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Two Dimensional Wavelet Energy Analysis on a Beat to Beat Basis: Application to Atrial Fibrillation

D. Filos, I. Chouvarda, *Member, IEEE*, G. Dakos, V. Vassilikos and N. Maglaveras, *Member, IEEE*

Abstract— **Atrial Fibrillation (AF) is a condition in which heart rhythm is not associated with normal sinoatrial (SA) node pacemaker but it derives from different areas on the atrium, often from the area of Pulmonary veins (PVs) A way to eliminate the influence of PVs in the inducement of AF is the PVs isolation surgery. In this study, an effort is made towards investigating the morphology and dynamics of P-waves, when the potentially arrhythmogenic tissue in PVs is involved or isolated via ablation. For this reason, 20 patients who were subjected to PVs isolation were studied, via vectrorcardiography recordings obtained before and after the ablation. Wavelet energies for five frequency bands were analyzed, using a two dimensional representation. The proposed technique was applied for the analysis of wavelet energies in consecutive beats, and their correlation with the RR interval. Features for the evaluation of those plots were extracted, such as the axes of a fitted to the plot ellipse and the center of the mass. The statistical analysis demonstrated significant differences between the groups, which imply the modification of the atrial substrate concerning electrical conduction toward to a more stable condition.**

I. Introduction

Atrial Fibrillation (AF) is one of the most common arrhythmias. It is estimated that 1-2% of the population is suffering from this cardiac disorder [1], while the incidences of AF occurrence show 13% of increase over the previous two decades [2]. AF is characterized by rapid and irregular activation of the atria, loss of atrial mechanical function and increase of atrial clot formation [3]. The origin and the persistence of AF result from a complex and multiscale interaction between triggers, substrate and modulating factors involved in atrial remodeling [4]. As a triggering factor for the inception of AF may be considered the role of pulmonary veins (PVs) [5], however the mechanisms of impulse initiation from PV have not been defined. Catheter ablation, including the electrical isolation of PVs to prevent ectopic signal propagation into atrial chambers, has emerged as a promising treatment strategy for AF patients.

Several computational models and methods were proposed toward the understanding of the electrophysiological properties of the atrium during of AF, at various spatial scales, form the level of the cell to the tissue and organ level. Phenotype study through the analysis of ECG recording gathers the interest of scientific society. The study of ECG has the major advantage of being a non-invasive diagnostic method that can serve as a tool for the personalization of the treatment strategy.

D. Filos, I. Chouvarda and N. Maglaveras are at the Lab of Medical Informatics, Aristotle University of Thessaloniki, Greece (+303210999922; fax: +3023109999263; e-mail: dimfilos@auth.gr, ioannach@auth.gr, nicmag@medauth.gr).

G. Dakos, is at the 1st Cardiology Department, AHEPA University Hospital, Aristotle University of Thessaloniki, Greece (e-mail: free11wax@yahoo.com)

V. Vassilikos is at the 3rd Cardiolocy Clinic, Ippokratio General Hospital, Aristotle University of Thessaloniki, Greece (e-mail:vvassil@med.auth.gr)

As it concerns the analysis of the ECG recordings, P wave can represent atrial conductance and a prolonged P complex may be associated with AF [6]. However, the variation of P wave duration may not be great and so, the difference on the atrial conductance, occurring in AF, may not be observed [7]. A number of methods, which analyze the morphological variations of the P wave in AF, are proposed. In [8] a method which is based on the wavelet transform for the analysis of the P wave morphology, in a time-frequency perspective, was proposed. For the completion of the study of the atrial excitation using surface electrocardiograms, we need to analyze the signal on a beat to beat bases rather than analyzing a random beat or an average one [9].

Poincaré plot is a nonlinear method for the analysis of heart rate variability. With that plot the consecutive RR intervals are portrayed in a bi-dimensional domain. This representation provides information regarding the beat to beat functionality of the heart [10].

