Flow Visualization for Bioelectric Activity in Human Body

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Abstract. Standard techniques used to visualize the human bioelectric activity are typically restricted to depictions of scalar potentials or activation times. Hence they offer no explicit representation of the geometry of the current. We show in this paper that advanced flow visualization techniques can be successfully applied to this type of data. Applications to cardiovascular research and source reconstruction in the brain are presented that demonstrate the potential of this approach to yield new insight into biomedical data sets.

1 Introduction

Electric potentials and currents enable vital functions of the human body. This bioelectric activity permits the transmission of information in nerves, the storage of metabolic energy in cells, and the contraction of muscles. From a clinical viewpoint, the measure of the resulting signals is of major significance in biomedicine because of the existence of non-invasive techniques that have become standard tools in diagnostics. The best known examples are *electrocardiography (ECG)* that is used to monitor the heart and to detect abnormal activity and *electroencephalography (EEG)* which records bioelectric waves resulting from the brain activity and is used to assess brain damages as well as diseases.

These two examples illustrate the major importance of a precise understanding of the patterns of this bioelectric activity and their relationship with physiological mechanisms. In particular, an in-depth knowledge is needed to fully leverage the information provided by non-invasive monitoring tools in order to identify pathological symptoms and be able to start the appropriate therapy at an early stage of a disease. However, in many cases diagnoses are still non-specific, even in situations where patients face very severe conditions.

The significance of this problem explains the large research effort in electrophysiology. Combining the study of physical experiments with numerical simulations scientists strive for deeper insight into the link between physiological mechanisms and bioelectric activity. With the refinement of measuring techniques and the increasing size and complexity of numerical models used to reproduce these phenomena, researchers are faced with a growing amount of data that must be evaluated and interpreted. The analysis of this data requires

powerful visualization tools, capable of extracting essential properties and show their interrelation. However, standard practice restricts the visual representation to scalar attributes like e.g. bioelectric potentials or activation times. As a direct consequence of this approach the geometric information contained in the vector-valued attributes present in those data sets, most prominently the bioelectric current flow, is essentially neglected during the visual analysis of the data, which deprives the scientists from a very important source of insight into complex bioelectric phenomena.

Given the traditional importance of vector visualization in Scientific Visualization research, it is therefore remarkable to observe that, for the most part, none of the corresponding techniques, especially the most advanced ones, has been integrated in the set of tools used for the post-processing analysis of bioelectric data sets. Several reasons can be named to explain this deficit. First and most obviously, vector visualization research has been historically focused on applications related to fluid dynamics in general, and aeronautics and aerodynamics in particular. Hence, techniques have been developed, for instance feature extraction schemes, whose relevance is limited to this type of application. A second reason is the intuition that biomedical practitioners have developed over the years based on depictions of their data made of color plots and isocontours. This mode of representation has become the de facto standard to present, explain, and compare results. As a consequence, the vector-valued information has always been, implicitly or explicitly assumed to convey little additional insight.

The goal of the present paper is both to advocate and demonstrate the practical use of flow visualization for the exploration and interpretation of complex bioelectric phenomena. The results presented in the following stem from several ongoing collaborations with biomedical researchers. They document the benefits of advanced vector visualization techniques for their particular applications. Beyond that, these results also underscore the potential of this approach for the study of bioelectricity throughout the human body.

The paper is organized as follows. The experimental and computational means used to acquire numerical data of the bioelectric activity are introduced in section 2, along with the data sets used in this work. Section 3 offers an overview of the visualization techniques commonly used in the day to day practice of electrophysiology researchers to interact with their data. Section 4 describes advanced flow visualization techniques that have proven useful in the context of electrophysiology and demonstrates their application to numerical data sets related to ongoing research in cardiovascular diseases and source reconstruction in the brain. Finally, we comment on lessons learned, as well as challenges and promising avenues for future work in section 5.

2 Data Acquisition

The data available to electrophysiologists comes from measurements and numerical simulations. In the following we briefly describe the main sources of numerical

data in electrophysiology before introducing in more details the data sets that were used in the work presented in section 4.

