Validation of an algorithm for automatic calculation of inter-lesion distance in radiofrequency catheter ablation of atrial fibrillation

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***Abstract*— Atrial Fibrillation (AF) is a heart rhythm disorder characterized by rapid and irregular atrial contractions, which can increase the risk of stroke and decrease patients' quality of life. One of the main techniques to treat AF is RF catheter ablation, which involves electrically isolating the pulmonary veins from the rest of the atrium, based on point lesions surrounding the veins. There is still discussion in the community as to what is the optimal interlesion distance to improve the long-term results of AF ablation. A Python tool has been developed that, starting from the AF ablation procedure data, finds the optimal sequence of ablations surrounding the pulmonary veins and thus can calculate the distance between the entire sequence of lesions. The automated algorithm proved to be effective in most cases and in almost all cases semi-automatically. The work provides a tool for the community that can help to optimize AF ablation. In the future, the algorithm could be improved to be 100% automatic, although right now it is already useful and several clinical studies are underway using this tool.**

***Keywords*— atrial fibrillation, RF ablation, inter-lesion distance**

I. Introduction

Atrial fibrillation (AF) is a heart rhythm disorder characterized by rapid, irregular contractions, that can lead to the formation of blood clots in the heart. These clots can break and travel through the bloodstream, reaching important organs such as the brain, where they can cause a cerebrovascular accident (CVA) or stroke. Atrial fibrillation affects 4.4% of the population over 40 years of age and 8.5% of the population over 60 years of age. It multiplies the risk of death between 1.5 and 3.5 times and is the main cause of between 20%-30% of strokes. It also worsens the quality of life of patients with up to 20% suicidal thoughts.

Pharmacological treatment is available, but it fails in up to 80% of cases. Consequently, in order to avoid vascular accidents, patients are treated with anti-coagulation, which is complicated and not without risk. Although the exact physiological causes that trigger it are still unknown, two principles of the disease are known. One is that when the atrium enters AF it loses contractility, which over time produces atrial dilatation, this dilatation modifies the electrical properties of the cardiac tissue, favoring the maintenance of AF [1]. The other one was discovered by Haïssaguerre [2]. It implies that often the original triggers of AF are located in the ostiums of the pulmonary veins and this discovery initiated the catheter ablation of AF. It is also known that there are other extrapulmonary foci, although of less relevance[3].

In a normal situation, the heart rhythm is set by the sinus node. Occasionally, there may be cells located elsewhere in the myocardium that produce a beat. In the ostiums of the pulmonary veins there is a transition of tissue between cardiac and venous, and these ectopic beats are frequently generated. The current objective of non-pharmacological treatment consists of electrical isolation of the pulmonary veins from the rest of the atrium. There are different techniques to perform this isolation, and radiofrequency (RF) catheter ablation is one of the most common. It can also be performed with cryo balloons, laser balloons, surgically or with electroporation catheters[4]. In catheter ablation, a polyurethane and steel catheter is introduced into the femoral vein to the heart. After transseptal puncture the catheters can be deflected to move freely through the cavity. The ablation is produced thermally by the radiofrequency current, producing cell death when the tissue temperature exceeds 50ºC [5]. Several precise and circular applications are necessary. The movement of the catheter inside the patient's heart was traditionally supported by fluoroscopy, that uses ionizing radiation, and only allows the visualization of a two-dimensional image. Ablation of pulmonary vein ostiums in the left atrium requires more precise visualization by electro-anatomical navigation systems, see Figure 1. A magnetic positioning sensor is placed at the tip of the catheters, which allows both visualization of the catheter and reconstruction of maps of the cardiac interior with electrical information from the myocardium. During all RF applications, position, force, temperature and other ablation parameters are recorded.

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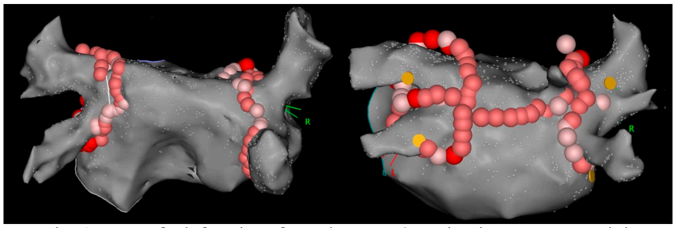

Fig. 1. Map of a left atrium from the Carto3 navigation systems and the radiofrequency lesions surrounding the pulmonary veins, often called crowns.The right image has additional linear lesions.

