Estimation of Atrial Fibrillatory Frequency by Spectral Subtraction of Wavelet Denoised ECG in Patients with Atrial Fibrillation

Jonathan Goodfellow[1], Omar J Escalona[1], Philip R Walsh[1], Vivek Kodoth[2], Ganesh Manoharan[2]

[1]University of Ulster, Newtownabbey, Northern Ireland, UK
[2]Royal Victoria Hospital, Belfast, Northern Ireland, UK

Abstract

The objective of this study was to assess the efficacy of a novel wavelet based dominant atrial fibrillatory frequency (DAFF) estimation technique on twenty patients who underwent internal cardioversion at Royal Victoria Hospital, Belfast. The results acquired using the wavelet technique were compared against results achieved using a conventional average template subtraction (ATS) method with three performance parameters: percentage noise reduction ratio, ventricular activity (QRST) correlation value and percentage DAFF similarity ratio.

The results for wavelet based estimation were 87.8%±5.3% and 0.983±0.006 respectively compared to 72.9%±9.3% and 0.981±0.010 for the ATS method.

These results indicate that the wavelet technique offers improved performance at attenuating noise in the Q-T intervals than conventional technique, yet there remains high retention of the ventricular morphology, suggesting that the proposed wavelet technique could be a useful method for isolating atrial activity for DAFF analysis. DAFF estimated values using both techniques were compared and found to be in good agreement, as percentage DAFF similarity ratio was 94.8%±3.8%.

1. Introduction

Atrial fibrillation (AF) is the most common cardiac arrhythmia, affecting approximately 2% of the population [1]. AF can be characterized by predominantly uncoordinated atrial activation, driven by disruptive vortex-like, rotating waves of electrical activity which consequently lead to atrial mechanical dysfunction [2]. The presence of AF is indicated on the electrocardiogram (ECG) as irregular fibrillatory waves, giving rise to a loss of normal P-wave, and also the presence of a very erratic ventricular rate.

It has been demonstrated that the dominant atrial fibrillatory frequency (DAFF), estimated via the implementation of frequency analysis on the atrial activity signal of the body surface ECG, reflects the average rate of AF present within the patient, and has been shown to be useful in the assessment of electrical remodelling [3,4] and provide indications on the response to treatment [5].

The purpose of this study was to assess the efficacy of a novel DAFF estimation technique based on wavelet transform by comparing performance to a conventional average template subtraction method.

2. Methods

2.1. Study population

Twenty fully anti-coagulated patients with persistent AF, who would clinically benefit from internal cardioversion and had previously failed transthoracic cardioversion were recruited for the study. Exclusion criteria and complete medical procedure were as previously described by Kodoth et al. [6].

2.2. Data acquisition

A standard ECG lead II was acquired during the entire cardioversion procedure. The signals were digitized at a sampling rate of 1000Hz with 16-bit resolution. ECG processing was performed using Matlab® version 2012a (The Mathworks Ins., Natick, MA, USA). Twenty second segments of baseline ECG prior to the first cardioversion attempt were analysed to assess the efficacy of the wavelet denoising technique for DAFF extraction in comparison to a conventional ATS method.

2.3. ATS DAFF estimation

The AF-ECG signal was initially treated with a high order bidirectional filter, with pass band 0.5Hz-40Hz to reduce baseline wander due to respiratory activity and also high frequency corruptive noise. A notch filter centred at 50Hz frequency was implemented to attenuate mains noise. QRST segment detection was carried out via the determination of the fiducial point relating to R-peak location and a fixed length window about this point. An average QRST template was then calculated over 20 individual complexes, which has been shown to be a satisfactory number to use in the averaging process [7]. The average template of QRST activity was time-aligned and subtracted from the original signal, resulting in the representation of a residual atrial activity signal (RAAS). Figure 1.0 below provides an example of an original signal along with its QRST ventricular template, and the residual atrial activity signal when cancellation is implemented.

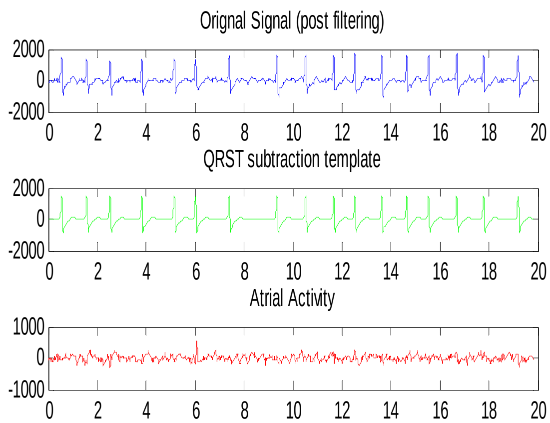

Figure 1. Representation of the ECG signal after linear filtering, the average ventricular template used for cancellation and the associated RAAS.

