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Comparison of Monopolar and Bipolar Cox-Maze Ablation Based on Clinical Data and Mathematical Modeling

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Purpose: Today radiofrequency heart ablation is gold standard for the radical surgical treatment of different types of heart rhythm disturbances. The purpose of the research is a comparative analysis of monopolar and bipolar electrodes for ablation during open heart surgery (Cox-Maze ablation). **Methods:** The analysis is made based on clinical data and mathematical modeling. By the use of system of electro-anatomical mapping of radiofrequency ablation zones a three-dimensional model of left atrium is created. Then a potential map, which represents the amplitude of myocardium activity, is imposed on this model. The amplitude of myocardium activity, the width and depth of the electro-thermal destruction zone and the ablation line continuity are main parameters of clinical data analysis. For mathematical modeling the COMSOL Multiphysics 5.4 software is used. Two variation of mathematical model for monopolar and bipolar ablation are created. Main analysis parameters of mathematical modeling are: diagrams of thermal field distribution, size of myocardial tissue destruction, and duration of the ablation procedure. **Results:** Both monopolar and bipolar ablation can be used for Cox-Maze procedure. But potential map and mathematical modeling show that with monopolar ablation the destruction zone has a hemispherical shape and scar line is not uniform along the depth of a heated myocardial tissue. It can lead to a recovery of pathological signals conduction from the pulmonary veins to the atrium. Uneven distribution of thermal fields with a clearly defined maximum increases the risk of evaporation and microexplosions. At the same time the duration of monopolar ablation is significantly longer. **Conclusion:** It is shown that bipolar ablation has advantages in pulmonary veins isolation. This type of instruments allows creation of effective and safe uniform thermal transmural destruction with only one application of radiofrequency current energy.

Key words: heart; arrhythmia; radiofrequency ablation; monopolar electrode; bipolar electrode; mathematical modeling

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Introduction

Statistics researches provide tendency of 0.5% of total population suffering from one of the most common arrhythmias – atrial fibrillation [4]. In search of ways for treating this heart rhythm disturbance Dr. James L. Cox in 1987 proposed the so-called Cox-Maze procedure [2]. It is used in cases when medicamental treatment isn't effective. In the classic version, it is "cut and saw" procedure. It is performed to create series of scars on heart that do not pass electrical impulses [6]. Thus, it is possible to create the only one possible way for electrical impulse to pass along heart wall in correct order. As shown by the practice of using the Cox-Maze procedure, its effectiveness is about 90%. However, due to the complexity of execution and duration it has not been widely used among cardiac surgeons [12].

The development of electro surgery has greatly simplified the radical treatment of cardiac arrhythmias. Today there is no need for performing surgical incisions of the heart wall for Cox-Maze procedure. Necessary scars can be obtained by thermal destruction of the corresponding heart areas. In world practice, radiofrequency ablation (RFA) and cryoablation have become the most widespread among the possible sources of energy for heart ablation procedure. Microwave and ultrasound also can be used to treat heart rhythm disturbances but they are not so popular [8]. As for Ukraine, only RFA is widely used in arrhythmias treatment. Radiofrequency ablation significantly reduces the time of Cox-Maze procedure, reduces the time of patient postoperative recovery and can be performed minimal invasion by catheters or laparoscopically. The combination of these advantages over a classic Cox-Maze has led to the widespread use of RFA in clinical practice.

Due to the high popularity of a radiofrequency ablation, there is a wide range of equipment for this procedure on the market. In general, it can be divided into radiofrequency current generators and electrodes for electro-thermal destruction. In turn, all electrodes can be divided into monopolar and bipolar. Monopolar electrodes for RFA are designed to carry out point destruction of small sizes. Also they can be used for linear destruction, as a combination of several tens of point ablations. Bipolar electrodes allow to instantly create large linear electro-thermal destruction.

