Trajectory Planning Applied to the Estimation of Cardiac Activation Circuits

Lorena González[1], Jerónimo J. Rubio[2], Enrique Baeyens[3], Juan C. Fraile[3], and Jose R. Perán[3]

[1] CARTIF, División de Ingeniería Biomédica,
Parque Tecnológico de Boecillo Parc. 205, Boecillo, Valladolid, Spain
lorgon@cartif.es
[2] Instituto de Ciencias del Corazon,
Hospital Clínico Universitario, Valladolid, Spain
jrubio@vitanet.nu
[3] Universidad de Valladolid,
Depto. de Ingeniería de Sistemas y Automática, Valladolid, Spain
{enrbae, jcfraile, peran}@eis.uva.es

Abstract. A procedure for helping the professional in electrophysiology in performing catheter ablation as a definitive treatment of certain types of arrythmia is presented here. This procedure uses trajectory planning techniques that have been developed in the robotics field. Starting off from signals obtained in an electrophysiological study of a patient, an electrical model of the heart with zones of different propagation properties is generated. Trajectory planning techniques are used to obtain the qualitative behavior of the heart under different types of arrythmia. A good point for ablation is computed as one that interrupts the trajectory that is sustaining the arrythmia.

1 Introduction

The upheavals of the heart rate are cause of 50% of the cardiac related deaths [1]. In addition, most of them are produced by sudden death. There are more than 300,000 sudden deaths per year only in the US and 90% are caused by cardiac arrhythmia. Cardiac arrhythmia is any alteration of the heart rate including changes of the cardiac characteristics or inadequate variations of the heart frequency. Unfortunatly, the available therapeutic arsenal for cardiac arrhythmia is still relatively limited [2].

The evidence that arrhythmia needs an anatomo-electrophysiological substratum (forced conduction circuits) for its maintenance motivated the development of catheter ablation techniques. This is the only form of definitive treatment. Its advantages are efficiency, safeness, practically null mortality, low cost and almost absence of counterindications [3].

Notwithstanding, this technique has several fundamental limitations. The location of isthmuses or zones of forced conduction requires a long time electrophysiological study (EPS) that has to be performed by an experienced profes-

A.F. Frangi et al. (Eds.): FIMH 2005, LNCS 3504, pp. 75–84, 2005.

sional. The success of the treatment depends on the electrophysiologist's skills. In some cases, the EEF stimulation to find these zones can represent a potential danger for the patient's life. On the other hand, presently there is no tool in the market that locates the optimal place for performing ablation.

The research presented here is motivated by this necessity and aims to the improvement of the conventional cardiac arrythmia treatments by catheter ablation.

This paper presents the outline of a new procedure for estimation of cardiac activation trajectories and location of the optimal point for ablation in a virtual map previously developed and adjusted from EPS signals.

2 Frame of Application: Electrophysiological Studies

Electrophysiological studies are carried out in a cardiac catheterization laboratory. They are based in obtaining intracavitary electrograms, with the purpose of studying its cardiac activation sequence in basal conditions, during different arrhythmias as a response to a programmed heart stimulation. The indications for the accomplishment of these studies are in a constant evolution [4].

The general procedure consists of introducing electrocatheters through the vessels of the leg and carry them to the heart. The guidance is accomplished by means of fluoroscopic control. An electrocatheter registers the electrical impulses of the heart allowing to obtain a map of the electrical conduction system.

The correspondence of cardiac signals is the technique by which the signals gathered from the multiple locations of the heart are drawn as a function of time in an integrated way [5]. It requires the determination of the local activation time for each electrode and the creation of activation maps providing space models of the activation sequence. It is used to unveil the arrythmia mechanisms, its prognosis and to delimit the structures implied in its maintenance with the purpose of eliminating it (or at least modifying it) by ablation. Therefore, this technique tries to locate the origin of the arrhythmia, *i.e.* the point that has the precocious electrical activity. Recent advances in this field are new correspondence systems that do not need fluoroscopy to guide catheters [2].