2.1 Non-invasive Measurement Techniques

Non-invasive measurement techniques are essential in clinical practice. *Electrocardiography* (ECG) monitors cardiac activity by recording the evolution of the electric potential on the chest induced by successive excitation and repolarization waves occurring in heart. At a cellular level, depolarization and repolarization are linked to a phenomenon called *action potential* under which the varying permeability of the cell membrane entails a rapid increase of the cell potential (excitation or depolarization) that is followed by a decrease back to its original value (repolarization or recovery). The corresponding impulse propagates along muscular bundles, generating waves that are responsible for the electric signals measured on the body surface. ECG is used to detect cardiac arrhythmia (e.g. a skipped heart beat). It is also used in the diagnosis of ischemia, a condition corresponding to a shortfall of the blood supply of the heart which reduces its pump function and can eventually lead to a heart attack. Similarly, the activity of the brain can be monitored through *Electroencephalography* (EEG), which records brain waves through the resulting variations of the electric potential on the scalp. In this case the electric signal is much weaker than the one produced by the heart and individual action potentials cannot be detected. Instead EEG measures the signal that arises form the synchronized bioelectric activity of a large number of neurons. This signal exhibits patterns of different frequencies that are related to different mental activities as well as pathologies. The latter includes *epilepsy* and *Alzheimer's disease* among others.

2.2 Numerical Simulation of Bioelectric Activity

On the computational side a precise anatomical modeling combined with the use of realistic values for the conductivity of individual anatomical structures can be used to simulate bioelectric activity. Two types of computation exist. The forward problem consists in solving for the potential on the body surface when bioelectric sources are known. On the opposite, inverse problems correspond to the localization of the source for which the boundary signal is known. Inverse problems are typically ill-posed and assumptions regarding the source model, the approximate location of the sources, and their number have to be made to obtain a unique solution. Source reconstruction by solution of an inverse problem is a prominent goal of the non-invasive techniques mentioned previously. Observe that the solution of the forward problem is instrumental in the solution of the corresponding inverse problem. The forward problem is typically solved numerically using either the Finite Element Method (FEM), the Finite Volume Method, or the Boundary Element Method.

2.3 Numerical Data Sets

In the following we apply several flow visualization techniques to numerical data sets related to cardiovascular and brain research.

The first data set corresponds to a forward FEM computation of the potential and current density distribution over a torso. The motivation of this computation is the study of ischemia. The FEM method is chosen for the flexibility it provides in the choice of the torso geometry (of which the heart surface, the epicardium, constitutes an internal boundary) and the distribution of tissue conductivity. The source information for the forward problem on the epicardium stems from invasive experimental measurements carried out at the Cardiovascular Research and Training Institute at the University of Utah. The elements used are linear tetrahedra. The resulting current density is piecewise constant over the mesh and an averaging over the control volume of each node combined with piecewise linear interpolation yields the projected value of this field in a C^0 space.

The second data set is related to brain research and more specifically to EEG source localization. The motivation of the research is to investigate the incidence of a proper modeling of white matter conductivity anisotropy on the solution of the forward problem and, by extension, on the accuracy of the solution of the inverse problem. Practically, the forward problem is solved over a high-resolution FEM mesh. The modeling of tissue conductivity is based on a segmentation that comprises skin, skull, cerebrospinal fluid (CSF), gray matter, and white matter. Different computations were carried out for different positions of a dipole source. The white matter conductivity was also modeled as anisotropic in some computations and compared to the solution of the forward problem using the approximation of isotropic conductivity.

3 Standard Visualization for Electrophysiological Data

As pointed out in the introduction, the visualization techniques commonly used to represent and analyze bioelectricity data sets are for the most part concerned with scalar quantities, typically bioelectric potentials and time intervals between two consecutive waves of an activation potential. In this section, we provide some sample illustrations of such widely used scalar representations and show some examples of methods used by biomedical researchers to depict vector-valued data.