1 The main objective of the article

The main objective of this article is to compare the possibilities of monopolar and bipolar ablation for a Cox-Maze procedure. The comparison is carried out both on the basis of clinical material (the potential map of myocardium tissue activity is used) and mathematical modeling of radiofrequency ablation during open-heart surgery.

2 Materials and Methods

2.1 Comparison of monopolar and bipolar Cox-Maze ablation based on clinical data

Comparison is performed based on analysis of RFA procedures results for bipolar and monopolar methods. Clinical data was collected in the Department of Arrhythmias (Amosov National Institute of cardiovascular surgery, Ukraine, Kyiv) with the use of the electro-anatomical mapping system of radiofrequency ablation zones (Ensite Velosity, Abbott, USA). This system allows to build a three-dimensional model of the cardiac chamber and to impose a potential map on it. That map gives quantitative values of the myocardium activity amplitude. It clearly shows in color-coding (Figure 1) areas of post-ablation scars that are formed in the postoperative period. Purple color in this map corresponds to the amplitude of heart tissue activity above 0.5 mV. In clinical practice it is a characteristic of the active tissue. The scale of amplitude from 0.1 to 0.5 mV corresponds to the heart scar tissue. The width of the ablation zone and the line continuity are evaluated for complete isolation of the pulmonary veins from the atrium. Recovery of myocardial activity in the destruction area is the main cause of recurrence of arrhythmia after RFA [10].

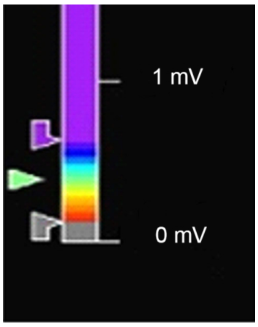


Fig. 1. The color coding of the heart tissue activity

The left atrium potential map of patient A is shown on Figure 2. He had RF isolation of the pulmonary veins by bipolar clamps (line 1) and the atrial lines by a monopolar electrode (line 2).

The potential map of patient B is shown on Figure 3. In this case RF pulmonary vein isolation was performed only by a monopolar electrode (line 3).

2.2 Comparison of monopolar and bipolar Cox-Maze ablation based on mathematical model

2.2.1 Main equation of the mathematical model

To compare monopolar and bipolar ablation during open heart surgery a mathematical model of this procedure is created. To simulate the resistive heating of biological tissue, COMSOL Multiphysics 5.4 software is used. Model is created based on combination of Bioheat Transfer and Electric Current modules. The main equation of the proposed model, as in its analogues [12, 14], is the heat transfer in biological tissue equation [1]:

$$\rho c\left(\frac{\partial T}{\partial t}\right)=\nabla\cdot k\nabla T+q+Q_m-Q_p, \tag{1}$$

where ρ is the density (kg/m^3), c is the specific heat (J/(kg·K)), k is the thermal conductivity (W/(m·K)), q is the amount of heat from the heating source (W/m^3), Q_p is the cooling by blood perfusion (W/m^3), Q_m is the amount of heat released due to metabolism (W/m^3).

In the proposed mathematical model the energy of the RF current is the heating source. A current frequency for RFA procedure is in the range of 300-1000 kHz. Taking into account current frequency, the small volume of the influence zone and fact that myocardium is a tissue with high water content, only the resistive component of the total impedance of biological tissue can be taken into account [3]. Thus, the heating source can be described by the equation:

$$q=\sigma|E|^2, \tag{2}$$

where $|E|$ is the magnitude of the electric field vector (V/m) and σ is the electrical conductivity (S/m).