El Haddad M, Taghji P, Phlips T, et al.[6] demonstrated that lesions in circumferential ablation of atrial fibrillation had to be contiguous to achieve long-lasting isolation of the PVs. Mattias Duytschaever[7] proposed and validated the CLOSE protocol as a method to achieve effective and durable ablation of pulmonary veins. The CLOSE protocol specifies a minimum interlesion distance (ILD) of 6mm and values of ablation index (an index that takes in account, power, time and force contact) of 400 on the posterior wall and 550 on the anterior wall. This strategy has been confirmed in 17 centers in the VISTAX study[8] . In this study, patients who did not meet the criterion of >6mm contiguity between nearby lesions were removed from the protocol.

Since then there has been little discussion [9] on the appropriate size of the inter-lesion distance and other ablation parameters. There are very few studies that have analyzed whether an inter-lesion distance of >5mm may be more appropriate than the 6mm of the CLOSE protocol. The automatic and community-wide accessible inter-lesion distance assessment procedure will allow to analyze large groups of patients and possibly shed light on this issue. While measuring the distance between two lesions is a trivial operation, determining which lesion to measure the distance to next is less so. In circumferential ablation, the electrophysiologist tries to perform an orderly sequence of lesions, but unfortunately, the procedure is complex, and very rarely do all the ablations follow an orderly sequence, see Figures 2 and 3. Moreover, on many occasions there are areas where ablations are repeated due to lack of stability or the path deviates from the expected trajectory. In order to measure the ILD we need to determine a sequence of contiguous lesions surrounding the vein with jumps such that minimize the ILD. This implies ignoring those injuries outside the sequence of minimum distance.

The objective of this work is to validate an automatic system for measuring the inter-lesion distance. This system requires an algorithm that finds the sequence of contiguous ablations in a circular fashion. This system will make it possible to study the effect of ILD on the success of AF ablation.

The algorithm will only consider the ablation lesions created during the procedure, without taking into account any other anatomical or physiological information that could be relevant for the success of the procedure, such as the voltage of the tissue being ablated.

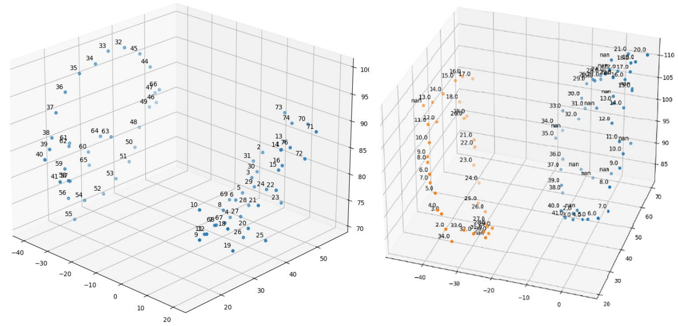

Fig. 2. List of lesions imported from the Navigation System (left), the numbers indicate the order where they were burned. In this example discontinuity on the sequence is clearly visible

Sequence of lesions searched (rigth), the numbers indicate the correct sequence to calculate inter lesion distance, those outside the sequence are tagged as nan.

II. Materials and Methods

A. *Patient selection and ablation*

Data from two different hospitals were used. In the first hospital, 227 ablations of both paroxysmal and persistent AF were analyzed. The procedures were performed according to CLOSE protocol, circumferential ablations with a target interlesion distance of 6mm. In a few patients, additional ablations of the cavotricuspid isthmus and superior vena cava were performed. In the second hospital, 450 ablations of both paroxysmal and persistent AF were analyzed. In this group of ablations, various ablation techniques were combined: CLOSE protocol with a target interlesion distance of 6mm; Circumferential isolation of the veins with the *dragging* technique (continuous displacement of the catheter), a new lesion is labeled each time the displacement exceeds 4mm; additional lines, depending on the patient, one or more lines are added to the circumferential ablation, such as: roof line, anterior line (between the mitral valve and the right superior vein) and posterior box line (between the inferior veins). Data were extracted from the Carto3™ Navigation System, which provides the position and value of the lesion at each point in a comma-separated file (csv).