The treatment of cardiac arrhythmias has evolved quickly during the last decade [6]. At the beginning of eighties, the development of invasive electrophysiology techniques as ablation revolutionized the treatment of many types of arrythmia. Ablation consists of producing a controlled injury in the vital zone for the initiation and/or the maintenance of the arrhythmia. The objective is to burn fibers and consequently suppress the electrical conduction in that zone. The controlled injury produces that an essential part of the electrical circuit responsible for the maintenance of the arrhythmia is eliminated and this avoids the initiation and/or the sustainment of it. The injury area produced, depends on the size of the electrode, the time and power of application, and the type of tissue. The development of these techniques allowed to introduce the only really curative treatment for many types of arrythmia. This has been one of the greatest electrophysiology advances.

The application of this treatment could be greatly improved with the aid of a tool able to locate the circuits without inducing a tachycardia. This tool should also minimize the registration time and locate the best point for ablation avoiding the detection of false places that are not essential part of the circuit. A computer tool supporting these features would be very valuable for the electrophysiologist and would make this treatment more reliable, simple, efficient and economic, with a minimal risk for the patient.

3 Hypothesis

The proposed hypothesis is that a model based on cardiac potential maps can be developed, where different conduction properties are given to distinct zones according to signals obtained in conventional EPS. Using this model, it is possible to apply trajectory planning ideas developed in the field of robotics [7] in order to, first elaborate a procedure that simulates the feasible propagation pathways from one point to another on the surface model; and second, search for the optimal point that would interrupt some specific trajectories. This point is selected by establishing previous conditions according to the mechanisms that originate or maintain the arrhythmia and also, according to the morphological characteristics of the involved conduction areas.

4 Methodology and Implementation

In order to validate the hypothesis, the following steps are proposed:

– Development of a basic cardiac conduction model running on a PC that integrates cardiac geometry information about origin, characteristics and propagation of the associated electrical signal from EPS.
– Development of a procedure to locate the forced conduction circuits in the model under certain given propagation conditions. The procedure would exploit the type of arrhythmia represented by the model and would apply trajectory planning techniques.
– Development of a procedure to search the points that interrupt the trajectories fulfilling the pre-established specifications.

In order to obtain this purpose, recent results about data processing, experimental modelling and system identification will be applied. These techniques will be combined with trajectory planning methods from the field of robotics and theoretical advances in heart electrophysiology.

A software tool called SCIRun/BioPSE [8] is being tested for the development of the models and simulation of the conduction features. SCIRun/BioPSE is a shareware (MIT license) scientific program, developed by The Scientific Computing and Imaging Institute (SCI Institute) of the University of Utah, that allows a modular and interactive development, error debugging and execution of scientific computations on a great scale. By using this computational tool, a data flow programming model is designed and tested by simulation. Geometric, mathematical and bioelectrical information are integrated in the model that also allows for automatic parameter adjustment, contour conditions, as well as fitting the discretization level necessary to obtain a suitable numerical solution. By comparison with the "off-line" procedures that are usually employed for this type of simulations, SCIRun allows an interactive handling of the design and simulation phases. Also, it avoids the excessive use of memory, that is one of the problems of data flow standard implementations, and improves the the computacional efficiency. In addition it allows the visualization of scalar, vectorial and tensor fields. This tool has being used to solve medical problems related to bioelectric fields and has been selected as a suitable tool for our purpose.

