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Characterization of typical and atypical Atrial Flutter Loops from the Vectorcardiogram

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Abstract— **Current techniques for atrial flutter (AFL) treatment involve radiofrequency ablation. This is a relatively simple and short procedure for typical AFL, whereas becomes more complex and unpredictable in the case of atypical AFL. Therefore, non-invasive characterization of AFL would be helpful for the management of ablation procedures.**

In this study the behavior of typical and atypical AFL groups is characterized from the vectorcardiographic AFL loops. The initial hypothesis is that typical AFL loops resemble each other, whereas atypical AFL loops differ from typical AFL ones. All patient loops were compared to a reference, by analyzing the global trajectory, pathway complexity and distance to the reference loop. The distance was the most significative parameter, being 0.445 ± 0.135 and 0.799 ± 0.144 for typical and atypical AFL ($p = 8.00e-5$). In addition, an intrapatient analysis revealed a higher stability of typical AFL loops than in the case of atypical AFL.

I. INTRODUCTION

Atrial flutter (AFL) is a supraventricular arrhythmia characterized by a stable reentrant circuit at the atria, with a typical cycle length of around 200-250ms (although it could be higher when treated with drugs) [1]. Under normal circumstances, the RR interval is closely fitted to a multiple of the atrial cycle length, dependant of the atrioventricular (AV) conduction ratio.

Atrial flutter is commonly treated by means of radiofrequency catheter ablation, which aims to create a barrier that hinders the reentry of the loop. Hence, the identification of the target sites to be ablated is a crucial step for the success of the surgical intervention [2]. These target sites depend on the reentrant circuit. In most cases (around 90%), the reentrant circuit circles the right atrium around the tricuspid valve [1]. This type of AFL is known as typical AFL, and can be further divided into counterclockwise (CCW, the most commonly observed) and clockwise (CW) depending on the propagation sense. In both cases, the target site for ablation is the cavo-tricuspid isthmus (CTI), as being the narrowest region along the path [3]. Any other case of AFL with a different reentrant circuit is, by definition, atypical AFL. This includes a large variety of loops, since each case of atypical AFL is different. The target sites for ablation are a priori unknown, since there is not much information available about the reentrant circuit until an intra-atrial electrical mapping is done [4].

Termination of typical AFL by means of CTI ablation is a relatively simple and short intervention. On the other hand, ablation of atypical AFL is unforeseeable and may become longer and much more complicated, specially if the target ablation site is located at the left atrium. In addition, ablation of atypical AFL is not always successful, and the arrhythmia still persists. For this reason, any additional information regarding the AFL type and/or the reentrant circuit that could be obtained in advance would be helpful for the management of the surgical intervention.

The standard method to analyze the loops described by the cardiac electrical activity is the vectorcardiogram (VCG) [5], which can be derived from the 12-lead electrocardiogram (ECG) by the Dower's Inverse Transform. The aim of this paper is to evaluate the VCG loop corresponding to the AFL reentrant circuit and search for differences in its behavior between typical and atypical AFL groups. Our hipotheses are firstly, that the pathways of the patients from the typical AFL group are relatively homogeneous. Secondly, we hipothesize that the pathways from the atypical AFL group are much more heterogeneous and are dissimilar from those observed in the typical AFL group. In this paper we propose a set of indicators defined from the VCG loop with the aim to extract this information.

II. MATERIALS

One of the requirements of this study was to obtain a database of ECGs from both typical and atypical AFL patients. In order to avoid errors and missclassifications, ECGs were registered during an ablation procedure, hence simultaneous intracardiac recordings were also available. These intracardiac recordings were used as the gold standard to classify each recording or segment as typical or atypical AFL, or just to discard it as not belonging to any of these arrhythmias.

An important drawback for AFL analysis is that many of the patients present a 2:1 AV conduction ratio (i.e. one ventricular activation every two atrial cycles), thus the atrial wave appears overlapped with either the QRS complex or the T-wave. Consequently, ECGs with 2:1 AV conduction ratios should be disregarded, and only longer TQ intervals could be employed for our analysis, so that isolated and unambiguous AFL waves can be extracted. With all these limitations, 11 typical and 15 atypical AFL valid registers were obtained.

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III. METHODS

This section describes the proposed methods to analyze the properties of AFL loops and compare them for both patient group. This includes preprocessing, parameters definition and statistical analysis.

A. Preprocessing

The available material to carry out this study is the raw ECG data. However, we are interested in analyzing the trajectory described by the AFL loop, so ECG recordings should be previously treated to meet our requirements. What we need at the end of the preprocessing step is to capture and align the AFL cycles of each patient, free from any ventricular or baseline residuals. Furthermore, in order to allow comparison among patients and groups, these loops should be normalized in terms of length, amplitude and rotation sense.