B. *Developed tool*

To measure the interlesion distance, software was developed in Python with the well-known scientific computing and machine learning libraries: *Pandas, Numpy, Sklearn, Scipy and Matplotlib*. The *Tkinter* library was used to create a semi-automatic graphic user interface. The constructed tool executed the following sequence of steps: remove excess lesions (optional and semi-automatic), the user can remove those lesions that will hinder the following steps; grouping (automatic or semi-automatic), the two crowns and possible lines are separated, the user can only set the number of zones; sequence search (automatic or semi-automatic), the user can point specific lesions to be inside de sequence; calculation of the interlesion distance (automatic), measurement of the ILD is a trivial operation once you have the sequence. AF ablation at a minimum consists of making two crowns, one left and one right, in addition to other possible lines. The first step is therefore to separate the two crowns and possible lines. For this task we use the Kmeans algorithm, which in the case of two crowns works correctly 100% of the time, see Figure 4. When there are additional lines, this is not always the case, making the subsequent steps more difficult. The problem of finding the shortest path between two points is a well-studied problem in graph theory and there are several algorithms that solve it such as Dijkstra's Algorithm, Bellman-Ford Algorithm, Floyd-Warshall Algorithm or Johnson's Algorithm[10], [11], [12]. However, the circular shortest path problem is not a classical computational problem. There are authors such as M. J. Atallah[13] who suggest efficient solutions with a change to polar coordinates. Using common algorithms for shortest path directly will only yield a trivial solution due to the nature of a circular path, where the beginning and end points are the same.

A simpler solution is to run any shortest path algorithm twice, once for the outward trip and once for the return trip so that a circular path is generated. This is the solution we have adopted.

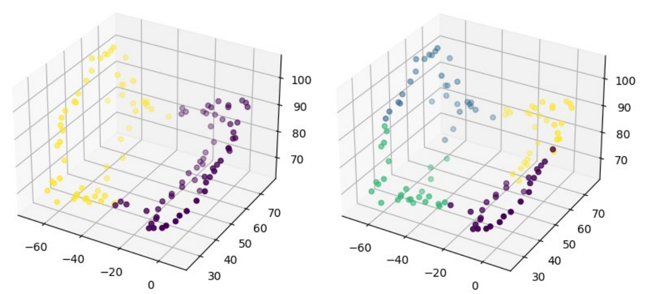

Fig 3. Kmeans is not able to differentiate the lines from the crowns, with different number of groups.

If we directly create a graph with all lesions and use the geometric distance, the shortest path algorithms will not solve our problem. The shortest distance is always the straight line, but we want to find the shortest distance by passing over all the lesions, thus obtaining a sequence.

The modification we make is to raise the geometric distance to an exponent, so that in this way the sum of small distances is shorter than a single large jump, see Figure 5. After several tests to refine the algorithm, it was decided to use the Floyd-Warshall algorithm with the following distance definition:

- Distances less than 3mm are considered 0mm. This avoids excessive jumping when injuries accumulate due to lack of stability.
- The distance in general is the linear distance raised to the 5th exponent. Raising the exponent higher had no effect and with lower exponents it sometimes "jumped injuries".
- If the distance is greater than a limit (12mm), it is considered infinite. Larger distances did not make sense in the problem and in this way we reduced the work of the algorithm.

To create a circular path, we perform the following sequence. First we choose a starting point and an end point. Then we look for the sequence from the starting point to the end point. Afterwards we delete from the network all the points (lesions) through which we have passed. And finally we look for the sequence from the end point to the initial one. In general, almost any pair of start and end points is suitable for the purpose. Only those points that will fall outside the optimal circular sequence are not suitable. In the first tests we tried the two points farthest from the corona in order to balance the number of points in each semi-path. It turned out that very often the farthest points were among the few that were not in the optimal sequence. We tried to look for alternatives such as points that were within a percentage of the maximum distance, but in the end we were not able to find a better solution than setting the initial points randomly. In case of failure, the algorithm can be reattempted semi-automatically by the user.

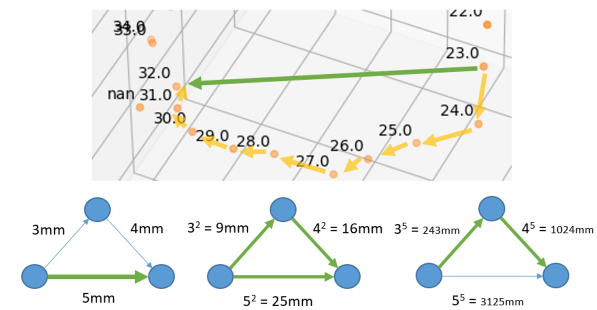

Fig. 4. Shortest path: Straight line in green, searched path in orange. Below the effect of elevating the distance to an exponent.