Color coding is by far the most popular visualization technique in electrophysiology. It is applied either to a curved geometry or to cutting planes slicing the data volume and is often combined with isocontouring to allow for a more effective understanding of quantitative aspects. An example is shown on the left in Fig. 1 corresponding to experimental measurements of the electric potential in a torso. This visualization was generated by Map3D [6].

The middle image in Fig. 1 exemplifies the use of glyphs to represent the bioelectric current. A similar use of glyphs can be seen on the right, where color coding depicts the magnitude of the return current in a coronal section of the brain, while segments show its orientation.

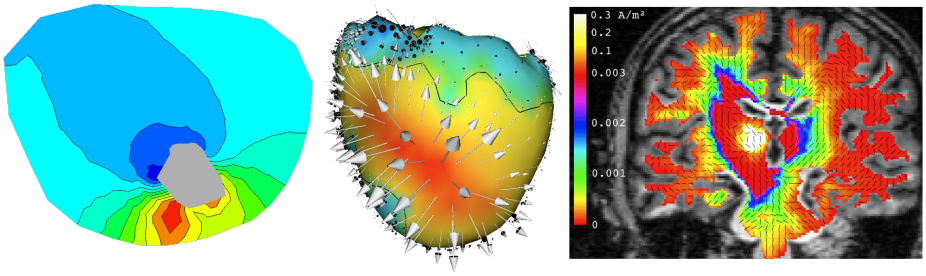

Fig. 1. Visualization of bioelectric potential. **Left.** Color plot of electric potential on cross section of the torso. Discrete colors and isocontours are used to simplify quantitative interpretation. **Middle.** Color plot of electric flux through epicardium combined with glyph representation of the current. **Right.** Color plot of return current density on a coronal slice. The data corresponds to a dipolar source located in the thalamus. Line segments indicate current direction. The results correspond to a model of white matter compartment with anisotropic conductivity (from Wolters et al. [14])

Beyond the visualization of the current as a combination of color map and discrete glyph representation, streamlines are also used to show the geometry of the current field lines. In that case, the conflicting goals consist in computing many streamlines to obtain a dense depiction of the geometry of the three-dimensional current, while having to limit that number of streamlines to avoid clutter and occlusion. Some illustrations generated by SCIRun/BioPSE are shown in Fig. 2.

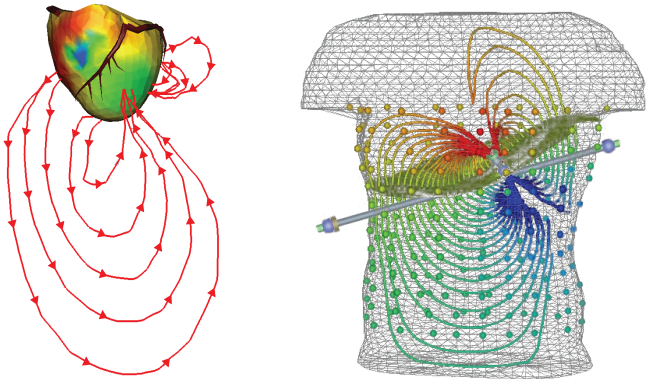

Fig. 2. Streamlines of the bioelectric current in the torso by Finite Element forward computation. The left image shows a color coding of the electric potential on the epicardium. The right image shows a rack for regular streamline seeding as well as a color coding of the bioelectric potential on the streamlines.

4 Flow Visualization Techniques

Different flow visualization techniques can be applied to represent the bioelectric current. Section 3 showed examples of glyphs on surfaces and streamlines used to elucidate the interconnections between different regions of the epicardial surface along the current flow. In this section, we consider more advanced flow visualization methods from the viewpoint of their applicability to numerical bioelectrical data.

4.1 Texture Representation

Texture representations can be seen as the natural vector counterpart of the color plots of scalar potentials. As a matter of fact this technique is best suited for the visualization of the flow defined over a surface. Practically, we apply in this work Line Integral Convolution [2] (LIC), combined with the visual enhancements proposed in [7]. Wenn dealing with curved surfaces without explicit parameterization several options are available, including image-based methods [4]. Here however, we substitute to the texture a high-resolution triangulation obtained by subdivision over which a piecewise constant vector field is defined. This prevents the problems caused by the discontinuity of the tangent plane and allows for a very fast computation [13].