In the present work, a method for a beat to beat analysis of the atrial activity is proposed. That method uses Poincaré plot for the study of the wavelet energies of the P wave. Additionally a two dimensional representation is used for the analysis of wavelet energy versus the respective RR interval. The energy of the continuous wavelet transform can reveal the morphological characteristics of the P wave. The analysis is focused on the evaluation of the changes occurred in human heart when it is undergone PVs isolation surgery.

II. Methodology

A. Data and Preprocessing

For the purposes of this study, X-Y-Z leads of vectorcardiography (VCG) recordings (1KHz sampling frequency) were obtained by the 1st Cardiology Clinic of AHEPA University Hospital of Thessaloniki. Signals from 20 patients were recorded before (group A) and after (group B) PVs isolation (Table I).

TABLE I. Distribution of Signals Included in the Analysis

Group	Mean RR duration (sec)	Mean Heart Rate, HR (bps)	Mean Standard Deviation of the HR	Recording Duration (sec)
A	910±131	67.1±8.9	4.1±3.8	164±67
B	833±122	73.5±10.9	5.4±4.2	162±59

B. Wavelet Energy in windows of atrial activity

The analysis of the atrial activity requires the localization of the P wave that corresponds to the depolarization of the atrium and the transfer of the electrical vector from the sinoatrial (SA) node towards the atrioventricular (AV) node. As this complex is weak, as well as its start and end are difficult to be identified, we use a method proposed by [11] for the localization of the segment of the ECG signal (segP) that includes the P wave. That method uses a P wave, marked by medical experts for one beat per signal, as well as each beat's peak of the Q as it is resulted by the use of the Ecgpuwave tool [12], for the extraction of the mean and standard deviation of PQ distances. As a result segP extends from [Q-250, Q-(meanPQ+stdPQ)] milliseconds and its durations were computed equal to 220msec. SegP was aligned so that its edges appear on the isoelectric line and finally was normalized by its maximum value.

TABLE II. SCALE BANDS AND FREQUENCY CORRESPONDANCE

Frequency Band	Starting Frequency	Ending Frequency
S1	6 Hz	16 Hz
S2	16 Hz	25 Hz
S3	25 Hz	50 Hz
S4	50 Hz	100 Hz
S5	100 Hz	200 Hz

Continuous wavelet transform with Morlet mother wavelet was performed in order to extract the wavelet coefficients of the segP. Morlet mother wavelet was previously found to achieve better discrimination between healthy and pathological signals compared to other wavelets [11]. The frequency range is of 6-200Hz (based on the central frequency of the mother wavelet), divided into 5 frequency bands with same density resolution of 40 scales per band (Table II). As a next step, each beat's wavelet energies was computed, for each lead and frequency band, as the integral of the energy along time. In the following, the wavelet energy of lead k, band s and beat n is denoted as Wks(n).

C. Two dimensional representation

The Poincaré plot is a non-linear analysis method which refers to the depiction in the two dimensional domain of each timeseries' point against the next one. This technique had extensively been used for HRV analysis (dynamics of RR intervals) and the evaluation of cardiac dysfunction, based on the shape of the plot and the categorization of the functional classes [10], providing useful information in a beat to beat base of the heart [13].

As this plot can be considered as a cloud of points, that can be represented as an ellipse. By defining the line of identity, the dispersion of points perpendicular to this line reflects the level of short term variability (SD1) while the dispersion of points along the line indicates the long term variability level (SD2) [14]. In other words, the standard deviation of the distance of the points from each axis, determine SD1 and SD2. The calculation of those features is being performed by rotating the cloud of X_n points to the new axis, by θ, by the use of (1):

$$\begin{bmatrix} X'_n \\ X'_{n+1} \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} X_n \\ X_{n+1} \end{bmatrix} \quad (1)$$

where, θ is the angle of the line of identity, X'_n and X'_{n+1} the x-y coordinates of the rotated point, where its initial coordinates are (X_n, X_{n+1}). SD1 and SD2 are calculated as the standard deviation of the distances of rotated points to the x-y axes respectively.