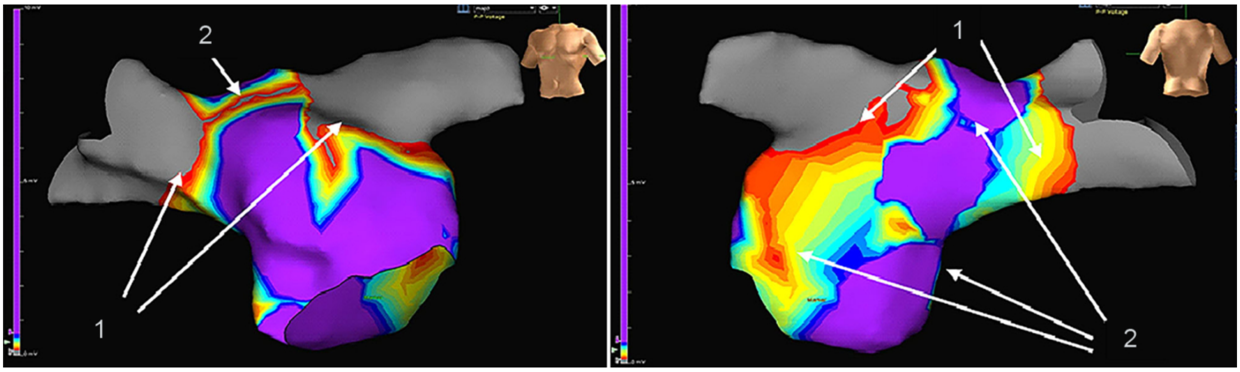


Fig. 2. The electro-anatomical mapping of the radiofrequency ablation zones in left atrium by bipolar clamps: 1– line of pulmonary vein isolation, 2 – atrial lines (mitral valve isthmus line, LA roof line, LA floor line)

