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The Effect of Fiber Orientation on Volume Measurement using Conductance Catheter Techniques

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Abstract—**Estimation of parallel conductance using the impedance electrode technique is usually done assuming isotropic conditions. This may not be the best solution since the myocardium is an anisotropic material. This paper exposes the effect of fiber orientation for volume measurement using a conductor model with asymmetrical source electrodes. Simulation results show calculated volumes between surrounding materials with and without myocardial fiber orientation included in the model. We plan to extend these study results to the real heart for developing conductance catheter techniques for use in blood volume measurements in the right ventricle.**

I. Introduction

We have previously used analytical and numerical techniques to investigate the electric field distribution in a uniform conductor and asymmetrical source/sink electrodes using both single and dual-excitation techniques [1, 2]. Traditional segmental intra-ventricular volume calculation methods [3] can suffer from inaccuracy in the calculated volume arising from irregularity in ventricular geometry, non-uniformity in the applied electric fields and parallel conductance. Previous workers have estimated parallel conductance in ventricular volume measurement using techniques involving methods such as hypertonic saline technique [4], multi-frequency conductance [5], and dynamic finite elements [6]. However, anisotropic conductance from myocardial fiber orientation is generally ignored in these methods. Here we explore the effect of myocardial fiber orientation on parallel conductance measurements using the conductance catheter technique.

II. Methodology

We used a simplified long conductor model of square cross section with and without fiber orientation on the wall (Fig. 1) to investigate our problem. Source and sink electrodes were placed at asymmetrical positions corresponding to those used in the right ventricle (Fig. 2). Segmental volumes were determined from the measurement electrode configuration using standard segmental methods [1]. Calculated volume results were compared with the known exact volume of the conductor model for three different configurations: inner isotropic conductor alone (representing right ventricular blood), inner conductor plus outer isotropic "myocardial" region, and inner conductor plus outer anisotropic "myocardial" region.

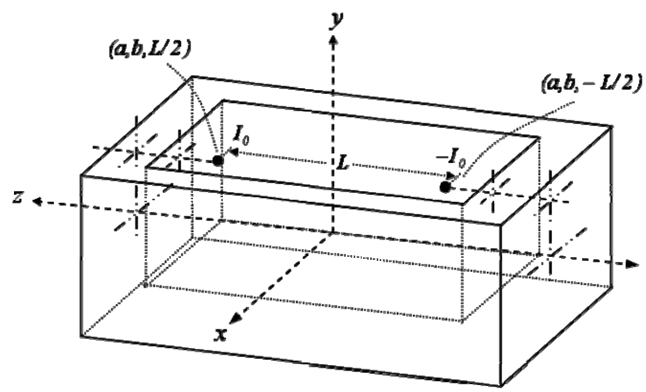

Fig. 1 The long conductor model of square cross section.

A. Modelling electrical properties of the myocardium

The myocardium was modeled as an anisotropic material with longitudinal and transverse fiber orientations aligned with the real fiber orientation of the heart. Real fiber orientation was taken from the canine heart [7]. We employed an effective conductivity of 0.21 S/m in the longitudinal direction (aligned with the fibers) and 0.06 S/m in the transverse direction [8]. A numerical solution using the Finite Element method was employed to solve our problem. The method involved using solid tetrahedral finite elements with anisotropic conductivity vectors corresponding to the myocardial fiber directions. Three fiber orientation vectors (Fig. 3.) were used to create an element with defined electric resistivity along each axis, and interpolated electric resistivity within the space between them.

B. Numerical Solution to the Potential Field

The long conductor of square cross section was configured with an asymmetric current source and sink (Fig. 3). The potential field distribution was determined using the Finite Element method with ANSYS multiphysics software (ANSYS, Inc., Canonsburg, USA). The 3D brick shaped function was selected to solve the problem. The electrode source and sink configuration consisted of applied currents on specified nodes. To investigate our problem, we firstly constructed an inner conductor volume alone which is an

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analogy to the right ventricular chamber and then added an outer block without fiber orientation data as surrounding tissue (isotropic material). Lastly, for the anisotropic problem, we replaced the anisotropic outer block with anisotropic elements representing myocardial fibers by mapping coordinates between canine heart geometry and the model of the outer conductor (Fig. 6).