In the present study, the two dimensional representation is used for the depiction of wavelet energy Wks(n) against Wks(n+1) (Poincare plot of Wks(n)) (Fig.1), as well as for the depiction of the Wks(n) against the respective RR(n), with each value normalized with the median value of the vector. The features extracted by the analysis are: a) SD1 and SD2, which reflect the dispersion along the two axes of the ellipse. SD1 represents the variability of points around the perpendicular to the line of identity while SD2 represents the dispersion of values around the line of identity, corresponding to short term and long term variability for the Poincare plot case, b) the x-y coordinates of the cloud's centroid (CMx, CMy), which are the mean values of the cluster's points along the respective axes. Finally, we calculate the product of SD1 and SD2, reflecting the surface of the ellipse, and their ratio, as well. A small value of SD1*SD2 would illustrate a solid cloud of small variability, while for the SD1/SD2, a value close to 1 would imply the existence of high linearity among the points of the cloud as derived by (2):

$$SD2^2 \cdot (1 - \varepsilon^2) = SD1^2 \quad (2)$$

where ε is the eccentricity of the ellipse ($0<\varepsilon<1$). When ε tends towards 1, SD1/SD2 tends to 1 and the ellipse tends towards a line across the major axis, while, if ε is close to 0, the ellipse tends to circle. Equation (2) is considered for SD1 the minor and SD2 the major axis of the ellipse.

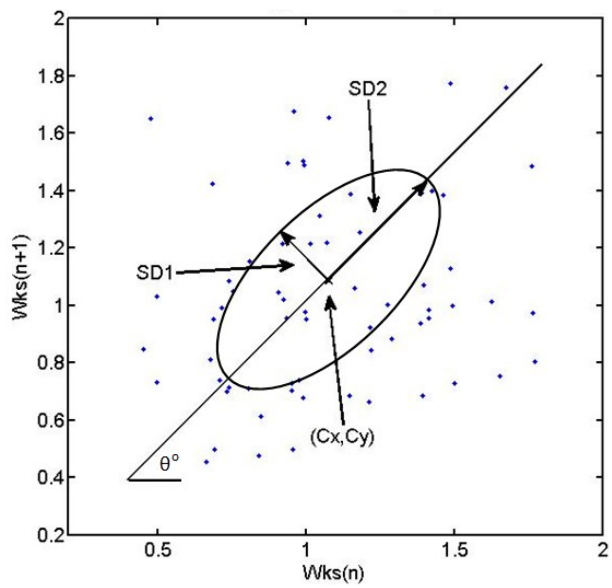

Figure 1. Poincaré plot and fitting in an ellipse techique.

D. Statistical Analysis

The RR intervals of an ECG represent the influence of Autonomic Nervous System (ANS) in cardiac function. Variations in the RR duration signal may affect the morphology of segP, which may not be derived from AF pathology. In order to eliminate the influence of ANS factor in the observations we analyze only those beats with the respective RR duration be included in the boundaries of ±25% of the signal's median RR duration.

For the evaluation of the results we used the Wilcoxon signed rank test which is a no-parametric statistical test for comparing samples belonging to the same subject, which were acquired in different time periods. Finally, we rank the features which present significant statistical differences by using the ROC criterion. That criterion was selected because the features observed do not follow a normal distribution.

III. Results

From the analysis, 6 features were derived for each frequency band and each lead. With respect to the differences between groups A and B, these features were analyzed for statistical differences.

From the observation of Table III, significant statistical differences are denoted, by the analysis of Poincaré plot of Wks(n), in all leads and in all frequency bands. In detail, SD1 and SD2 seem to be greater in group A rather than in B. Additionally SD1*SD2 as well as SD1/SD2 have lower values in group B than in A. These findings imply a smaller temporal variability of the atrial activity after PVs isolation. This, in addition to the lower values of the centroids' coordinates in group B (smoother P wave morphology), may reflect the changes in the electrical pathways and atrial activity introduced by the ablation.