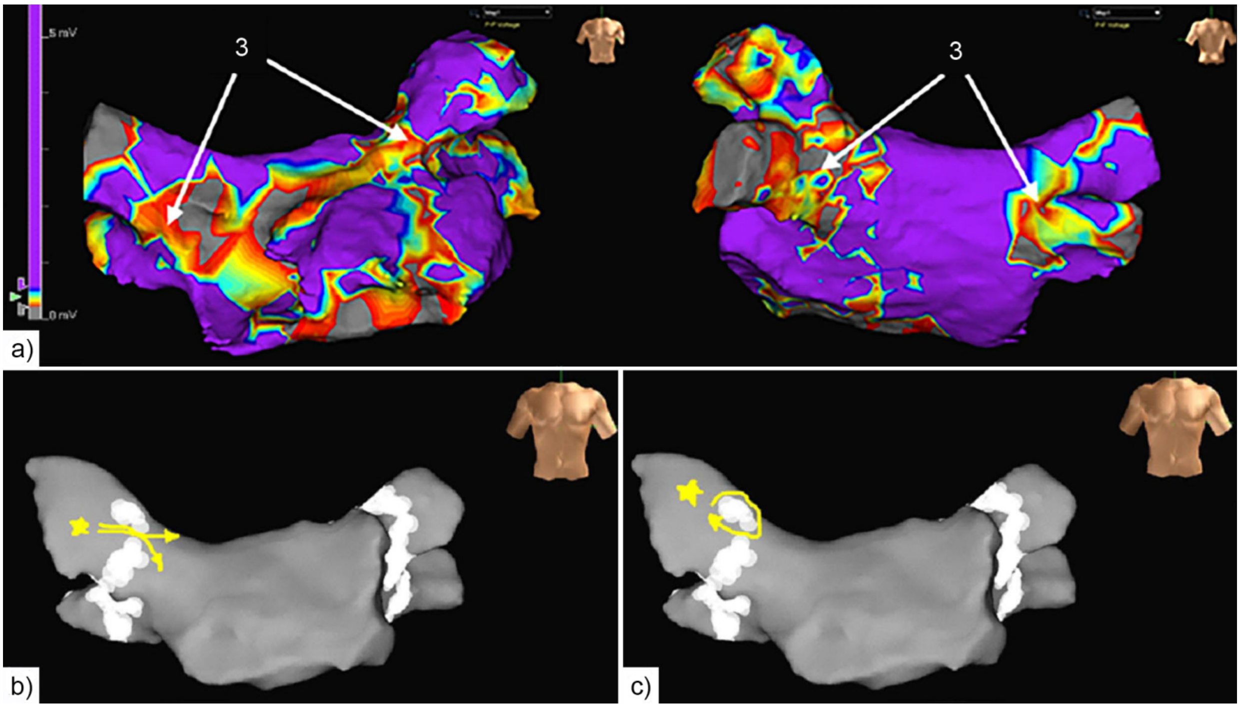


Fig. 3. The electro-anatomical mapping of the radiofrequency ablation zones in left atrium by a monopolar electrode: a) 3 – line of pulmonary vein isolation; b) the recovery of conduction of pathological signals from the vein to the atrium; c) the formation of conditions for the generation of arrhythmia substrate in the middle of the destruction zone, around scar

The radiofrequency ablation procedure during open-heart surgery is carried out under the condition of cardiopulmonary bypass. That's why there is no cooling by the blood flow in heart chambers. However, it is appropriate to take into account cooling from the blood flow of small vessels and capillaries of the heart wall. It is indicated as Q_p [1]. At the same time the influence of the environment is present. It can be indicated as Q_a. The amount of heat released as a result of metabolic processes during the duration of application up to 60 s is negligible [5]. Therefore it is not taken into account in the model. With all refinements the final version of the equation for heart RFA modeling is:

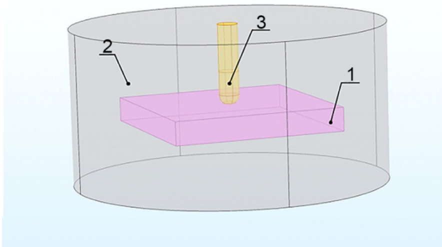
$$\rho c\left(\frac{\partial T}{\partial t}\right)=\nabla\cdot k\nabla T+\sigma|E|^2-Q_p-Q_a. \qquad (3)$$

2.2.2 Geometry and thermoelectric characteristics of mathematical model components

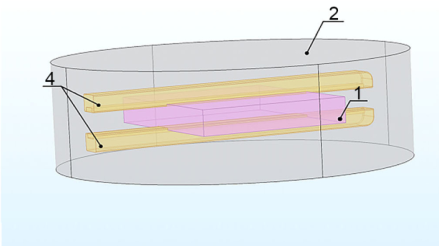
Two versions of the mathematical model geometry for simulating monopolar and bipolar ablation are considered (Fig. 4). In both cases, there is an element of myocardial tissue surrounded by ambient air flow at a speed of 0.3 m/s. For Cox-Maze RFA the affected area is in the left atrium near the mouth of pulmonary veins. In this zone thickness of heart walls is approximately 1-4 mm [16]. An average value of 3 mm is chosen for modeling. In the case of bipolar ablation modeling, the thickness of myocardial tissue element is twice as large, since the clamp branches are applied on both sides of pulmonary veins. [9,11].

As a tool for monopolar ablation, a classical electrode with a diameter of 7 F and a length of

4 mm is chosen (Fig. 4a). To simulate a bipolar clamp, two electrodes with a length of 7 cm and a width of 3 mm located in acrylic plastic branches are considered (Fig. 4b). The electrode material is platinum-iridium alloy. The thermoelectric characteristics of all elements of the mathematical model are presented in Table 1



(a)



(b)

Fig. 4. Geometry of mathematical models for monopolar (a) and bipolar (b) ablation, where 1 – is the myocardium tissue, 2 – is the ambient air, 3 – is the monopolar electrode, 4 – is clamps of the bipolar electrode

2.2.3 Initial and boundary conditions of the mathematical model

The initial temperature for an element - myocardial tissue, as well as blood of small capillaries in heart wall is set at 36.6°C, for electrodes – 20°C. In the mathematical model, it is believed that the electrical conductivity of myocardial tissue increases linearly with a temperature coefficient of 2%/°C [1].