5 Basic Conduction Model

The purpose is the development of a base whose elements will be basic maps of propagation. Each map will be generated on a 3D geometric heart model (elaborated by means of the finite elements method) and a tensor of parameters is associated to each cell of the model. This tensor would gathers, at least, the three electrical properties of cardiac fibers:

– Automatism or the capacity to generate impulses that can propagate through the tissues. Sinus node cells and also atrio-ventricular ones are fundamentally automatic.
– Excitability or the capacity that has any cardiac cell to respond to an effective impulse. Contractile cells only respond to propagated impulses from an automatic structure. Once excited, every cell requires of a time to recover its excitability (refractory period).
– Conductivity or the capacity to propagate the impulses. This propagation takes place by an electrical phenomenon that crosses the cellular membrane and all the cardiac structures. The normal speed of conduction varies for the different cardiac structures (atrium, 1–2 m/s; atrio-ventricular node, 0.05 m/s; Purkinje system, 1.5–4 m/s; ventricle, 0.3 m/s).

These properties will be assigned to a tensor according to the signals gathered from EEF. Starting off from these signals is possible to build a map of cardiac potentials and relate the characteristics of this map to the properties associated to the tensors at each cell of the model.

In [9] a three-dimensional atlas of the human heart is given. It is based on the image data obtained by tomography, accessible magnetic resonance and cryosection in the Visible Human Project. This heart atlas offers great possibilities for analysis using computer vision techniques. The underlying cardiac model has been complemented with the addition of a temporal dimension for simulation of the excitation. For this purpose, an algorithm based on second generation of cellular automata has been implemented. It is adapted to the kinetic of the cardiac tissue excitation. This system demonstrates to be a right method for visualizing and researching the cardiac excitation.

During the last years, the resolution of the inverse problem in the field of cardiology has acquired a greater importance [10]. This problem consists of obtaining the bioelectrical image projection. The projection of the electrocardiographic image (ECG) uses an applied inverse solution to the electrical voltages registered in the surface of the thorax, and/or the actual characteristics of the cardiac source that produces the surface distributions.

6 Location of the Circuits

Our proposal here is to apply the trajectory planning techniques used in robotics to solve this step. Trajectory speed is making reference to a path associated to a kinematic profile.

The theoretical formalization of the planning problem has been widely studied by Latombe [7]. Many particular planners are found in the literature, for example those implemented by Farvejon and Tournassoud [11] or Kondo [12].

Most of the abovementioned results are applicable to static environments because the traditional algorithms for movement planning in deformable spaces are designed to work in spaces where the obstacles are rigid. This restriction is important because it limits the complexity of the model. A widely accepted method is that of L. Kavraki *et al.* [13]. There are also studies of movement planning for dynamic environments [14], but in order to validate our hypothesis a simpler model is preferred. The methodology will be later improved by using deformable space models.

A plan is a set of actions that allows an agent (in our case it will be a stimulus) to go from an initial state to a final state. Thus, the plan will be defined by searching trajectories or propagation paths in the cardiac map. The basic elements to formulate the plan will be the states (*e.g.* stimulus position, initial state), and the operators. The following elements are considered to be given:

- States:
  - position (X, Y, Z) of the cell in the map,
  - propagation tensor associated to each cell.
- Operators (or actions):
  - Movement to some neighboring cell: $X \pm 1$, $Y \pm 1$, $Z \pm 1$
  - Propagation conditions determined according to the type of arrhythmia subject of study.

Initial considerations are:

- A stimulus will be modeled as a point and a tail (with time-varying properties depending on the refractory time).
- A static environment with known obstacles (nonconduction zones).

If a set of cells or a road-map, free of obstacles, obtained previously by means of Voronoi diagrams is considered, an approximate diagram derived from the first one can be used. This auxiliary diagram considers a maximum distance to the obstacles corresponding to the limitations given by the sensors (catheter).

Applying potential field techniques [7] the following analogy could be made:

- The stimulus is a particle with electrical charge.
- The free space is considered a potential field.
- The obstacles have an electrical charge of the same sign than the stimulus.
- The goal has an electrical charge of opposed sign to the stimulus.