The power spectrum of the residual atrial signal was calculated by a 4096 point window FFT, 1024 point Gaussian window and 768 point overlap, as previously described in [8]. Peak power value was investigated in the 3-15Hz range, and DAFF was estimated as the frequency component with maximum amplitude in this range.

2.4. Wavelet based DAFF estimation

A novel technique for the estimation of DAFF was then implemented which utilized the discrete wavelet transform (DWT) and multi-resolution analysis to denoise the signal and isolate an accurate representation of ventricular activity. Each signal underwent a 10-level decomposition using Daubechie's 'Db4' analyzing function. The Db4 wavelet was chosen due to its similarity with the morphology of ventricular activity observed in a typical ECG signal.

Once 10-level decomposition has been implemented, the signal can be fully represented as a collection of detail coefficients (D1-D10) and one approximation coefficient at the lowest level of decomposition (A10) as seen in Figure 2.0. In order to attenuate DC component and baseline wander from the signal, the A10 coefficient which contained the lowest frequency content of the signal was discarded, which has been previously shown to be an effective method of baseline correction in [9]. High frequency components such as electromyographic and electrosurgical noise significantly corrupt the ECG signal, therefore it is critical that they are removed. High frequency corruptive noises were removed by

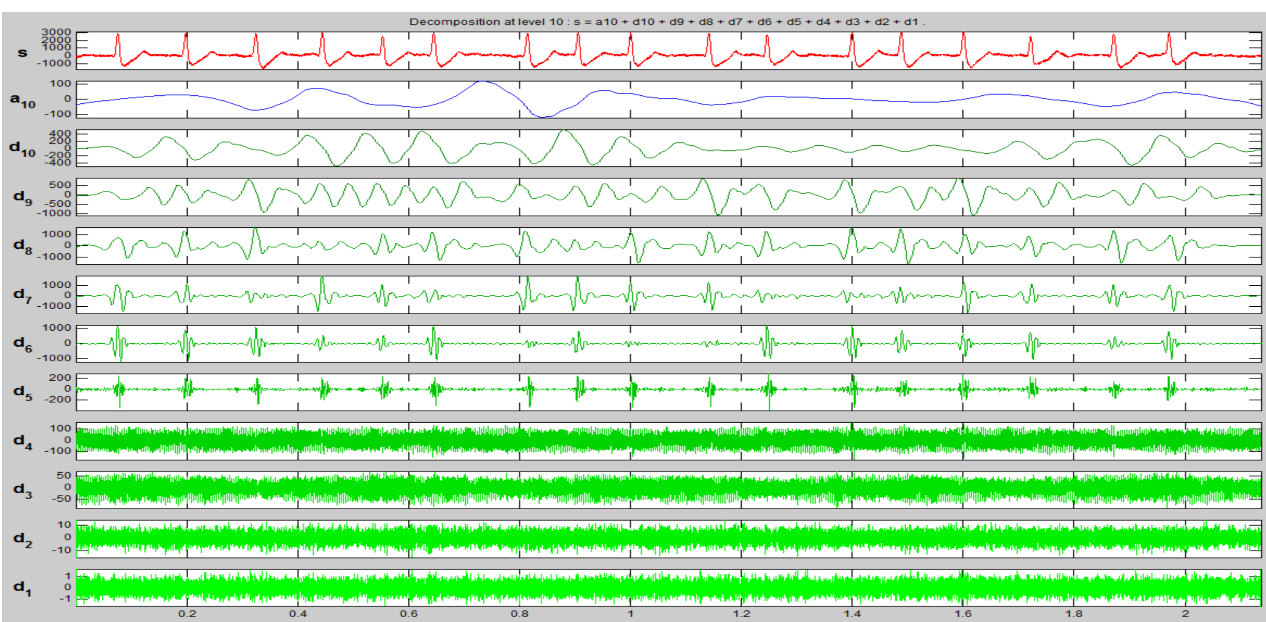

Figure 2. Original ECG signal (red) undergoing 10-level DWT decomposition, resulting in approximation signal at lowest level, A10 (blue), and detail coefficients at each level, D1-D10 (green).