An important property of bioelectric fields is the Neumann boundary condition which imposes that the current be tangent to the boundary of the domain. In particular, the current is tangential to the outer boundary of the chest and to the scalp. An example is shown in the left image of Fig. 3. Yet, in cardiovascular data sets, the epicardial surface is crossed by the current originating at sources contained in the cardiac tissue. For that reason, the visualization of the restriction of the current to the heart surface by means of textures requires to first project it onto the corresponding geometry.

As in the case of color plots, an obvious way to address the occlusion problems encountered when applying LIC to volume data is to restrict the representation to a cutting plane. Typically, the choice of this plane will be made based on the symmetry of the geometry and on the known position of a bioelectric source. However, a single plane is often unable to convey an informative picture of the three-dimensional current structure. This is especially true in the case where the conductivity of the tissue is anisotropic which breaks the symmetry of the current flow patterns and accentuate their geometric complexity. Two simple solutions were used to address this limitation.

The first one consists in displaying two or more such planes in combination and using transparency to allow the user to see the spatial relationship between the patterns exhibited by each texture. An example is shown in the right image of Fig. 3. The second solution consists in generating an animation corresponding to the evolution of the LIC representation associated with the motion (e.g., rotation around a symmetry axis) of a single cutting plane across the flow volume. Several techniques exist in the visualization literature that produce an animated texture representation of an unsteady flow [5]. One of the key ingredients of those

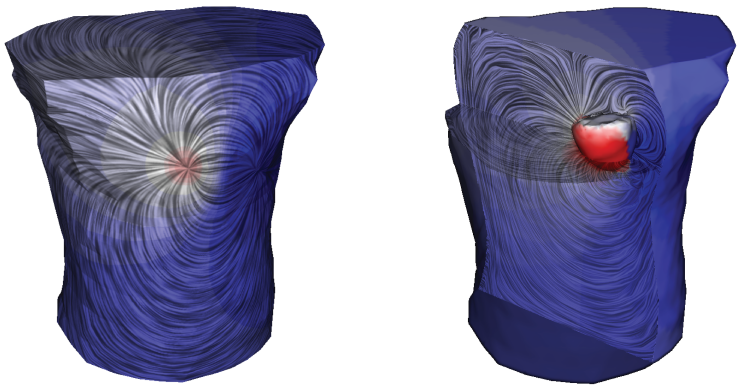

Fig. 3. Left. LIC representation of the current on the boundary of a Finite Element grid used in forward computation. The color coded electric potential (negative values in blue, positive values in red) are superimposed on the texture. **Right.** Two LIC textures computed over cutting planes combined by transparency. The geometry of the heart remains opaque for context.

methods is the use of flow integration along pathlines to obtain frame-to-frame coherency of the resulting animation. In our case, the vector field obtained by the projection of the bioelectric current onto a plane with varying orientation can be seen as a parameter-dependent flow, as well. The premise of this approach is that variations of the projected vector field are going to be small between consecutive orientations of the cutting plane, by continuity of the three-dimensional vector field. However, the essential difference with a real time-dependent vector field lies in the fact that the notion of pathline does not apply in our context: the values of the projected vector field which change as the cutting plane is being moved through the volume do not describe the trajectory of a current field line in 3-space. Therefore we have to resort to an alternative approach to ensure frame-to-frame coherency. The solution used is in fact inspired by UFLIC [12]. In this method, the coherency between frames is achieved essentially by recycling the output texture of one frame to be used as input texture for the computation of the next frame. Then, at each frame, the color attributes inherited from the previous frame are advected and deposited along the flow defined by the values of the vector field associated with the current time coordinate. Observe that in a post-processing stage the output texture corresponding to the deposited and pixel-wise averaged attributes is enhanced by a combination of high-pass filtering and combination with jittered noise [12]. In our setting, we use the same basic principle.