Environmental cooling is simulated by a laminar flow of air with a temperature of 20°C and at a constant speed of 0.3 m/s. Cooling by the blood flow of small capillaries is realized by a boundary condition Biological Tissue. The perfusion rate is 0.0012 m/s and is considered uniform over the entire surface of the heart.

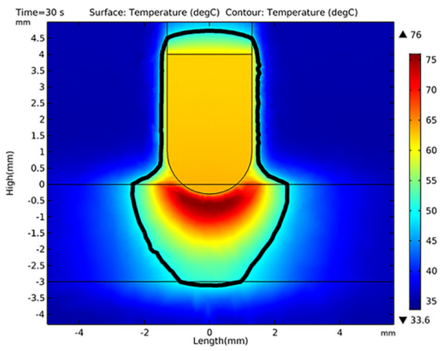
To simulate monopolar ablation it is believed that the lower surface of the myocardial tissue element acts as a passive electrode. Therefore, a boundary condition Ground is applied to it. When modeling bipolar ablation, the upper jaw is considered active, the lower one – passive.

Calculation of the mathematical model is carried out for a current frequency of 500 kHz, with maximum application duration of 60 s. The potential of the radiofrequency current is applied to surfaces of the active electrode and in both cases is set to 20 V. The size of destruction is estimated by the area of heart tissue that is heated to more than 50°C. It corresponds to the area of irreversible thermal destruction [7]. The critical temperature is 100°C, since its achievement will lead to a sharp evaporation of fluid and ruptures of a heart wall as a result of micro explosions [17].

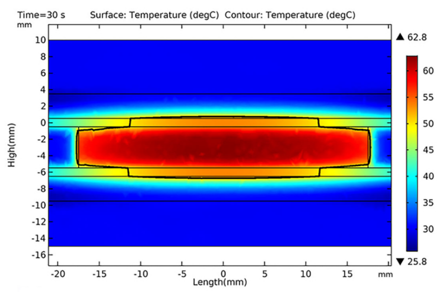
3 Results

Comparisons of line 1 and lines 2, 3 on Figure 2 and Figure 3 shows that single-phase RFA with bipolar clamps (1) provides a uniform in width and depth destruction line around pulmonary veins. In clinical efficiency it is equivalent to creating a complete blockade for conduction of pathological signals from veins to the atrium and vice versa. Lines 2 and 3 are more chaotic and scattered in space. That is due to they are a set of ablation points, each with some differences in the electrical parameters. Thus, they create a non-uniform zone of destruction. It is confirmed by the presence of more colors on the scale of the myocardial tissue activity amplitude.

The thermal field distribution diagrams for mono- and bipolar ablation are shown on Figure 5. It can be concluded, that the proper transmural destruction is achieved in both cases. Also the heating does not exceed the critical temperature of 100°C.



(a)



(b)

Fig. 5. Diagrams of thermal field spreading in time: monopolar electrode (a), bipolar electrode (b)

The use of a monopolar electrode in one application causes destruction up to 5 mm long (Fig. 5a). It should be noted, that the destruction zone has a hemispherical

Табл. 1 Thermo-electrical parameters of model materials

Material	Density, ρ (kg/m^3)	Electrical conductivity, σ (S/m)	Thermal conductivity, k (W/(m·K))	Specific heat, c (J/(kg·K))
Left atrium	1200	0.225	0.531	3600
Platinum-iridium	21500	$4 \cdot 10^6$	71	132
Acrylic plastic	1190	10^{-6}	0.18	1470
Air	1.225	0	0.028	1006
Blood	1000	0.667	0.543	4180

shape and it is not uniform along the depth of a heated tissue. A heating maximum is observed at depths of up to 1 mm from the tip of the electrode.