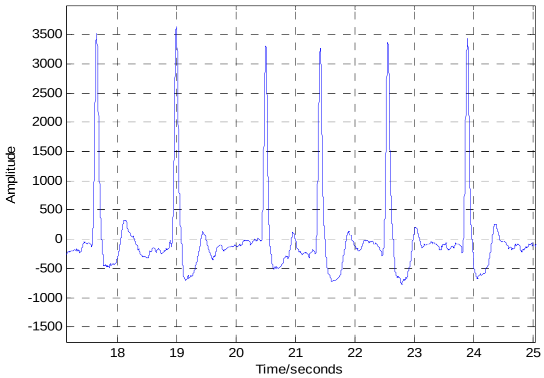

Figure 3. Reconstructed ECG signal after discarding a number of coefficients related to various noise sources.

discarding the D1-D4 coefficients, resulting in a denoised signal upon reconstruction (See Figure 3.0).

The next phase of the wavelet based DAFF estimation technique was to treat the AF as a noise component of a ventricular signal, and exploit the non-linear thresholding capability of the DWT to attenuate fine details from the D5-D8 coefficients. This was achieved through the implementation of soft thresholding with a threshold value set at 15% of the peak value observed at each level. The thresholding process smooths the T-Q intervals, which are representative of atrial activity (AA), whilst maintaining the morphology of the QRST segment. The FFT of the AA attenuated signal was acquired by implementing the same process described in 2.3. The FFT of the wavelet denoised signal prior to AA attenuation was also computed, and the subtraction of the two spectra resulted in a residual power density spectrum, where the DAFF was ascertained as the peak amplitude in the 3-15Hz range.

2.5. Performance parameters

In order to assess the efficacy of the wavelet based method for denoising and DAFF estimation, a number of performance measures were implemented and directly compared to that of the conventional ATS technique. Denoising ability of both methods were assessed via the implementation of a 200ms noise measuring window positioned within the T-Q intervals of each individual beat which assessed noise as the standard deviation of the signal before and after denoising for each method. An average of the values taken at each point in the signal was calculated to represent the noise present over the entire signal. A percentage noise reduction ratio (%NRR) was calculated by assessing the reduction in the signal standard deviation value.

It is an important consideration in DAFF determination that ventricular activity in the ECG is removed as effectively as possible. In order to assess the ability of the ATS and wavelet methods to accurately replicate ventricular activity, a cross correlation method was employed. For the ATS method, correlation coefficients were calculated, assessing how accurately the ventricular template correlated with the QRST segments within the original signal. This was achieved for each QRST complex within the signal and an average correlation coefficient was derived to represent how well the ventricular activity was replicated by the average template used. The same method was used to assess the ventricular activity preservation of the wavelet based method. Correlation coefficients were calculated from the signal both before and after thresholding to assess how effectively the wavelet thresholding technique preserved the ventricular activity, represented by a ventricular activity correlation value (VACV).

The final performance measure assessed how effectively the wavelet based denoising technique, accompanied by spectral subtraction could estimate DAFF values. This was assessed by comparison with the DAFF values obtained via the conventional technique and the calculation of a percentage DAFF similarity ratio (%DSR).

3. Results

Table 1.0 below contains the results acquired for both the ATS and wavelet based DAFF estimation methods when assessed with the three performance parameters outlined in section 2.5. It is evident from the results that the wavelet based method was more effective at attenuating noise in the T-Q intervals in comparison to the conventional technique in every case, resulting in an average %NRR of 87.8%±5.3% across the entire study population compared with 72.9%%±9.3% for the ATS method. VCV results indicate that the ability for the wavelet method to preserve ventricular activity morphology is just as effective, if not marginally better than the ATS method with mean results of 0.983±0.006 and 0.981±0.010 for ATS. Finally, when comparing the DAFF values obtained for both the ATS and wavelet based methods; it is evident that there is good agreement with the values obtained, as the %DSR was an average of 94.8%±3.8% over the study population.

4. Discussion and conclusions

The experimental results obtained from this investigation suggest that the wavelet based technique can provide an alternative method for DAFF estimation which can produce results that are in good agreement with the conventional ATS method. In terms of

Table 1. Table of results showing %NRR, VCV and %DSR of ATS and Wavelet based DAFF estimation methods.