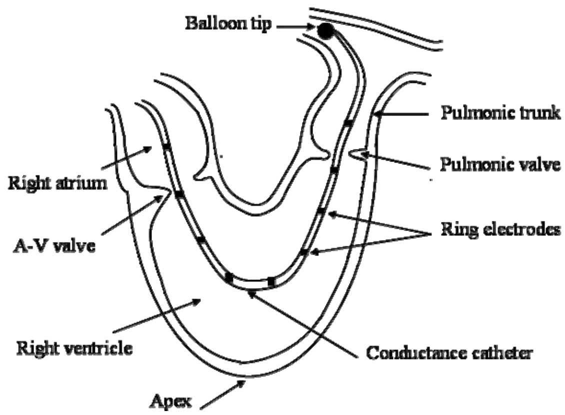

Fig. 2. Conductance catheter in the right ventricle

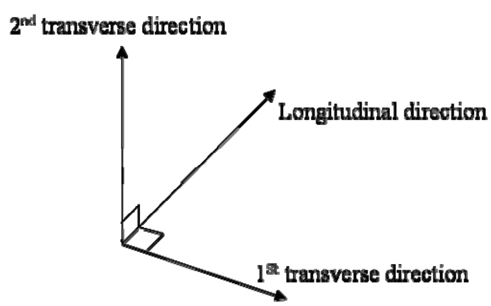

Fig. 3. The element model of fiber vector

The bipolar current magnitude was ± 500 μ A [1], and inner conductor conductivity was 0.67 S/m [6]. The outer conductor isotropic conductivity was 0.67 S/m. The sink and source current were the same at $x = a = 0$, $y = b = 30$ but different at z = -70, and 70, respectively. I_0 = source/sink current magnitude (electrode current).

C. Configuration of the model

The inner conductor geometry is defined from $-35 \leq x \leq 35$, $-35 \leq y \leq 50$, and $-110 \leq z \leq 110$ mm. For the outer conductor, the geometry is defined from $-50 \leq x \leq 50$, $-50 \leq y \leq 50$, and $-125 \leq z \leq 125$ mm. The problem was configured with $L = 140$ mm.

D. Measurement Electrodes

Six measurement electrodes (5 segments) were located at $x = y = 0$ and parallel to the z-axis with 20 mm intervals. Distal measurement electrodes were at z = $\pm$ 50 mm.

III. Results

The contour plot of electric potential field within the inner block without any surrounding materials is shown in Fig. 4. The electric potential field distribution after adding isotropic surrounding material (outer block) is plotted in Fig. 5. Mapping myocardial fibers of the canine heart into the outer conductor of the regular model is shown in Fig. 6. The electric potential field distribution for the anisotropic problem is shown in Fig. 7.

The numerical result for the electric potential at the measurement electrodes is in table I, and the results of conductance volume and leakage volume (parallel conductance) are in table II and III, respectively. The true total volume within the region was 595 μm^3 .

The model of canine heart with fiber orientation is shown in Fig. 8.

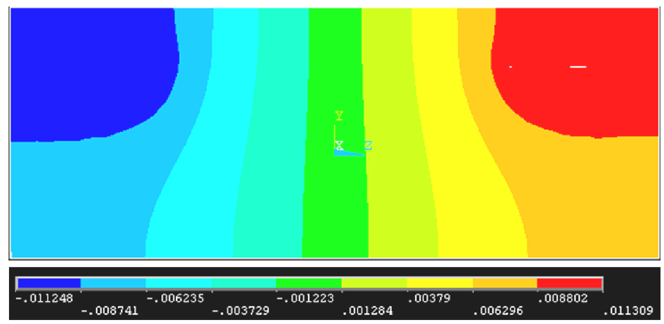

Fig. 4. Electric potential field distribution within the inner block without any surrounding materials

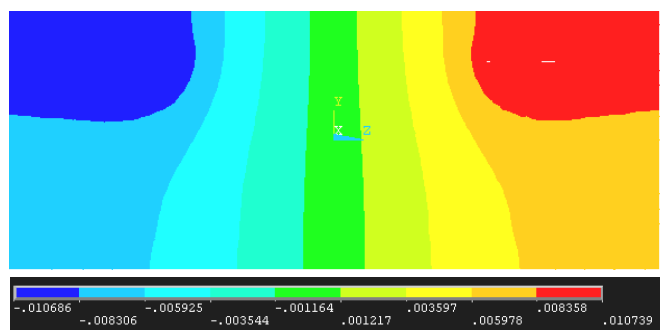

Fig. 5. Electric potential field distribution in the case of isotropic surrounding material.

IV. Discussion

The results presented in Figs. 4, 6, and 7 show the electric potential of a bipolar current was a non-uniform field that became more uniform with distance from the exciting electrodes. The magnitude of the electric potential gradient was very high near both exciting electrodes and decreased gradually until it was relatively constant at the middle of the conductor. However, the position of the measurement electrodes were not along the line joining both exciting electrodes. As a result, calculated volumes may not vary significantly with distance from the exciting electrodes.

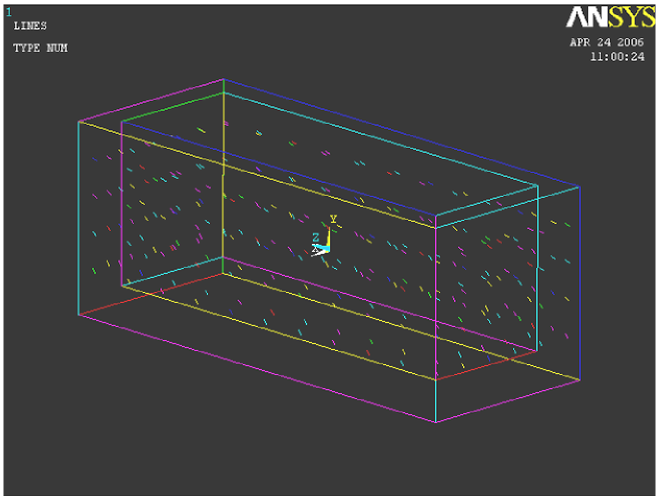

Fig. 6. The regular model with anisotropic conductivity in outer conductor (“mapped” from canine myocardial fiber orientation)

