Modeling and in vitro Measurement of the Electric Field of Selective Esophageal Pacing Lead

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Abstract

The advantage of selective esophageal pacing lead over standard esophageal pacing leads is that it produces the electric field that is not axially symmetric, but directed towards the targeted tissue. In order to evaluate that property of the selective esophageal pacing lead, we made a 3D finite element model of the lead in tissue and calculated the electric field for different configurations of the lead i.e. for different interelectrode distances and different electrode angles. We also performed *in vitro* measurements with the lead immersed in saline bath. Both the numerical calculations and the *in vitro* measurements showed that parameters that define the selectivity of the lead (the field rejection ratio and the directivity angle) have better values (higher field rejection ratio, smaller directivity angle) for smaller central angles. For electrodes with larger central angles, the directivity angle is generally larger meaning that the electric field is less directed. With increasing the interelectrode distance the field rejection ratio decreases and the intensity of electric field in the transversal midplane between electrodes steeply falls. The results of modeling and *in vitro* measurement of the electric field of our selective esophageal pacing lead indicate that efficient pacing can be obtained with considerably reduced side effects.

Introduction

Cardiac pacing with the lead introduced through the mouth or nose in the esophagus is known as transesophageal pacing. It is a method of choice in many situations when temporary cardiac pacing or suppression of supraventricular arrhythmia is required [1, 2]. It is also widely used for studies in cardiac electrophysiology [3].

Standard esophageal pacing leads produce axially symmetric electric field and stimulate not only the targeted area of the heart muscle but the surrounding tissues as well, causing unwanted side effects. Since the esophageal pacing threshold depends on the relative position of the lead and the myocardium, a way to reduce the side effects and to improve the reliability of esophageal pacing is to direct the electric field towards the heart [4]. We introduced a new type of esophageal lead, a selective esophageal pacing lead, suitable for both the recording of esophageal ECG and pacing of either atria or ventricles, Figure 1 [5].

The selective lead consists of the mechanical part with built-in angular electrodes and of the electronic circuits that enable its proper functioning. Producing of an electric field oriented into the desired direction towards the heart is achieved by suitable electrode geometry. Each electrode of the selective lead consists of three, electrically insulated, conductive cylindrical shells – angular electrodes. Our selective esophageal lead has an even number of angular electrodes set at different interelectrode spacings.

In order to evaluate the selective properties of the lead, we made a 3D finite element model of the lead in tissue and calculated the electric field and current density distributions for different configurations of the lead i.e. for different interelectrode distance and different central angle of the electrode. We also performed *in vitro* measurements of lead's electric field in a tank filled with physiological saline.

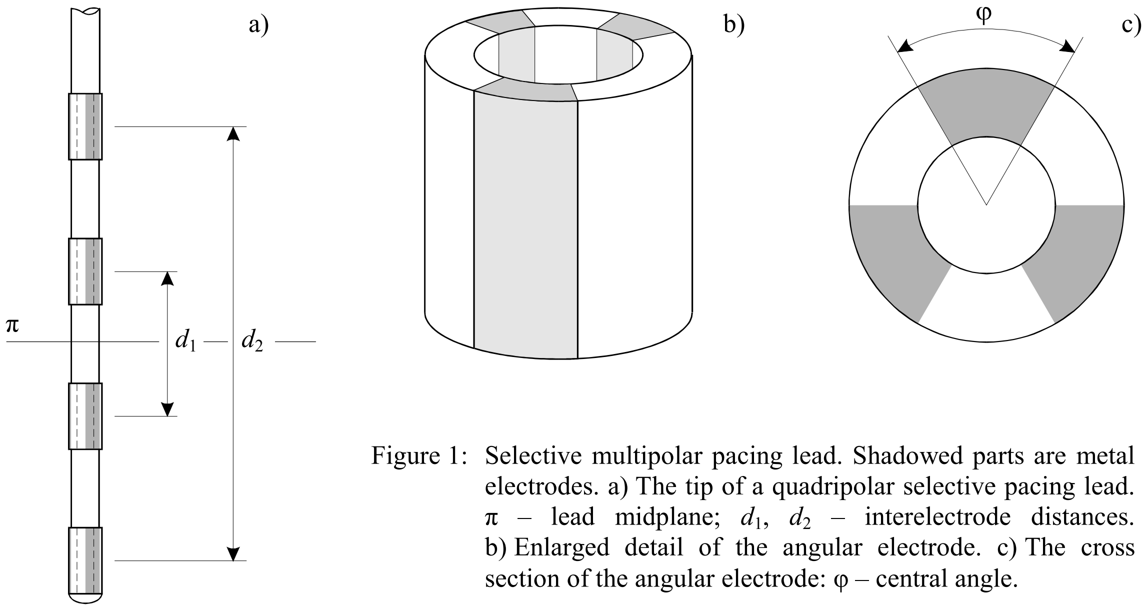

Figure 1: Selective multipolar pacing lead. Shadowed parts are metal electrodes. a) The tip of a quadripolar selective pacing lead. π – lead midplane; d_1, d_2 – interelectrode distances. b) Enlarged detail of the angular electrode. c) The cross section of the angular electrode: φ – central angle.