TABLE III. Statistical Significant Differences by Analysing the Wavelet Energy in Concecutive Beats Between A and B

Lead	Band	feature	p	Median A	Median B
X	S1	SD1	0.0363	0.039067	0.037508
		SD2	0.0079	0.041609	0.035827
		SD1/SD2	0.0079	0.925083	1.036339
		SD1*SD2	0.0157	0.001623	0.001428
	S2	SD1/SD2	0.0442	0.909398	1.039797
	S3	CMx	0.0486	1.079462	1.049591
		SD1/SD2	0.0401	0.955631	1.039781
Y	S1	SD1	0.0158	0.044666	0.024584
		SD2	0.0329	0.045745	0.023933
		SD1*SD2	0.0486	0.002047	0.000538
	S2	SD2	0.0298	0.503982	0.323121
		CMx	0.0364	1.114143	1.037353
	S3	SD2	0.0486	0.381545	0.276956
Z	S2	SD1	0.0242	0.310575	0.259282
		SD2	0.0442	0.338765	0.272748
		SD1/SD2	0.0242	0.822259	0.933534
	S4	SD2	0.0364	0.479252	0.410737
		SD1/SD2	0.0486	0.925283	0.985083
	S5	SD1	0.0055	0.479425	0.36688
		SD2	0.0008	0.500094	0.374225
		CMx	0.0003	1.131704	1.058028
		CMy	0.0242	1.123134	1.072217
		SD1*SD2	0.0015	0.242308	0.139219

As regards to the analysis of Wks(n) versus the respective RR interval (Table IV), significant statistical differences are observed. SD1 and SD2 are greater in group A rather that in group B, as well as SD1*SD2. As for the SD1/SD2, in most cases it seems to be greater in group B rather than in group A. These findings denote the decrease of the dispersion of the cloud's points and the formation of a more solid ellipse which tends to a line. These observations illustrate the appearance of linearity between a RR interval and the atrial wavelet energy of the respective beat. That linearity implies that after the ablation there exists an alternation in the influence of ANS in cardiac function and a modification of the atrial arrhythmogenic properties.

TABLE IV. Statistical Significant Differences by Analysing the Wavelet Energy Versus RR Intervals Between A and B

Lead	Band	feature	p	Median A	Median B
X	S1	SD1	0.0364	0.031707	0.030375
		SD2	0.0364	0.032267	0.030655
		SD1*SD2	0.0329	0.001023	0.000932
Y	S1	SD1	0.0141	0.038767	0.018158
		SD2	0.0126	0.035447	0.01930
		SD1/SD2	0.0401	1.041498	0.99468
		SD1*SD2	0.0141	0.001300	0.000351
		SD1/SD2	0.0242	0.900312	0.952667
	S3	SD1	0.0079	0.290630	0.187702
		SD2	0.01	0.312547	0.189974
		CMy	0.0486	1.069288	1.041088
		SD1/SD2	0.0176	0.910428	0.964423
		SD1*SD2	0.0242	0.09182	0.035482
Z	S2	SD1	0.0442	0.232183	0.190823
		SD2	0.0442	0.244106	0.193437
	S4	SD1	0.0363	0.33998	0.275462
		SD2	0.0442	0.356267	0.288578
		SD1*SD2	0.0442	0.121125	0.079607
	S5	SD1	0.0011	0.310558	0.251331
		SD2	0.001	0.33644	0.267207
		CMy	0.0005	1.114591	1.062419
		SD1/SD2	0.0017	0.907681	0.941265
		SD1*SD2	0.0011	0.104489	0.067122

The feature that seem to have better ability to distinguish the signals from the groups A and B, by the use of ROC criterion are depicted in Table V. As regards the Poincaré plot, we observe that Z and Y lead of the signal and frequency band S5 includes most of these features. In addition, features from frequency band S1 and S5 of lead Y and Z are among the most important. In particular, SD2 in both cases may reveal better information regarding the discrimination of such signals. As depicted in the fifth column of the Table V, the values of all the afore mentioned features seem to decrease after the ablation.

