB). The 'Noisy' ECG signals were generated via equation 1 below:

$$Clean\_ECG + 50Hz\ Sine\ Wave = Noisy\_ECG \quad (1)$$

In order to assess the effect of wavelet denoising on underlying f-wave morphology, fibrillatory wave signals were extracted from real AF-ECG data. The process involved linear filtering and average template subtraction of ventricu-

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lar activity [6] from 20 seconds segments of AF-ECG in order to isolate f-wave activity. Five of these signals were acquired in total and added to five simulated ECG signals along with 50Hz mains corruption. This resulted in a noise corrupted ECG signal which also contained underlying f-wave activity.

$$Noisy\_ECG + f\_waves = Noisy\ AF\_ECG \qquad (2)$$

C. Mains Interference Cancellation

The noise corrupted ECG signals were processed in Matlab® using a 2nd order, IIR notch filter centered at 50 Hz with 2 Hz bandwidth (49 Hz – 51 Hz) in order to attenuate power line interference. An example of a noisy and notch filtered ECG signal can be observed in Figure 1 below. It is evident from visual inspection that notch filtering can successfully attenuate mains interference, however, it is not without its limitations such as the initial ringing affect introduced by the processing transients observed during the first 0.3 s.

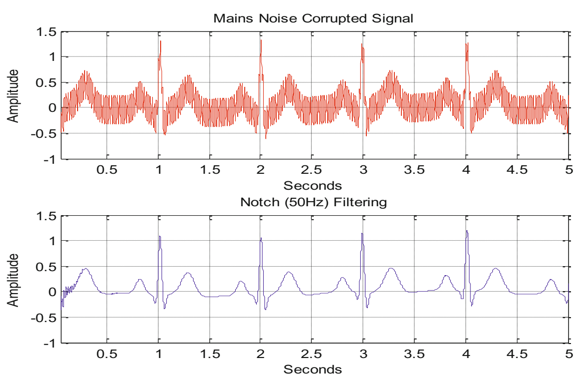

Fig. 1 Example of mains corrupted ECG signal (top) and the same signal after notch filtering (bottom).

A DWT method of PLI cancellation was implemented across the entire signal population, assessing the capability of 32 different mother wavelets from the Haar, Daubechies, Symlet, Coiflet, Biorthogonal, Reverse Biorthogonal and DMeyer wavelet families. The purpose of this was to determine which wavelet configurations performed the best in this application and in comparison to a traditional notch filtering technique in order to validate performance. The DWT PLI denoising method involved 10-level decomposition, followed by full-band cancellation of the D1-D4 coefficients. Examples of the resulting signals after wavelet denoising can be observed in Figure 2.

It is evident from Figure 2 that the choice of mother wavelet is an important consideration in signal denoising, as each will achieve varying levels of success when trying to attenuate a specific noise source. It is visually apparent that the Db10 wavelet performs better at attenuating the 50Hz noise interference compared to Bior3.3, however, in order to quantitatively assess the denoising performance of each wavelet function in our signal population, three performance parameters were considered.

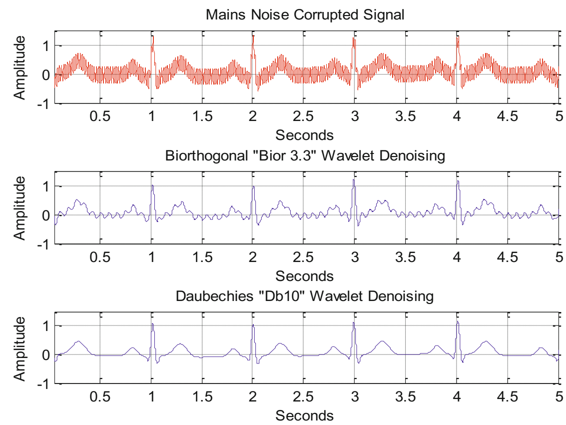

Fig. 2 Example of mains corrupted ECG signal (top) and the same signal after Bior3.3 (middle) and Db10 (bottom) wavelet denoising.

D. Performance Evaluation

Denoising performance of each individual wavelet function was assessed using three parameters: Signal to Noise Ratio (SNR), Mean Square Error (MSE) and Signal Correlation Value (SCV).