Methods

Electric field distribution in tissue having the conductivity distribution σ can be obtained by solving the Laplace's equation for scalar electric potential u

$$\nabla(\sigma\nabla u) = 0$$

with appropriate boundary conditions. Electric field **E** and current density **J** in tissue as a result of pacing with the selective esophageal lead were obtained by solving the Laplace's equation in three dimensions using finite element method (FEM) and taking into account the well known relations:

$$\mathbf{E} = -\nabla u \qquad \mathbf{J} = \sigma\mathbf{E}\,.$$

In our FEM model, tissue was assumed to be homogenous and isotropic volume conductor. Dirichlet boundary conditions (fixed values of electric potential) were applied to the electrodes, and Neumann boundary conditions to other boundaries. In order to evaluate the directivity of the lead, the electric field of electrodes with different central angles (20^o, 40^o, 60^o) placed on an esophageal lead at different interelectrode distances (4 cm, 6 cm, 8 cm) were modeled. Nonuniform mesh (elements of the mesh were smaller near the lead and coarser at the surface) was constructed to obtain acceptable solution accuracy in reasonable time.

For *in vitro* measurements, we developed an experimental setup comprised of a lead under test immersed in a physiological saline bath, a custom designed esophageal pacemaker, a probe lead (measuring probe), a current probe (Tektronix AM503) and a differential amplifier (Tektronix AM502) both connected to a storage oscilloscope (Tektronix 2211A). We measured the spatial distribution of the electric field generated by our leads in the lead midplane by means of a bipolar probe-lead having interelectrode spacing 18 mm which was connected to the input of the differential amplifier.

For a given radial distance from the lead axis two parameters were used to evaluate the selectivity of the lead: the directivity angle and the filed rejection ratio. The directivity angle Ψ_D is defined as the angular displacement in the transversal lead midplane from the axis of maximal current density at which the value of current density is reduced $\sqrt{2}$ times. We obtained the directivity angles for leads with different angular electrodes and different interelectrode distances from the measured potential difference in the lead midplane.

The field rejection ratio F_R is the ratio of the maximal J_{max} and the minimal J_{max} current density measured for a pair of angular electrodes in the lead midplane:

$$F_R = \frac{J_{max}}{J_{min}} = \frac{J(\vartheta = 0°)}{J(\vartheta = 180°)}$$

The field rejection ratio is a measure for the depth of the electric field penetration in the wanted direction.

Results

Selected results of numerical field calculation using 3D FEM model are shown in Figure 2 and 4, while the results of *in vitro* measurements are presented in Figure 3.

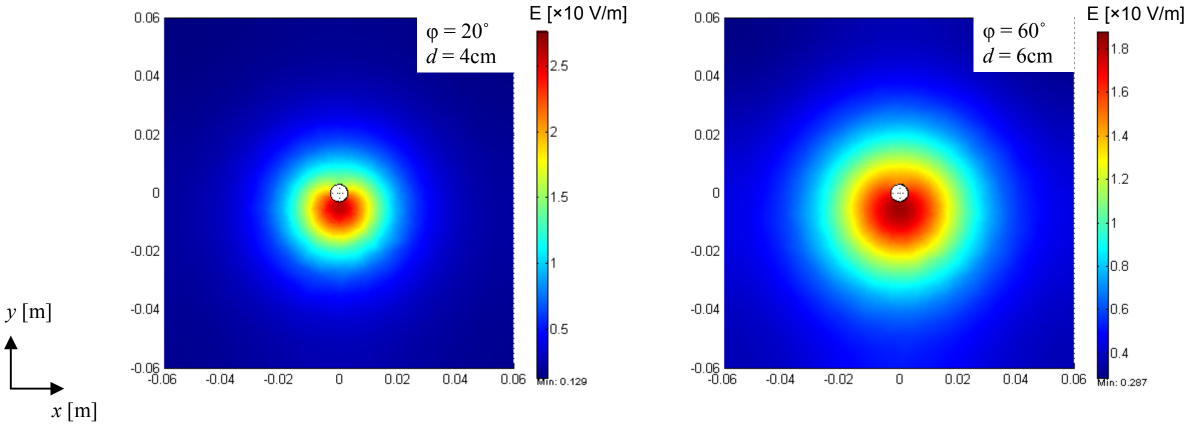

Figure 2: Electric field intensity in the selective lead midplane for different central angles φ and interelectrode distances d as obtained by 3D FEM model. Boundary conditions on electrodes: 5 V (upper electrode) and –5 V (lower electrode).