Patient	**PAF01**	**PAF02**	**PAF03**	**PAF04**	**PAF05**	**PAF06**	**PAF07**	**PAF09**	**PAF11**	**PAF12**	
(I) ATS DAFF											
NRR(%)	65.04	43.53	73.07	70.48	80.40	84.43	73.50	82.51	74.06	67.78	
VACV	0.9839	0.9801	0.9916	0.9886	0.9817	0.9685	0.9787	0.9945	0.9801	0.9911	
(II) Wavelet DAFF											
NRR(%)	89.87	80.45	82.51	87.57	93.18	96.52	91.54	84.69	87.08	89.98	
VACV	0.9792	0.9754	0.9811	0.9719	0.9817	0.9753	0.987	0.9854	0.9754	0.9879	
DSR(%)	91.66	95.55	91.06	97.65	96.89	93.21	86.97	99.98	97.37	96.72	
Patient	**PAF13**	**PAF14**	**PAF15**	**PAF18**	**PAF19**	**PAF20**	**PAF23**	**PAF25**	**PAF27**	**PAF29**	**Average +/- (SD)**
(I) ATS DAFF											
NRR(%)	69.55	70.32	73.05	83.05	70.33	68.01	66.23	76.45	88.72	77.09	**72.88 +/- 9.26**
VCV	0.9812	0.9709	0.9681	0.9894	0.9831	0.9834	0.9525	0.9699	0.9866	0.9903	**0.9807 +/- 0.0101**
(II) Wavelet DAFF											
NRR(%)	84.76	95.03	85.19	89.52	92.78	73.98	86.45	89.88	92.28	82.20	**87.77 +/- 5.31**
VCV	0.9842	0.9806	0.9791	0.9925	0.9796	0.9907	0.9874	0.9855	0.9824	0.9893	**0.9826 +/- 0.0055**
DSR(%)	92.29	87.14	93.23	97.77	98.84	98.14	90.71	98.86	94.00	97.30	**94.77 +/- 3.75**

implementation, the wavelet technique can avoid some of the complex and computationally taxing processes involved in the ATS method, namely the requirement for time-alignment for cancellation of ventricular activity. Due to the averaging process implemented in the determination of the average ventricular template, it is a concern that the beat to beat morphological changes of the ECG signal are not fully considered with the ATS method. It could be argued that the wavelet method is better equipped in isolating ventricular activity which is more accurate in representing the original signal morphology than the ATS method based on the VACV results calculated. Further studies are currently underway to investigate how estimation of the atrial fibrillatory frequency by spectral subtraction of wavelet denoised ECG could potentially be combined with synchronised AF defibrillation shock sequencing [2,10,11] to develop new and more efficacious low-energy AF cardioversion protocols.

References

[1] Wilke T, Groth A, Mueller S, Pfannkuche M, Verheyen F, Linder R, et al. Incidence and prevalence of atrial fibrillation: An analysis based on 8.3 million patients. Europace 2013;15:486-493.

[2] Luther S, Fenton FH, Kornreich BG, Squires A, Bittihn P, Hornung D, et al. Low-energy control of electrical turbulence in the heart. Nature 2011;475:235-239.

[3] Grubitzsch H, Haverkamp W. Atrial remodelling :Role in atrial fibrillation ablation. Journal of Atrial Fibrillation 2012;5:64-72.

[4] Walters TE, Teh AW, Spence S, Kistler PM, Morton JB, Kalman JM. Relationship between the electrocardiographic atrial fibrillation cycle length and left atrial remodeling: A detailed electroanatomic mapping study. Heart Rhythm 2014;11:670-676.

[5] Romero I, Fleck E, Kriatselis C. Frequency analysis of atrial fibrillation surface and intracardiac electrograms during pulmonary vein isolation. Europace 2011;13:1340-1345.

[6] Kodoth V, Castro NC, Glover BM, Anderson JM, Escalona OJ, Lau E, et al. Waveform optimization for internal cardioversion of atrial fibrillation. J Electrocardiol 2011;44:689-693.

[7] Alcaraz R, Rieta JJ. Adaptive singular value cancelation of ventricular activity in single-lead atrial fibrillation electrocardiograms. Physiol Meas 2008;29:1351.

[8] Diaz J, Escalona O, Glover BM, Manoharan G. Use of frequency analysis on the ECG for the prognosis of low energy cardioversion treatment of atrial fibrillation. Conference proceedings : 31st Annual International Conference of the IEEE EMBS, EMBC 2009:372-375.

[9] Banerjee S, Gupta R, Mitra M. Delineation of ECG characteristic features using multiresolution wavelet analysis method. Measurement J Int Meas Confed 2012;45:474-487.

[10] Walsh PR, Escalona OJ, Kodoth V, McEneaney D, Lau E, Manoharan G. Dynamic changes in intracardiac impedance as a predictive marker during internal cardioversion of atrial fibrillation. Comput in Cardiol 2013;40:611-614.

[11] Walsh PR, Rodrigues PA, Velasquez JJ, Watermann N, Escalona OJ. Impedance compensated passive implantable atrial defibrillator. Electronics Letters 2014; 50: 1192-1193.

Address for correspondence:
Omar J Escalona,
University of Ulster, Newtownabbey, BT37 0QB.
United Kingdom. E-mail: oj.escalona@ulster.ac.uk