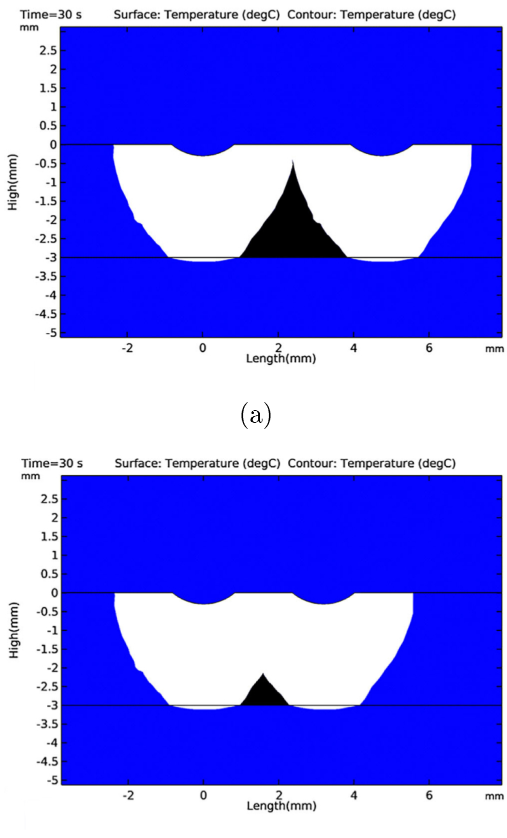
By the use of bipolar clamp, one application with duration up to 30 s is enough to create uniform in depth and thickness thermal destruction along the entire length of the pulmonary vein (Fig. 5b). The heating zone is uniform throughout the thickness of the heart wall. There are no pronounced maxima, as with monopolar ablation. Also, there is practically no temperature gradient. Only at the edges of the sample can a slightly lower heating temperature be observed. That is due to the cooling by ambient air flow.

4 Discussion

Based on clinical data (Fig. 2 and Fig. 3) it can be said that monopolar ablation scar line isn't uniform in width and depth. It is a common cause of the recovery of pathological signals conduction from the vein to the atrium. Also it can lead to the formation of conditions for the generation of arrhythmia substrate in the middle of the destruction zone, around some scar. Therefore, for the formation of linear destruction along the entire length of pulmonary veins mouth dozens of ablation points must be applied.

With hemispherical shape of destruction for monopolar ablation, to ensure proper destruction transmurality, the surgeon must overlap points of thermal damage by at least 30% (Fig. 6). The improper implementation of monopolar ablation is shown on Figure 6a. The destruction points practically do not overlap. The zone between two points of destruction which is heated to less than 50°C is marked in black. Here it's possible that over time electrical conductivity will be restored and arrhythmia as well. The minimum permissible overlap of destruction points (30%) is shown on Figure 6b. In this case, the tissue between two points of destruction that is not heated to more than 50°C is still preserved, but its size is not significant. Therefore, the risk of restoration of electrical conductivity is considered not significant.

Width of the destruction, obtained by mathematical modeling of monopolar RFA is about 5 mm. The diameters of pulmonary veins are individually for each patient and average is 15,6±3,2 mm [15]. A total length of the line of pulmonary veins mouth is 55±10 mm. With a minimum overlap of destruction points in 30% it is necessary to carry out about 20 points of monopolar ablation. Application duration for each RFA point is about 30 s with power 30-40 W to ensure effective linear destruction. This means that it will take at least 10 minutes to isolate one pulmonary vein. That is why a total duration of the RFA procedure, taking into account the time for electrode positioning, will be about 25-30 minutes.



(a)

(b)

Fig. 6. Diagrams of destruction points overlapping: no overlaping (a), with the minimum allowed overlapping of 30% (b)

Bipolar RFA that simultaneously clamps the entire diameter of the pulmonary vein between branches lasts 30 seconds for one application. In most cases is sufficient for complete isolation of pulmonary veins.