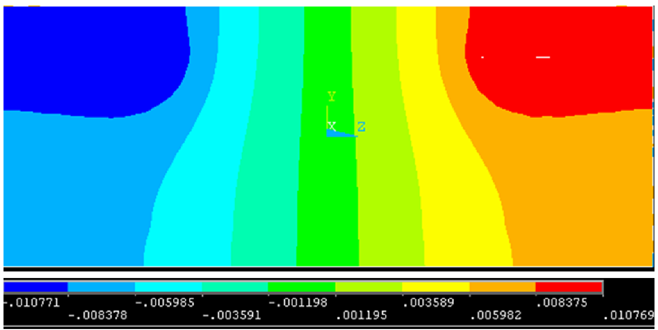

Fig. 7. Electric potential field distribution for the case of anisotropic surrounding material.

TABLE I.
ELECTRIC POTENTIALS AT MEASUREMENT ELECTRODES (*mV.*)

Electrode	Inner conductor alone (“blood”)	Isotropic outer “myocardium”	Anisotropic “myocardium”
1	-5.9700	-5.5767	-5.6361
2	-3.6444	-3.3952	-3.4416
3	-1.2216	-1.1364	-1.1529
4	1.2207	1.1357	1.1522
5	3.6435	3.3944	3.4410
6	5.9691	5.5759	5.6375

TABLE II.
CONDUCTANCE VOLUMES (μm^3) ARE CALCULATED WITH VARYING KINDS OF MATERIAL. TRUE TOTAL VOLUME IS 595 μm^3 .

Segments	Inner conductor alone	Isotropic “myocardium”	Anisotropic “myocardium”
1	128.99	137.52	136.70
2	123.82	132.81	131.07
3	122.83	132.04	130.14
4	123.82	132.82	131.07
5	128.99	137.52	136.58
Summation	628.48	672.71	665.58

TABLE III.
PARALLEL CONDUCTANCE VOLUMES (μm^3) ARE CALCULATED WITH VARYING KINDS OF MATERIAL.

Segments	Isotropic “myocardium”	Anisotropic myocardium”
1	8.52	7.69
2	8.99	7.25
3	9.20	7.31
4	8.99	7.24
5	8.52	7.58
Summation	44.23	37.11

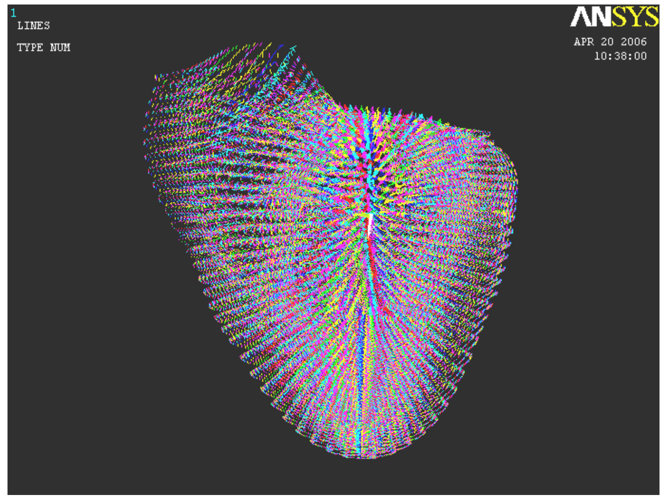

Fig. 8. The model of canine heart with fiber orientation (data from [7])

When the inner conductor was surrounded by isotropic material, electric potential field changed (Fig. 5) due to be electric current leakage out from inner conductor to outer conductor. When the surrounding materials were changed from isotropic to anisotropic, the electric potential field was also different, although not distinctly so (Table I). Leakage current preferentially flowed along fiber directions, limiting current flow more to the inner region (Fig. 6). In the isotropic problem, leakage current can penetrate the wall of surrounding tissue more easily than in the anisotropic problem. In our regular model, the volume of surrounding tissue (outer conductor) is quite small. This may be a reason why we could not see a large difference in calculated parallel volume (Table II, III). Also, the block geometry used is not realistically shaped, and this may be another reason for not getting so significantly different results between the isotropic and anisotropic problem (Fig. 8).

In general, the electric potential distribution was slightly different, corresponding to surrounding material properties.

V. CONCLUSION

The simulation results showed that the electric potential distribution was different when the surrounding material was isotropic and anisotropic. Calculated volumes were not greatly different between isotropic and anisotropic materials. Future work will involve using realistically shaped geometries with fiber orientation in a numerical model (Fig. 8), corresponding to use of a conductance catheter in the right ventricle. We hope to use this model to investigate the effect of fiber orientation with parallel conductance when using the conductance catheter technique, for the purpose of achieving more accurate measurements of blood volume within the right ventricle.

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