The differential potential field, U, is constructed adding the goal field U_g, and the obstacles field, U_o:

$$U(q) = U_g(q) + \sum U_o(q)$$

From this differential potential field, U, an artificial force field, F is obtained as:

$$F = -\nabla U(q)$$

Once derived the force field, the stimulus movement is based on the local force. A robust scheme is obtained and it has implicit a plan for any point of the space. The potential functions of the goal (parabolic attractor), center (parabolic repulsor) and obstacles (exponential potential barriers) has to be modeled. Later, the potential for each point of the free space can be computed and the forces are obtained by potencial derivation. The main advantages of this technique are the following:

- Trajectories can be generated from the force field in real time.
- Generated trajectories are smooth.
- It allows direct connection of the planning phase with the control phase.

7 Location of the Interruption Point

After obtaining the plan, a procedure for searching spheres of radius R that interrupt the abnormal circuits of propagation is developed. Criteria to decide their location will be previously established by an electrophysiologist and implemented on the computer in order to be automatically detected or even interactively selected. Certain fundamental premises are considered in order to formulate the problem:

- The spheres must have a minimum surface.
- The natural propagation path cannot be interrupted under any circumstances.
- Particular conditions for each type of arrhythmia are teaken into account.

An algorithm to estimate the risk of a wrong or false interruption will be implemented in order to avoid *bystanders* or local minima. The algorithm evaluates the convenience of one greater sphere in a place strategically better placed. Strategies used in the trajectory planning can also be applied to avoid *tramps*, as backtracking or wall pursuit (in our case, null conduction zones pursuit), and so on.

8 Study Case

Let consider the simple 2D heart model with an accesory pathway depicted in figure 1 that represent a patient suffering Wolff-Parkinson-White Syndrome (WPW). Certain properties as automatism, excitability, conductivity and speed are given to each cell and are also graphically shown in figure 1.

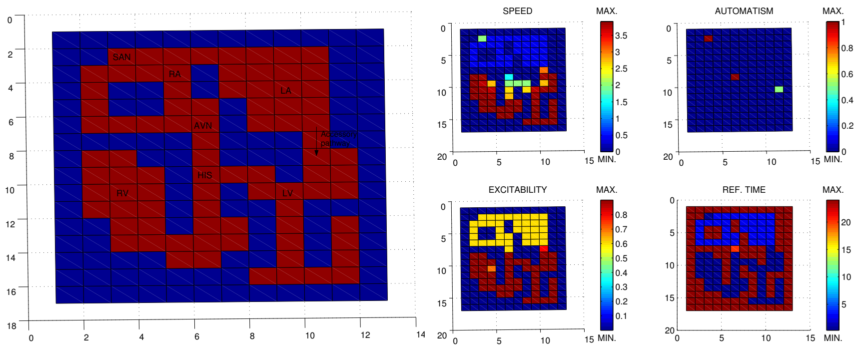

Fig. 1. Simple 2D model of a patient with WPW and properties assigned to each cell in the model

WPW is a form of supraventricular tachycardia characterized by the presence of extra pathways called accessory pathways in addition to the normal conduction ones. This is graphically shown in figure 2. The impulses travel through the extra pathway (shortcut) as well as through the normal AV-HIS Purkinje system.

The simulation of the propagation during only one beat in the model permits to observe that stimulus travels through different pathways, as can be checked in figure 3.

Points A and B represent places where two impulses collide so that they cannot continue the propagation in that direction. In that case they do not travel around the heart in a circular pattern. The collision at point B will generate a signal characterized by the *delta* wave in the ECG. The most the ventricle is depolarized by the accessory pathway, the greater *delta* wave is.

However, when multiple beats are simulated, the cell with high automatism capacity in the left ventricule of the model (see figure 1) could originate an impulse. If the neighboring cells are capable of responding to this impulse then it could occur the situation depicted at left in figure 4. Stimulous could travel very quickly through the heart in a circular pattern, causing the heart to beat unusually fast. Sinus node (SN) is inhibited and the circular pattern is sustained. Under such circumstances, a re-entry tachycardia is observed in the ECG.