Conclusion

Clinical data and mathematical modeling results are presented showing, that effective transmural destruction can be achieved with both monopolar and bipolar instruments for open-heart ablation. However, bipolar ablation has some advantages for pulmonary veins isolation. First of all, this is a quick and effective method. It allows creation of continuous linear destruction along the entire line of pulmonary veins mouth. At the same time, as shown by mathematical modeling, when using a bipolar electrode, a uniform thermal destruction is observed. The temperature gradient is minimal, unlike in monopolar ablation. In this case, it is enough to perform only one application of radiofrequency current energy to create a block of conductivity. That reduces the duration of the procedure to several minutes. The limitation of bipolar ablation method is the convenience of its using only for the isolation of pulmonary veins on the heart surface. A monopolar electrode for RFA is the method of choice in case of linear ablation in heart chambers cavity.

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Порівняння монополярної та біполярної Cox-Maze абляції на основі клінічних даних та математичного моделювання

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Мета: Сьогодні радіочастотна абляція серця є золотим стандартом для радикального хірургічного лікування різних типів порушень ритму серця. Метою дослідження був порівняльний аналіз монополярних та біполярних електродів для абляції під час операції на відкритому серці (Cox-Maze абляція).

Матеріали і методи: Аналіз проводився на основі клінічних даних та за результатами математичного моделювання. За допомогою системи електроанатомічного картографування зон радіочастотної абляції була створена тривимірна модель лівого передсердя. Потім на цю модель було накладено карту потенціалів, яка представляє амплітуду електричної активності міокарда. Основними параметрами для аналізу клінічних даних були: амплітуда електричної активності міокарда; ширина та глибина зони абляції; безперервність лінії абляції. Для математичного моделювання було використано програмне забезпечення COMSOL Multiphysics 5.4. Створено дві варіації математичної моделі для монополярної та біполярної абляції. Основними параметрами аналізу результатів математичного моделювання були: діаграми поширення термічних полів; розміри зони деструкції; тривалість процедури абляції.

Результати: Для Cox-Maze абляції можна використовувати як монополярні, так і біполярні електроди. Однак карта потенціалів та математичне моделювання показали, що при монополярній абляції зона деструкції має напівсферичну форму, а лінія рубця не рівномірна по глибині зони впливу. Це може призвести до відновлення патологічних сигналів від легеневих вен до передсердя. Нерівномірний розподіл термічних полів з чітко вираженим максимумом збільшує ризик випаровування та мікровибухів. У той же час тривалість монополярної абляції значно більша.

Висновок: В представленій роботі показано, що біполярна абляція має переваги при ізоляції легеневих вен. Цей тип електродів дозволяє створити ефективну та безпечну рівномірну термічну трансмуральну деструкцію лише з одним застосуванням енергії радіочастотного струму.

Ключові слова: серце; аритмія; радіочастотна абляція; монополярний електрод; біполярний електрод; математичне моделювання

Сравнение монополярной и биполярной Cox-Maze абляции на основе клинических данных и математического моделирования

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Данная работа посвящена сравнительному анализу монополярного и биполярного методов радиочастотной изоляции легочных вен при абляции на открытом сердце. Для исследования использовались клинические данные и математическое моделирование. С использованием системы электроанатомического картирования (Ensite Velosity, Abbott, USA) построено трехмерную модель предсердия пациента и наложено на нее карту потенциалов. Проанализированы амплитуда электрической активности ткани миокарда, а также ширина и непрерывность линии абляции. В среде COMSOL Multiphysics разработано математическую модель процедуры радиочастотной абляции (РЧА) сердца. Проанализированы особенности распространения термических полей при монополярной и биполярной РЧА. Показано, что биполярная абляция имеет преимущества при изоляции легочных вен. Она позволяет осуществить эффективную, безопасную, однородную, трансмуральную электротермическую деструкцию стенки сердца при одной аппликации радиочастотного тока.

Ключевые слова: сердце; аритмия; радиочастотная абляция; монополярный электрод; биполярный электрод; математическое моделирование