4.2 Topology on Boundary Surfaces

The second flow visualization technique that we consider here is topology extraction [10]. This technique proves primarily interesting in the visualization of the

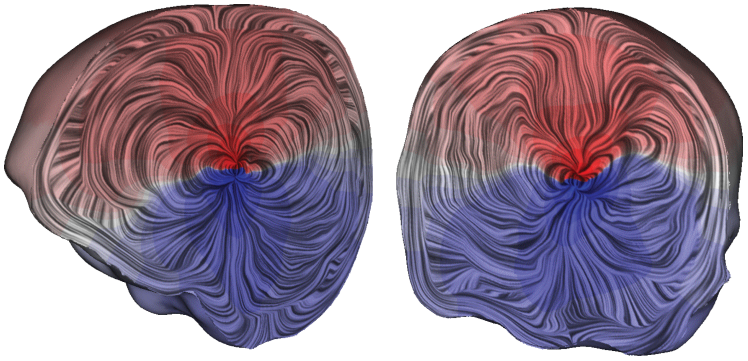

Fig. 4. LIC applied to coronal-sagital and coronal clipping planes reveals details of the dipolar source and its interaction with the surrounding anisotropic tissue. Rather than a typical smooth, symmetric dipolar pattern, the electric current is clearly diverted by the presence of white matter tracts that lie close to the source. The field also changes direction very rapidly as it ap- proaches the skull just beneath the surface of the head.

bioelectric current on the epicardial surface. In this case, the topological features visualized by this method are believed to correspond to what is known in cardiac electrophysiology as epicardial breakthroughs. This phenomenon occurs when an activation wave in the cardiac tissue breaks through the surface, generating a local potential minimum in the epicardial surface. Since the epicardial surface is a curved polygonal geometry, the integration of the separatrices was done using the technique proposed by Polthier and Schmies [9]. Refer to Fig. 5.

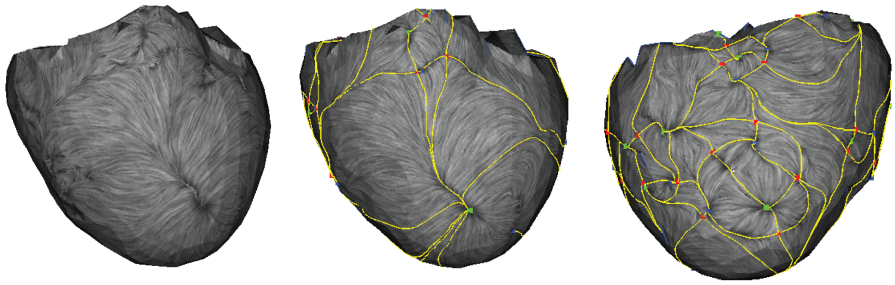

Fig. 5. Topology of bioelectric field on epicardium. The images show a LIC representation of the potential gradient on the surface enhanced by the depiction of the associated topological graph. Green points correspond to potential minima, blue points mark potentials maxima. Left and middle images show an anterior view of the epicardium. Right image is seen from the left of the torso.

The usability of three-dimensional topology for the characterization of salient patterns of the bioelectric current turns out to be fairly limited. The explanation comes from the structure of a bioelectric field. As a matter of fact, bioelectric sources typically behave as dipoles. These dipoles generate a current that flows through the conductive medium (e.g., torso or brain) where it remains before returning to the dipole. It follows that 3D saddle points are absent from this topological picture. Therefore, a flow volume segmentation based on the separating surfaces emanating from them does not apply here.

4.3 Stream Surfaces

The intuitive representations offered by stream surfaces make them a very valuable tool in the exploration of the three-dimensional bioelectric current flow. To obtain surfaces of high visual quality, we use the algorithm proposed by Garth et al. [3]. The major difficulty with stream surfaces however lies in the tedious selection of a proper seeding curve in order to capture interesting structural properties of the flow with the resulting surface. Three-dimensional topology, in particular the surface separatrices originating at saddle points, provide objective seeding strategies. Yet, as mentioned previously, topology is not directly suitable for that class of problems. As an alternative, flow structures can be defined in terms of the interconnections between zones of inflow and outflow on a surface enclosing sources and sinks. We have applied this solution and used isocontours of either the electric potential or electric flux as seed curves. An example is shown in Fig. 6, where seeding curves are defined on the epicardium.