The ECG signal is firstly pass-band filtered between 0.7Hz and 70Hz to reduce baseline wandering and high frequency noise, while keeping all ECG components.

The next step is to capture AFL waves. For this purpose, only long enough RR intervals should be considered. Obviously, in the case of 2:1 AV conduction ratio, the second AFL wave appears mixed with the T-wave. In the case of 3:1 conduction ratio, it could be possible to observe one complete AFL cycle. However, the end of the previous T-wave and the beginning of the following QRS complex would be extremely close to the boundaries, and hence leaving no margin even for slights errors in the interval selection. Therefore, at least 4:1 AV conduction ratios are ideally desired, although some segments with 3:1 AV conduction ratio could be employed if carefully supervised.

At this point, one key aspect is to estimate the average atrial cycle length, for two reasons. The first and more important one is to extract an AFL wave segment with a length of exactly one cycle. The second one is to determine if a RR interval is long enough, since this is a relative measure respect to the atrial cycle length. The method we employ to determine the atrial cycle length is the following: firstly, the atrial source is estimated according to a Blind Source Separation method. This extracts one single signal corresponding to the atrial activity (although this is not referred to a well-defined lead or site). Next, the dominant frequency is computed in the spectral domain according to the Welch's method. Finally, the atrial cycle length is computed as the inverse of the dominant frequency.

Once the atrial waves are captured from valid RR intervals, they are further band-pass filtered with a narrower filter (between 3Hz and 25Hz) in order to remove remaining baseline components and high frequency oscillations that could hinder the closing of the loop. Subsequently, the length of each AFL wave is limited to the duration of one exact cycle, and all the waves for the same AFL episode are aligned.

The last step of the preprocessing stage is to obtain the normalized VCGs of the AFL cycles. For this, the Dower's Inverse Transform is applied to the 12-lead AFL waves, thus obtaining the spatial representation (X, Y and Z leads). Finally, the waves are normalized in terms of length and equidistance of consecutive points (thus, resampling the appropriately the VCG), amplitude (in terms of energy) and rotation sense (CW is converted to CCW by reverting the VCG segment, i.e. from the end to the beginning).

B. Parameter Definition

Once the normalized VCG is obtained, several parameters are proposed to extract and quantify different features regarding the AFL loop. Two different kinds of analysis are possible: (1) interpatient analysis, where the average AFL loops of the different patients are compared and (2) intrapatient analysis, where the stability of the AFL loop with time is analyzed for each individual.

1) Interpatient analysis: For interpatient analysis, all AFL waves from the same patient are averaged, hence a unique and representative AFL wave is obtained for each patient. Subsequently, the waves for all patients are temporally aligned.

The first parameter aims to capture the main trends of the trajectory (hence excluding local variations) and evaluate whether it is compatible with the typical AFL group or not. We will refer to this parameter as Main Trend Correlation C. To compute this parameter, the AFL loop is firstly simplified to an ellipse in the 3D space and compared to the averaged typical AFL loop (also simplified to an ellipse). If the patient under analysis belongs to the typical AFL group, then the reference typical AFL loop is computed from a Leave One Out (LOO) algorithm, i.e. excluding the patient under analysis. Since both the patient and reference loops are aligned, they can be compared point by point. The way we use for comparing two points (which are temporally aligned) is the scalar product of the unitary vectors that point to them from the coordinates origin. The Main Trend Correlation is then computed as the average of the scalar product for all points in the loop:

$$C = \frac{1}{N} \sum_i \frac{\mathbf{x}_i^T \mathbf{y}_i}{\|\mathbf{x}_i\| \, \|\mathbf{y}_i\|}, \tag{1}$$

where $\mathbf{x_i}$ and $\mathbf{y_i}$ are the i-th points (considering its X, Y and Z components) of the patient and reference AFL loops, respectively, and being N the total number of points in the loop (which is the same in all cases as having previously normalized them). The rationale for this parameter is that, if the global trajectory of the individual AFL loop matches the reference loop, then both vectors would be coincident for every point, and hence this parameter is upper bounded by 1. On the other hand, in the case of orthogonal ellipses (worst case), the vectors are coincident at some points, but orthogonals at the other extremes, and in this case the value of this parameter is 0.5, which is the lower bound.