Determining the optimal place for ablation is easy in this case. At right in figure 4 it can be seen the precocious activity that has been generated in point B. Nevertheless, eliminating this point is not the solution because after some time,

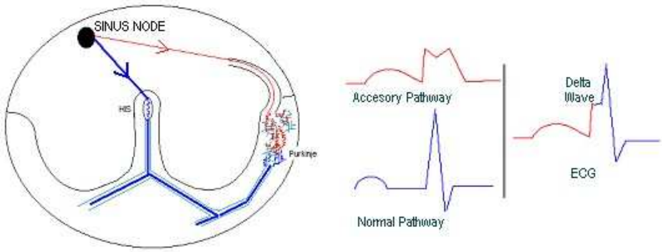

Fig. 2. Propagation in a WPW patient

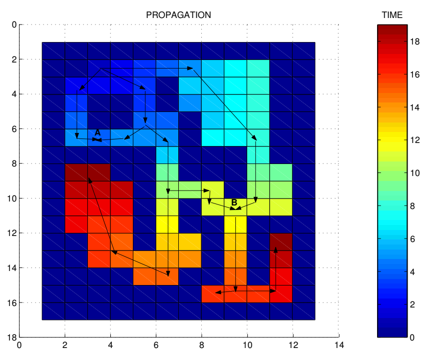

Fig. 3. Propagation of a signal characterized by the *delta* wave in the ECG

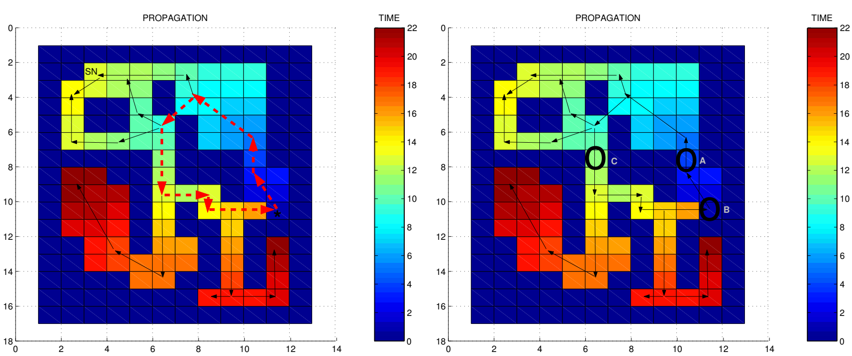

Fig. 4. Propagation in a re-entry tachycardia in a WPW patient and searching for the place for ablation

it could appear another pulse generator point in the ventricule and cause another re-entry tachycardia. This could be easily checked by simulation of the model but changing automatism properties of a contiguous cell to point B and changing cell B speed properties to zero. The elimination of other cells of the circuit will modify the trajectory but not open the circuit. Therefore, the candidate places for ablation are points A and C. Point A is not a good alternative, because it would interrupt the normal propagation pathway. As a consequence, point C is the best candidate.

Finally, it is convenient to remark that the models used here are very simple and the conclusions obtained are very promising and good from a qualitative point of view. However, more detailed models have to be developed and tested for a precise prediction of arrythmia mechanisms and for the reliable determination of ablation points. Speeds and accuracy in the location will depend on some factors (*i.e.* complexity of the model, software and hardware implementation, other systems involved, etc.).

9 Conclusions

Some deficiencies and lacks in the therapeutic arsenal used for conventional procedures of definitive treatment of patients with cardiac arrhythmias have been detected and exposed here. The essential steps to develop a procedure that carries out a significant contribution to the progress and the qualitative improvement of catheter ablation treatments have been studied and reported. The specific techniques to be used at each of the steps previously mentioned have been described. Also, a tool to be used for the implementation of the procedure, according to our criteria has been selected.

Finally, a simple example of a simulated model of a heart suffering Wolff-Parkinson-White Syndrome (WPW) has been studied using the proposed methodology. Properties as automatism, excitability, conductivity and speed are given to the model. Using this model, some propagation trajectories that validates the behavior of a WPW patient have been obtained and the optimal suggested point to apply the radiofrequency ablation has been computed.