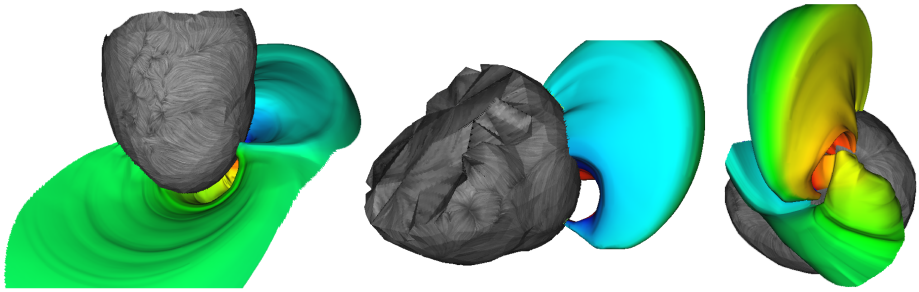

Fig. 6. Visualization of bioelectric field in the direct vicinity of epicardium with stream surfaces. The surfaces capture the geometry of the current induced by the dipole equivalent cardiac source. They also provide an effective representation of the interconnections that exist between different regions on the heart surface. The seeding curves correspond to isocontours of the electric potential selected close to local extrema. A rainbow color map is used along each seeding curve to visualize flow stretching.

For the brain data set no such obvious surface exists that encloses an isolated source in the white matter. Therefore one of the solutions used consists in

introducing an artifial sphere surface surrounding the source. This is shown in left image of Fig. 7. As previously, culling can be used to address the occlusion caused by the intricate shape of the stream surface.

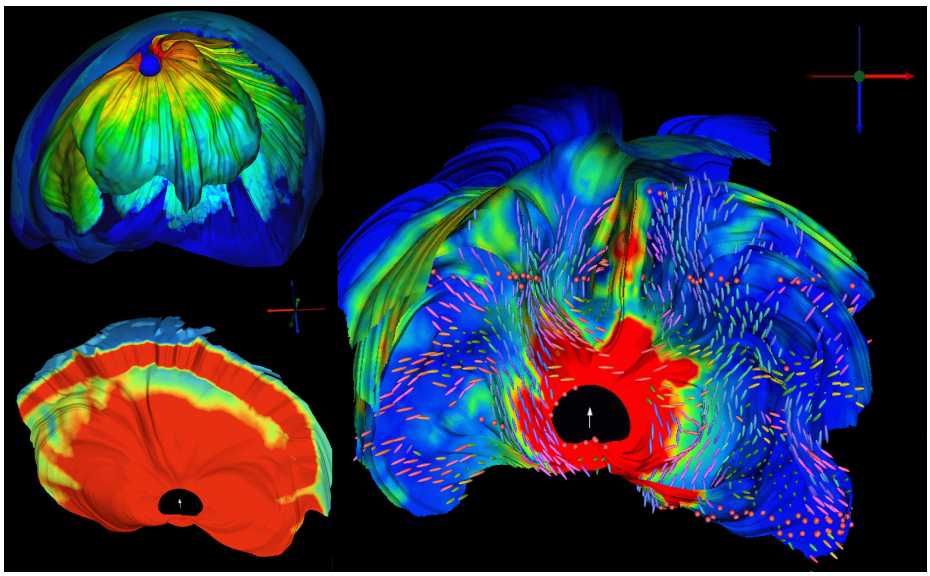

Fig. 7. Stream surface isualization of bioelectric field induced by a dipolar source in left thalamus. **Left top.** Stream surfaces seeded along isocontour of electric flux on sphere enclosing the source. Culling is used to address occlusion. White matter has anisotropic conductivity. **Left bottom.** Stream surface started along circle contained in coronal slice and centered around source location. White matter is assumed isotropic. Color coding corresponds to magnitude of electric field. **Right.** Similar image obtained for anisotropic white matter. Glyphs visualize major eigenvector of conductivity tensor. Color coding shows magnitude of return current.