The second parameter intends to capture local variations in order to evaluate the complexity (or simplicity, if seen as its inverse) of the trajectory, regardless of the global trajectory. The more changes in the direction, the more the complexity

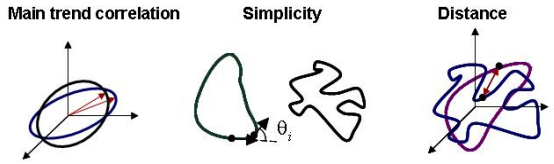

Fig. 1. Illustration of the definition of Main Trend Correlation (left), Similarity (center) and Distance (right).

of the pathway. Therefore, the complexity can be regarded as the accumulation of the instantaneous angle variation Θ_i, which for the i-th point is computed as:

$$\Theta_i = \arccos\left(\frac{(\mathbf{x}_i - \mathbf{x}_{i-1})^T(\mathbf{x}_{i+1} - \mathbf{x}_i)}{\|\mathbf{x}_i - \mathbf{x}_{i-1}\|\,\|\mathbf{x}_{i+1} - \mathbf{x}_i\|}\right) \quad (2)$$

The accumulation of all angle variations Θ_i along the full pathway is lower bounded by 2πrad, which is the value obtained in the simplest case (i.e. the direction vector gives a complete turn). However, since there is not an upper bound for this parameter, we define the simplicity S as:

$$S = \frac{2\pi}{\sum_i \Theta_i}, \quad (3)$$

which is lower bounded by 0 (very complex trajectory) and upper bounded by 1 (with no local variations). Notice that this parameter is not related to a reference loop.

The third and last parameter intends to capture both global and local information. For this purpose, the relative distance is defined as:

$$D(i) = \frac{\sqrt{(\mathbf{y}_i - \mathbf{x}_i)^T(\mathbf{y}_i - \mathbf{x}_i)}}{\|\mathbf{y}_i\|}, \quad (4)$$

which is averaged for all points in the AFL loop to obtain the distance D.

Figure 1 illustrates the definition of these parameters. Notice that in the case of the Main Trend Correlation (left), the loops are simplified to ellipses. The two vectors pointing at the same sample of the respective ellipse are correlated. In the case of the Simplicity of the trajectory (center), two examples corresponding to simple (left) and complex (right) trajectories are given. The parameter Θ_i is illustrated as the angle variation as the direction changes. Finally, the Distance (right) between both loops is computed for each sample as the modulus of the vector that connects both points.

2) Intrapatient analysis: The intrapatient analysis is carried out in order to measure the variability of the AFL loop. In this case, only the main trend correlation and the distance are computed. For each patient and loop, a correlation and distance value are computed. The reference loop to compare with is the average AFL loop of the patient using a LOO procedure, i.e. by excluding the current loop to be analyzed. Then, the correlation and distance is obtained by averaging the values for all loops in each patient.

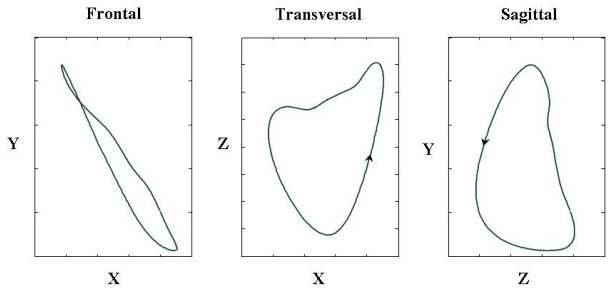

Fig. 2. Averaged atrial loop for the typical AFL group, in the frontal, transversal and sagittal projections.

C. Statistical Analysis

Once the parameters are computed, the results from both patient groups are compared in order to find statistically significant differences. For each parameter, a Lilliefors test for normality is applied. If normality can be assumed, then the t-test is performed. Otherwise, the Mann-Whitney test applied.

IV. Results

The average AFL loop for the typical patient group is shown in Figure 2. Although this illustration does not correspond to a real patient, it could be considered as a representative one, since all typical AFL reentrant circuits are CTI dependant. For a better interpretation of the loop, it is represented from its three projections: frontal, transversal and sagittal (notice that these projections are only used for visual representation, but for parameter estimation the full 3D coordinates are always considered). The CCW sense of the propagation is specially noticeable in the transversal and sagittal projections. In our database, 9 out of 11 typical AFL patients presented CCW sense, whereas a CW sense was observed in the other two patients. In these two cases, signals were reverted to CCW pattern for AFL loop averaging and parameter estimation. With respect to the atypical patient group, no average AFL loop for is represented since, due to the larger hetereogeneity of the reentrant circuit, a representative loop is no longer meaningful.