In order to calculate SNR, the residual noise must first be determined:

$$Resid\_Noise = Noisy\_ECG - Denoised\_ECG \qquad (3)$$

SNR is then calculated by equation (4) and converted to decibels (dB) using equation (5):

$$SNR = (mean\ (Noisy\_ECG^2)/mean\ (Resid\_Noise^2)) \qquad (4)$$

$$SNR\_dB = 10 * \log_{10}(SNR) \qquad (5)$$

The second parameter utilized to assess denoising performance was Mean Square Error (MSE) which measures the average of the square of the errors between the desired ‘clean’ ECG signal and the acquired ‘Denoised_ECG’ signal in any case. The equation for calculating MSE can be written as:

$$MSE = mean\ ((Clean\_ECG - Denoised\_ECG)^2) \qquad (6)$$

The third performance parameter utilized in this section of the study was Signal Correlation Value (SCV). The denoised ECG signals were compared against the ‘clean’ ECG (the reference signal) and the correlation coefficient value was calculated. This value determines how closely the denoised signal correlates with the clean signal, with a value of 1 being the maximum. With this parameter, we can assess quantitatively whether or not the denoising process has a detrimental effect on the temporal compatibility of the signal under analysis, as any phase shift would result in a reduction in the SCV.

E. Assessing the Effect of DWT on Fibrillatory Waves

Once the top performing wavelets for power line interference attenuation have been identified, it is important to assess whether this type of processing has a degrading effect on residual signal components within the denoised ECG. Of particular consideration is the effect that DWT denoising has on fibrillatory waves (f-waves) which are present in AF-ECG. This is due to the fact that a number of studies have used parameters derived from f-waves that contain prognostic attributes which are important for AF characterization and treatment [7].

In order to investigate this, five 50Hz noise corrupted AF-ECG signals were simulated as described in section I, part B, and the mains interference was removed via DWT denoising. For this part of the study, the top four performing wavelets for PLI removal were investigated. The f-waves signal was recovered via the cancellation of the original ‘clean’ ECG and two commonly used f-wave parameters: Dominant Frequency (DF) and Total Spectral Power (TPS) were calculated for both the original and recovered f-waves signals, and compared via percentage difference between the two values.

The power spectra of the f-waves signals were calculated by a 4096 point window FFT, 1024 point Gaussian window and 768 point overlap, as previously described in [8]. DF was estimated as peak amplitude in the 4-12 Hz range.

III. Results & discussion

A. DWT Mains Interference Denoising Results

Results indicate that 12 out of the 32 wavelet functions assessed outperform notch filtering in the removal of power line interference. Results across the study population (mean ± standard deviation) for notch filtering produced SNR, MSE and SCV results of 25.67 ± 6.27, $1.19 \times 10^{-3} \pm 3.39 \times 10^{-3}$ and 0.9952 ± 0.0063 respectively. The top performing wavelet, ‘DMey’ produced comparable results of 33.41 ± 4.71, $5.84 \times 10^{-5} \pm 7.33 \times 10^{-5}$ and 0.9994 ± 0.0007 which indicates an increase in denoising performance across all three performance criteria in comparison to notch filtering.

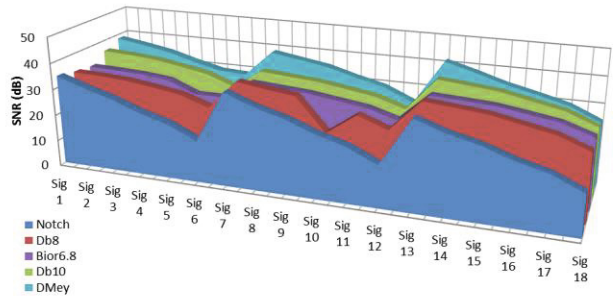

Fig. 3 SNR values after notch and wavelet filtering of eighteen mains interference corrupted signals.

Figure 3 presents the SNR values across the study population for notch filtering (blue) and the top four performing wavelets in this category: Db8 (red), Bior6.8 (purple), Db10 (green) and DMey (aqua).