The preliminary results obtained are quite promising, at least from a qualitative point of view, although more detailed models have to be developed and tested for prediction of particular arrhythmia mechanisms and for the consistent determination of ablation points. The validation of all the established hypotheses in this formal proposal strongly depends on the multidisciplinar cooperation between the medical and the engineering teams.

The final goal is to integrate the new procedure in the same computers that are used now for catheter mapping and make interactive use of it during the interventions.

Acknowledgments

We would to acknowledge the medical personnel of the Cardiac Electrophysiology Laboratory of the Clinical Hospital of Valladolid for their unvaluable efforts and collaboration.

References

1. Myerberg, R.J., Kessier, K.M., Kimura, S., Basset, A.L., Cox, M.M., Castellanos, A.: Life-threatening ventricular arrhythmias: The link between epidemiology and pathophysiology. In Zipes and Jalife (eds.): Cardiac electrophysiology. From cell to bedside, W.B. Saunders Company (1995)
2. Rezk, G.: Instrumentación para Electrofisiología Intervensionista. Monografías del XIII Seminario de Ingeniería Biomédica 2004, Facultades de Medicina e Ingeniería, Universidad de la República Oriental del Uruguay, Junio (2004)
3. Singer, I.: Interventional electrophysiology. Willians & Wilkins, (1997)
4. ACC/AHA guidelines for clinical intracardiac electrophysiological and catheter ablation procedures. Circulation **92** (1995) 675–691
5. Berbari, E.J., Landr, P., Geselowitz, D.B., et al.: The methodology of cardiac mapping. In Shenasa M., Borggrefe M., Breithhardt G. (eds): Cardiac mapping, Mount Kisco, New York, Futura Publishing (1993) 11–34.
6. Helguera, M., Pinski, S., de Elizalde, G., Corrado, G., Schargrodsky, H., Bazzino, O.: Ablación por radiofrecuencia de arritmias cardiacas. Servicio de Electrofisiología y Dispositivos Implantables. Departamento de Cardiología. Hospital Italiano de Buenos Aires. Argentina.
7. Latombe, J.C.: Robot motion Planning, Kluwer Academic Publishers (1991)
8. The Scientific and Computing Institute (SCI), SCIRun User Guide, para SCIRun/BioPSE version 1.22.0, University of Utah, www.sci.utah.edu (2004)
9. Freudenberg, J., Schiemann, T., Tiede, U., Hohne, K.H.: Simulation of cardiac excitation patterns in a three-dimensional anatomical heart atlas. Comput. Biol. Med. **30**(4) (2000) 191–205
10. Johnson, C.R., Mohr, M. Rüde, U., Samsonov, A., Zyp, K.: Multilevel methods for bioelectric field inverse problems. In Barth, T.J., Chan, T.F., Haimes, R., (eds.): Lecture Notes in Computational Science and Engineering-Multiscale and Multiresolution Methods: Theory and Applications. Springer-Verlag, Heidelberg (2001) 331–346
11. B. Faverjon and P. Tournassoud: A local based method for path planning of manipulators with a high number of degrees of freedom. IEEE Int. Conf. on Robotics and Automation, pages 1152-1159, 1987.
12. K. Kondo: Motion Planning with Six Degrees of Freedom by Multistrategic Bidirectional Heuristic Free-Space Enumeration. IEEE Transactions on Robotics and Automation, vol. 7, no. 3, 267-277, 1991.
13. Kavraki, L., Svestka, P., Latombe, J.-C., Overmars, M.H.,: Probabilistic roadmaps for path planning in high-dimensional configuration spaces. IEEE Trans. Rob. Autom. **12** (1996) 566-580
14. Berg, J.P.v.d., Overmars, M.H.: Roadmap-based motion planning in dynamic environments. Institute of information and computing sciences, Utrecht University, Technical Report UU-CS-2004-020, www.cs.uu.nl (2004)