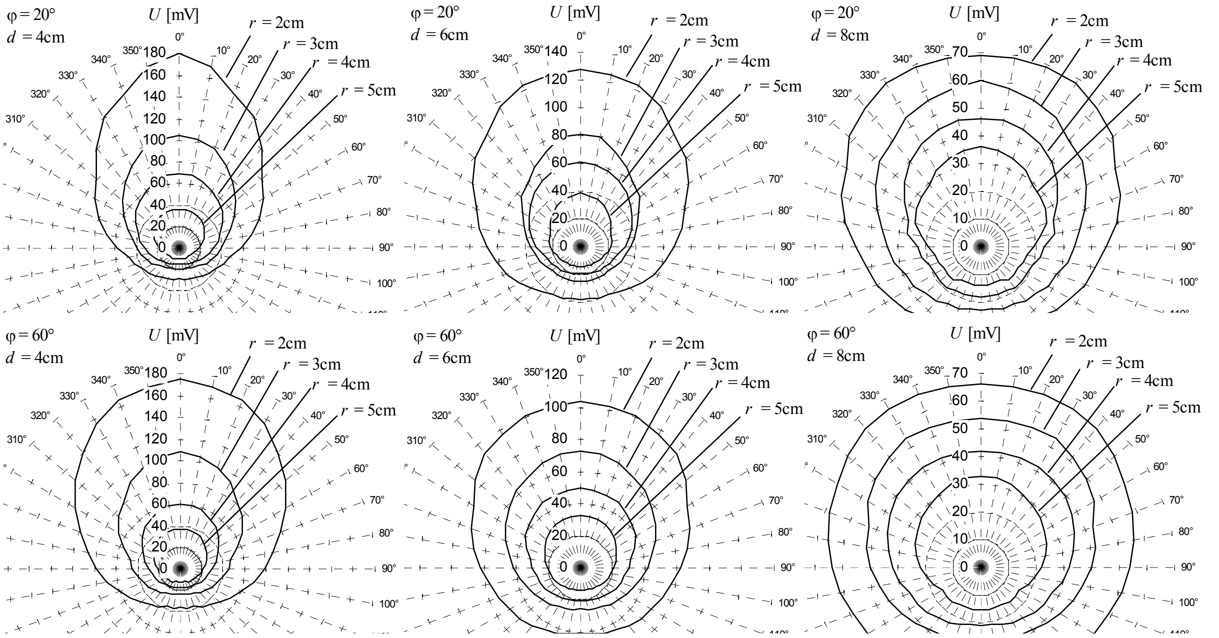

Figure 3: The values of potential difference measured with a probe lead in the selective lead midplane for different central angles φ and interelectrode distances d. Parameter is the radial distance r.

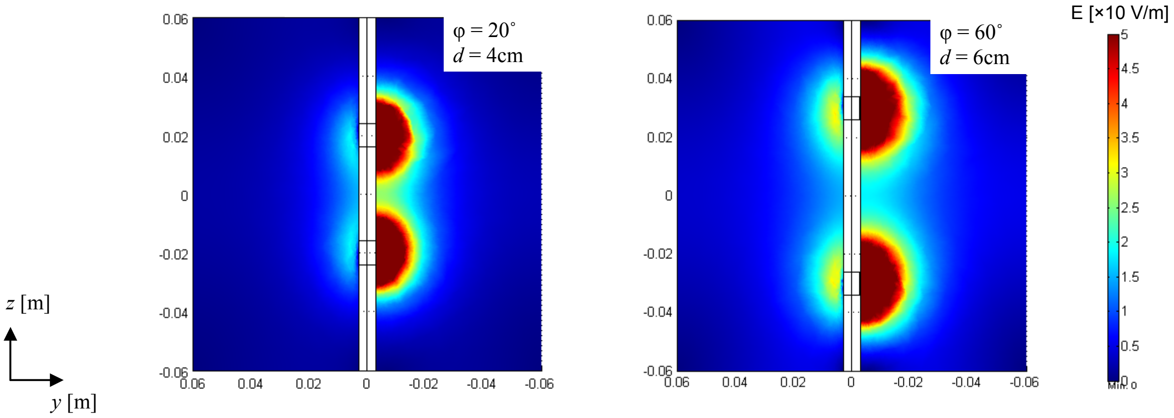

Figure 4: Electric field intensity in the longitudinal plane for selective lead with interelectrode spacings *d* and central angle φ. Boundary conditions on electrodes: 5 V (upper electrode) and –5 V (lower electrode).

It is important to notice that plots in Figure 3 do not represent the electric field, but are constructed to emphasize selectivity parameters F_R and Ψ_D.

The results of modeling and *in vitro* measurements clearly demonstrate that with smaller interelectrode distances and smaller central angles, significant increase of the directed field penetration is obtained.

Discussion and Conclusions

Electrodes on commercial leads are spheroidal and form axially symmetrical electric field which spreads uniformly in transversal plane in all radial directions around the lead axis. Application of selective leads enables that electric field is directed towards the heart.

The model of the tissue as a homogenous volume conductor is inadequate for real situation of transesophageal pacing since it neglects nonhomogenity and anisotropy of conductivity distribution in the mediastinum (esophagus, pericardium, myocardium, other structures). However, it can serve well for evaluation of the electric field of selective pacing lead. Nevertheless, the advantage of selective over standard lead cannot be disputed whatsoever.

Modeling and *in vitro* measurement of the electric field of our selective esophageal pacing lead indicate that efficient esophageal pacing can be obtained with considerably reduced side effects. The selectivity of the lead, measured by the field rejection ratio and the directivity angle, is obtained for smaller central angle of the angular electrodes.

References

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