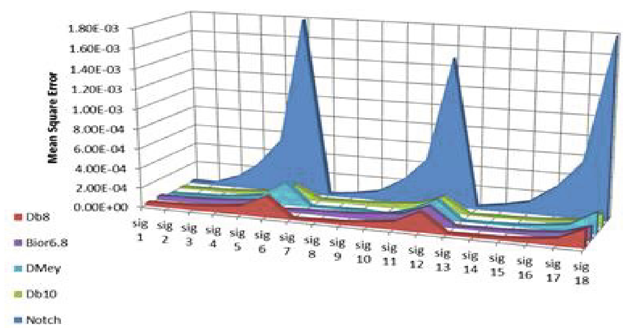

Fig. 4 MSE values after notch and wavelet filtering of eighteen mains interference corrupted signals.

In Figure 4 above it is evident that the MSE values of the wavelets are considerably smaller than those calculated using notch filtering. It could be argued that wavelet denoising is a more robust technique as the varying levels of noise corruption have less effect on wavelet MSE values.

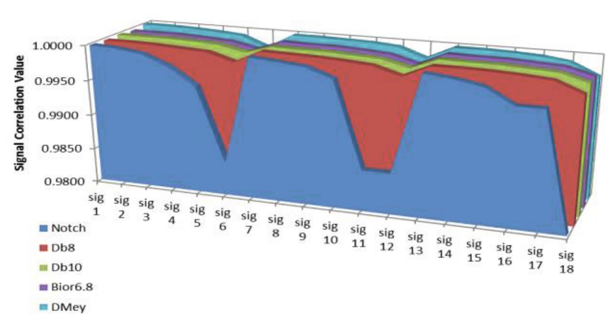

Fig. 5 SCV after notch and wavelet filtering of eighteen mains interference corrupted signals.

The SCV's of the top performing wavelets are presented in Figure 5. Once again there is an indication that the wavelet technique is more robust at handling a range of 50Hz noise corruption intensities.

B. Results of DWT Processing on Fibrillatory Waves

When averaged across the signal population, recovered f-wave signals processed via DWT denoising provided DF values identical to the originally extracted f-wave signals, resulting in a % difference for this parameter of 0%. TPS values when averaged across the entire population show that the total power of the frequency domain spectrum is minimally disrupted by DWT processing as the recovered f-waves signals provided % difference in TPS values of 0.17% ± 0.25%.

C. Discussion

The research in this study has assessed the efficacy of DWT techniques for mains interference removal by testing a range of mother wavelets in order to determine the top performers. The results above in section III, part A, indicate that there are a number of DWT wavelets which have the ability to significantly attenuate 50Hz interference. The top performing wavelets, namely DMey, Db10, Sym8 and Bior6.8 have all substantially outperformed a traditional notch filtering technique across three performance parameters, indicating that DWT denoising of PLI is efficacious as long as consideration is given to the wavelet function that is implemented. Furthermore, it is important that such signal processing techniques do not have a detrimental effect on residual signal morphology. Results presented above, indicate that the morphology of underlying fibrillatory waves present in ECG of AF patients is not disrupted by wavelet denoising. A limitation of this study is that although the effect of varying noise amplitude has been taking into consideration, the effect of noise phase shift on denoising performance has not been addressed in this instance.

IV. CONCLUSIONS

DWT processing is a useful technique for the removal of 50Hz PLI. Consideration must be given to the mother wavelet used when implementing DWT denoising as certain wavelets perform better than others for this application. A number of top performing wavelets which have been identified as a result of this work include; DMey, Db10, Db8 and Bior6.8, all of which outperform notch filtering when assessed over three performance parameters: SNR, MSE and SCV. The use of wavelet denoising is a viable option for AF-ECG signals as it has been shown that the f-waves signal is not distorted by wavelet processing, and key prognostic markers such as dominant frequency are preserved.

Future work will include assessing the efficacy of DWT denoising for other corruptive noises encountered in ECG signal processing such as baseline wander and muscle artifacts. Understanding the capabilities of DWT in the removal of corruptive noise sources will assist in developing novel methods for f-waves extraction in patients with AF [8].

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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