TABLE V. Most Significant Features Using ROC criterion

Case	Lead	Band	Feature	Alteration
Wks(n) versus Wks(n+1)	Z	S5	CMx[1]	↓
	Z	S5	SD2[2]	↓
	Z	S5	SD1*SD2	↓
	Y	S1	SD2	↓
	Y	S1	SD1*SD2	↓
Wks(n) versus RR(n)	Z	S5	CMy[3]	↓
	Y	S1	SD1	↓
	Y	S1	SD1*SD2	↓
	Y	S3	SD2	↓
	Z	S5	SD2	↓

1, 2, 3. denote the most significant features including both cases.

IV. Discussion

A number of studies denoted the necessity of a beat to beat perspective concerning the analysis of AF [8, 9, 11]. In the present study, a method for the beat to beat analysis of the atrial activity is proposed, based on a continuous wavelet transform performed in a window of interest, which includes the atrial excitation (P wave). Wavelet energy is calculated in different frequency bands that extend from 6 to 200 Hz. This approach is based on a two dimensional representation of wavelet energies. The advantage of this method is that it does not require the accurate detection of the P wave, additionally to the visual interpretation of the information concerning the differences occurring in human atrium over pathological conditions.

With the present study, a Poincaré plot of wavelet energy is displayed, as well as a two dimensional representation of the wavelet energy versus the respective RR interval. The quantification of the information is obtained by extracting a number of features including the major and minor axis of a fitted to the cloud ellipse, which represent the long and short term variability, in the Poincaré plot case, the product and the ratio of these parameters, as well as the center of the mass of the cloud. The method has been evaluated in VCG recordings from patients with AF, before and after they have undergone the PVs isolation procedure.

As far as the analysis of Poincaré plot concerns, significant statistical differences were found in all the leads of the VCG recordings and in all the frequency bands, mainly suggesting a decrease in value (CMx, CMy) and variability (Table III). The conversion of Poincaré plot to a more solid cloud with reduced dispersion, along the lines of interest, as well as with reduced temporal variability of the atrial activity may illustrate modifications in the electrical pathways in the atrium after the ablation procedure.

As regards to the analysis of the wavelet energy versus the respective RR interval, significant statistical differences were presented in all leads and scales bands. These differences include the decrease of the axes of the fitted to the cloud ellipse as well as their product, the ratio and the center of mass (Table IV). Lower values of SD1 imply a reduced variability of wavelet energies whereas the reduction of SD2 values denotes the decrease of RR intervals variation. The reduced values of the ratio and product of SD1 and SD2 denote the existence of a linear correspondence between RR interval and the atrial wavelet energy of the respective beat. Those results may imply a change of the arrhythmogenic properties of the atria in people undergone PVs isolation. As it concerns the most discriminative features from both cases, we found that SD2 as well as frequency bands S1 and S5 of lead Y and Z reflect in better way the changes, introduced by the ablation procedure, in the atrial electrical activity (Table V).

The study was made in signals obtained from patients with AF, before and after the PVs isolation procedure. Yet, approximately 30% of procedures fail to terminate AF [15], while at the same time these patients manifest increased atrial fibrosis compared to those in which AF is successfully terminated. A PVs isolation procedure is considered as being successful when there is not recurrence of AF episodes, which implies that the arrhythmogenic foci were ablated successfully. A new study should be deducted on signals from people experienced a successful PVs isolation, compared to signals from healthy subjects, which might answer the question whether the success of the ablation may be attributed to the modification of the electrical characteristics towards those of the normal's propagation.

V. Conclusion

The two dimensional representation of the wavelet energy of atrial activity (Poincaré plot), as well as its association with RR intervals, could reveal significant information concerning the atrial arrhythmogenic substrate. The method that has been used, in addition to its promising results, can help us towards to the better understanding of the conduction mechanisms in the human atria and the detection of the irregularities occurring in pathological conditions as well.

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