Another solution consists in exploring the dependency of stream surfaces on the parameterization of their seeding curves. The corresponding evolution can then be visualized as an animation. We have used this technique to allow for a better understanding of the three-dimensional structure of the return current in the brain. Specifically, a circle of increasing radius centered around the dipolar source and lying in the horizontal plane orthogonal to the dipole axis can be used as a parameterized seeding curve. An analysis of the differences between isotropic and anisotropic conductivity of the white matter can then be made in a side by side comparison of the corresponding animations. This method is illustrated in Fig. 8.

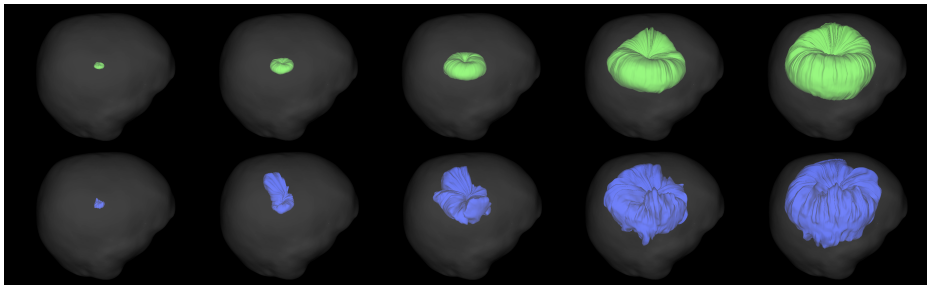

Fig. 8. Evolution of a stream surface integrated along the current under the increasing radius of its seeding circle. **Top row.** Frames from an animation corresponding to isotropic white matter. **Bottom row.** Frames of the animation obtained for anisotropic white matter.

5 Discussion

The work described in this paper was motivated by the virtual lack of satisfying visual representation for the vector-valued information contained in numerical data sets of bioelectric activity in the human body. We showed how the visualization techniques used in this context are typically restricted to representations of the electric potential on boundary surfaces or cutting planes. The idea that we followed consist in addressing this deficit by deploying in the electrophysiological setting several flow visualization techniques originally developed for application to fluid flow problems. The potential benefits of this approach were investigated for two biomedical problems corresponding to cardiovascular and brain research.

Originally, the goal was to offer to our biomedical collaborators alternative visualizations of their data that would prove more expressive. However, the experience gained through this work shows that, beyond the appealing images that they produce, flow visualization techniques have a great potential in providing deeper insight into the complex three-dimensional structures created by bioelectric sources and their fields. One significant example is the ability of stream surfaces and texture representations to provide a new understanding of the impact of tissue characteristics, e.g. anisotropy, on the resulting bioelectric field. Another example is the use of flow topology as a means to offer an objective and accurate characterization of the connections between different regions of the epicardium along the current, with direct applications in the study of ischemia.

Our work so far opens several avenues for future research. The first one concerns the occlusion problems induced by the typical complexity of bioelectric currents and their dipolar patterns. We have described several options for texture and stream surface representations but new solutions are needed that fully match the intuition of biomedical researchers in the exploration of their own data. Another open problem is the effective seeding of stream surfaces. We have found stream surfaces to provide depictions that our collaborators deemed expressive and insightful. Yet, the choice of a proper seeding curve remains challenging.

One way to solve this problem may lie in the extraction of features of interest in the context of a specific electrophysiological problem. The identification of such features will only be possible in close collaboration with biomedical experts. Finally, a precise assessment of the uncertainty introduced by the visualization processing will be required to evaluate the reliability of the corresponding results and eventually integrate them into clinical practice.

Acknowledgments

We would like to thank Bruno Taccardi, Frank Sachse, and Rob MacLeod from CVRTI at the University of Utah, as well as Carsten Wolters, University of Muenster, Germany for their close collaboration, fruitful discussions and for providing the data sets that were used in the examples shown in the paper.

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