III. Results and Discussion

Successive runs of the algorithm were performed, in a first run the data were processed automatically, supervised by an operator only to check the level of success achieved. In the event that the operation was not correct, a second run was performed semi-automatically. In this second run, lesions could be deleted, the initial, final and intermediate points could be set for the circular path search. At the end of the second run, the semi-automatic success rate was measured, see Table 1. In 94% of cases from first hospital and 73% of cases of the second, the algorithm correctly segmented both ablation circles and determined the sequence of ablated lesions fully automatically, on the first run. In only three cases (0.4%) was it not possible to find the lesion sequence even semi-automatically. Although it is true that the quality of the lesions in these cases, basically a cloud full of lesions, would most likely exclude them from any clinical study.

TABLE I. PROPOSED ALGORITHM RESULTS

Group	Automatic success	Semi-automatic success	Failure	Total
Hospital 1	214	12	1	227
Hospital 2	328	120	2	450

Only three sources accounted for the majority (99.6%) of the automatic algorithm failure: incorrect selection of the initial points; sequence follows ablation lines contiguous to the crowns; clusters of lesions generate sequence loops, usually in the lower part of the veins. All problems can be easily mitigated in semi-automatic execution. The first problem is trivial, and it is enough to run the algorithm again and let it choose other starting points, see Figure 6. The second issue is very similar; it's only needed to do not select any starting points on the additional ablation lines. You can repeat the execution until it works correctly or select the points manually, see Figure 7. The last problem is the toughest. In order to avoid loops in the lesion clusters, it is necessary to mark intermediate points and thus prevent the algorithm from entering and exiting the lesion clusters by creating a loop.

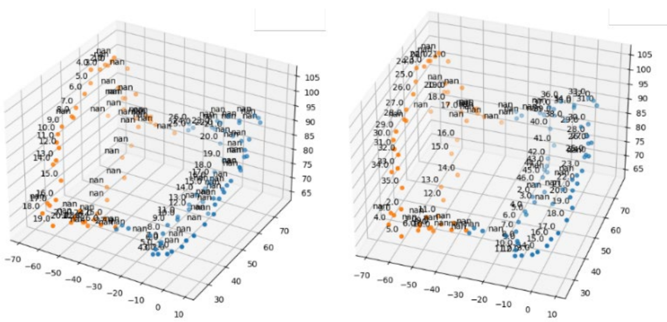

Fig. 5. In the first run the lines confuse the algorithm, in the second run with other initial points within the crowns (randomly chosen) it is able to ignore them, the nan values appear on the lines and not on the crowns.

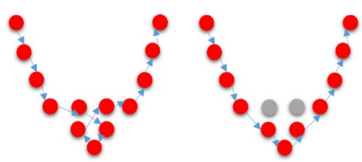

Fig. 6. On the left the wrong loop sequence is generated (although the image is in 2D, 3D is required in order to happen). On the right the expected sequence with two lesions in gray ignored.

IV. Conclusions

This paper shows a semi-automatic algorithm to measure the interlesion distance of an AF ablation procedure and makes it available to the community[14]. This data is important for optimizing the RF catheter ablation procedure, since there is still no optimal value of interlesion distance for efficacy and efficiency. It is not yet possible to use it 100% automatically, although in most cases the operator will only have to accept the results. In the future, two areas for improvement are proposed. One is to determine a way to choose the initial points that work better than random. Another one is to improve the initial segmentation with a more suitable algorithm than Kmeans, perhaps machine learning or a change to polar coordinates.

A. Actual and future use in clinical trials

At the time we are sending corrections for this communication, the tool validated and described in this paper has been used for a retrospective clinical study that is being submitted for peer review. One surprising finding is that physicians are systematically not achieving their inter-lesion objectives. Moreover, in the procedures where they meet their objectives, the success rate of the procedure is significantly higher. As a consequence, the tool has already changed the routine of the cathlabs involved in this research. They are paying much more attention to the precise measurement of the inter-lesion distance during the procedure. Currently, the tool is not used inside the procedure because integrating it with the navigation system would take more time than taking manual measurements. Other groups may download the tool with minimal technical assistance to check if they are achieving their inter-lesion objectives. It also permits the design of prospective clinical trials where different inter-lesion strategies are compared based on the real inter-lesion achieved, rather than physician intention.

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