A. Interpatient analysis

Main Trend Correlation C, Simplicity S and Distance D were computed for each patient and averaged for each patient group. Main Trend Correlation was 0.952 ± 0.035 and 0.826 ± 0.087 for typical and atypical patient groups, respectively ($p < 10^{-3}$), showing that the global trajectories of the atypical AFL group were significantly different than those of the typical AFL group. The Simplicity was 0.459 ± 0.184 and 0.344 ± 0.083 for typical and atypical patients groups, respectively ($p < 0.05$), showing that the trajectory was slightly more complex in the atypical patient group. Finally, the Distance was 0.445 ± 0.135 and 0.799 ± 0.144 for typical and atypical patient groups, respectively ($p < 10^{-4}$), showing a much higher loop difference with respect to the reference typical AFL loop when the atypical AFL group is evaluated. Table I summarizes these results.

TABLE I

RESULTS FOR INTERPATIENT ANALYSIS

	Typical AFL	Atypical AFL	p-value
C	0.952 ± 0.035	0.826 ± 0.087	1.38e-4
S	0.459 ± 0.184	0.344 ± 0.083	0.043
D	0.445 ± 0.135	0.799 ± 0.144	8.00e-5

TABLE II

RESULTS FOR INTRAPATIENT ANALYSIS

	Typical AFL	Atypical AFL	p-value
C	0.982 ± 0.031	0.936 ± 0.076	0.035
D	0.195 ± 0.131	0.359 ± 0.206	8.94e-3

B. Intrapatient analysis

Main Trend Correlation C and Distance D are computed for each loop in order to evaluate intrapatient variability. Main Trend Correlation was 0.982 ± 0.031 and 0.936 ± 0.076 for typical and atypical AFL patient groups, respectively ($p < 0.05$). This shows a slightly higher stability in the case of typical AFL and, in any case, these values are higher than in the case of interpatient analysis. The Distance is 0.195 ± 0.131 and 0.359 ± 0.206 for typical and atypical AFL patient groups, respectively ($p < 0.01$), which reveals much less variations in the AFL loop within the same patient in the case of typical AFL. Table II summarizes these results.

V. DISCUSSION

The first remarkable aspect inferred from this study is the ability of the proposed parameters to capture features to characterize the AFL loop trajectory. Two of these parameters are designed to isolate the properties regarding the global trends of the trajectory and the local fluctuations, respectively. The third parameter aims to capture all this information joined in a single indicator. Thus, it is possible to evaluate which of both aspects is more significant, and whether the combination of them becomes more powerful or not. From the results in Table I, it can be inferred that the Main Trend Correlation is much more significant than the simplicity. Actually, simplicity values show that typical AFL loops present somehow less fluctuations, but this difference is very slight. By computing the Distance, the significance of the results is slightly increased, and is the parameter we recommend.

As expected, there is certainly a resemblance between AFL loops from different typical AFL patients. Although the loops are not exactly the same, there are at least some common aspects. This correspondence is faded when evaluating the atypical AFL group, i.e. atypical AFL loops are different from typical AFL loops.

One of the limitations of the proposed parameters for interpatient analysis is the fact that these measurements are relative to a reference loop, which is empirically obtained from a set of typical AFL patients. Although the independence of the data is guaranteed by means of a LOO algorithm, the reference typical AFL loop should be derived from a more universal database with a larger number of patients.

In the case of intrapatient analysis, the results show that, within the same patient, the AFL loop is more homogenous and stable in the typical AFL group. This result was a priori uncertain and unpredictable, since AFL is, by definition, a supraventricular arrhythmia with a stable atrial reentrant loop, independently of being typical or atypical. Interestingly, the results show that the intrapatient variations for the atypical AFL group are comparable to interpatient differences for the typical AFL group. This result can also give an idea regarding the homogeneity of the AFL loop in the typical patient group.

In spite of having obtained consistent and statistically significant results, this study still presents some limitations that could be improved in future work. Firstly, as previously indicated, the database should be enlarged to improve statistical robustness. Another aspect that could be addressed is the inclusion of simulations by artificially creating AFL loops parameterized by plane orientation, as well as the complexity of the pathway. The analysis with simulated data would be helpful for a better interpretation regarding the properties of the proposed parameters. Finally, although this methodology are able to characterize the behavior of both groups, it is not able to classify with 100% reliability among both groups, nor to identify the atrial region (right or left atrium) to be ablated. Therefore, further research is still needed to overcome this problem.

VI. CONCLUSION

A non-invasive methodology is proposed to characterize AFL and differentiate the behavior between typical and atypical AFL. The proposed method is based on the VCG, more specifically, on the evaluation of the loop trajectory. This study shows that AFL loops from typical AFL patients present some similarities, which are no longer observed in the atypical AFL group. Moreover, the stability of the AFL loop within the same patient is significantly higher in the typical AFL group.

The results from this study helps to better characaterize this arrhythmia in a non-invasive way, as well as to improve clinical planification and managment of surgical interventions for AFL ablation.

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