Mathematical modeling of a new way of renal artery denervation

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Abstract. The aim of the work is to create a new design of electrodes for renal denervation. In standard RFA systems, monopolar heating is most often used, by introducing an RF electrode inside the vessel. This approach leads to the need to interrupt blood flow during the procedure. In addition, the monopolar mode of operation requires the contact of the inserted electrode with the vessel walls, which greatly complicates the design of the electrode system. Point contact of the electrode system with the vessel can damage the inner walls of the artery. It is proposed to use a multi-electrode structure for external stimulation by creating a hollow cylindrical thermal field for effective treatment. It has been established that external heating will create the required thermal field without direct contact with the walls of the artery. The external arrangement of the electrodes makes it possible to regulate the temperature on the external surface of the vessel. With such heating, it is not necessary to block the blood flow, and due to the symmetry of the arrangement, continuous heating can be obtained without moving the electrodes during the procedure. Mathematical modeling confirms the possibility of vascular denervation during external heating.

1. Introduction
The method of radiofrequency ablation (RFA) has established itself in the treatment of human oncological diseases and rightfully takes its place among other methods of therapy. In some cases, the effectiveness of the method reaches 90% or more [1-6].

In addition to cancer, several other diseases can be treated with RFA, including arterial hypertension. Arterial hypertension is very widespread. In the practice of cardiologists, patients periodically meet in whom, despite the long and systematic intake of four to five drugs in maximum doses, the normalization of blood pressure does not occur. Of course, with such patients, it is necessary first of all to exclude the cause of resistance, often it is problems with the kidneys, hormonal background, or congenital anomalies, but it so happens that the reason remains not found. Ablation of the orifices of the renal arteries (renal denervation) is possible for these patients. The kidneys are significantly involved in the regulation of pressure, when activating substances are released into the blood, a significant increase in blood pressure occurs. Information about the pressure of the kidneys is "obtained" from a number of receptors through the nerve pathways, it is on the intersection of these pathways that the renal denervation method is based. After the loss of connection with the nervous system, the kidneys no longer have such a strong effect on the level of blood pressure, which leads to its decrease [7].
Renal denervation is a relatively new treatment for refractory arterial hypertension. Its essence consists in radiofrequency ablation (RFA) of sympathetic nerve fibers, which pass directly into the thickness of the wall of the renal arteries. These sympathetic nerves play a major role in the pathogenesis of hypertension.

After denervation of the kidneys, patients showed a decrease in blood pressure. The level of systolic pressure decreased by an average of 30 mm Hg. Art., the level of diastolic pressure - by 10 mm Hg. Art. The maximum effect of lowering blood pressure occurs no earlier than 3 months after this procedure. Renal denervation does not allow to completely stop taking antihypertensive drugs, however, against the background of continuing antihypertensive therapy, blood pressure becomes controllable and often reaches normal values.

Usually, denervation is carried out by exposure from the inside by inserting a radiofrequency electrode into the blood vessel. The structure of RFA devices for denervation is unchanged - the working electrode is powered from a radiofrequency generator, the power is from 8 to 20 W. A prerequisite for the operation of the electrode is its direct contact with the surface of the artery since most installations operate in a monopolar mode. To ensure contact, it is necessary to greatly complicate the design of the electrode and the operating mode [8-10]. Currently, electrodes are produced by several companies, for example, Medtronic, Medical Cent, Biosense Webster, etc. Significant disadvantages of the classical denervation method are the need to interrupt blood flow during the procedure. The monopolar mode of operation, requiring contact of the inserted electrode with the vessel walls, greatly complicates the design of the electrode system. In addition, the actual point contact of the electrode system with the vessel can damage the inner walls of the artery.

To improve the heating parameters and simplify the procedure, it is proposed to switch to bipolar mode and heat the desired area from the outside - outside the blood vessel. In addition, denervation of nerve endings is more effective because the nerve endings are located on the outside of the artery wall.

The essence of our idea is to create an external thermal field in the desired area of the artery, covering the artery. To create the required temperature loop, it is proposed to use multi-electrode systems operating in bipolar mode. To confirm the proposed idea, model calculations were carried out.

2. Materials and methods
The general view of the model is shown in Figure 1. The model used to construct the electrode system is a cylinder with a hollow tube passing through the center, simulating an artery. Electrodes are inserted into this tissue at a distance not exceeding 1 mm from the artery wall, the length of the working surface of which is equal to the length of the surface to be coagulated. The initial preset temperature of biological tissue is 36.6 °C. The electrodes are positioned along the centerline of the cylinder so that the artery is symmetrically surrounded by the electrodes.
Figure 1. General view of the computational model.

Figure 2 shows a biological tissue (1) with an artery located in the center (2), the artery has walls (3). The artery is externally surrounded by an electrode system (4). The diameter of the model was 20 mm, the height was 10 mm, the diameter of the putative artery was 5 mm, the thickness of the artery wall was 0.5 mm, the height of the artery coincided with the height of the tissue and was 10 mm, the height of the electrodes was 5 mm, and the diameter was 0.8 mm. The biological tissue and electrode materials had the physical parameters shown in Table 1.

Table 1. Physical parameters of the model materials.

|          | Heat capacity, \( [J / (kg \cdot K)] \) | Density, \( [kg / m^3] \) | Thermal conductivity, \( [W / (m \cdot K)] \) | Electrical conductivity, \( [Cm / m] \) |
|----------|--------------------------------------|-------------------|---------------------------------|----------------------------------|
| Textile  | 3540                                  | 1079              | 0.52                            | 0.02                             |
| Artery   | 4180                                  | 1000              | 0.543                           | 0.667                            |
| Electrodes | 840                                   | 6450              | eighteen                        | 1 108                            |

Calculations of such a thermal field were carried out in the COMSOL Multiphysics software (version 5.6) using an eight-electrode system as an example [11]. The following COMSOL modules were used to simulate radiofrequency ablation in tissues: AC / DC - Electric Currents; BioHeat Transfer; Multiphysics - Electromagnetic Heating. The physical foundations of the model can be described by the Pennes thermal conductivity equation for living tissues:

\[
\rho C_p \frac{dT}{dt} - \nabla \cdot (k \nabla T) = Q_e + Q_{\text{met}} + \rho_b C_{p,b} G_b (T_b - T)
\]  

(1)
ρ - the density of the tissue;
C - the heat capacity of the tissue;
k - the thermal conductivity of the tissue;
Tb - arterial blood temperature, in model calculations, is 37 °C;
Qe - the heat from space heating (W/m³);
Qmet - heat released in tissues as a result of metabolism (was not taken into account in the model);
ρb and Cp,b - density and specific heat capacity of blood that flows through tissues at a rate \( \varpi_b \) (ml/min), in the model, the influence of this parameter is insignificant.
As a result, the equation takes the form:
\[
\rho C_p \frac{dT}{dt} - \nabla \cdot (k \nabla T) = Q_e
\]  
(2)

Current potential was determined from the Laplace equation:
\[
-\nabla \cdot (\sigma \nabla V) = 0
\]  
(3)

V - potential [V];
\( \sigma \) - electrical conductivity (Sim/m).
In the model, the opposite potential V1 and V2 are set on the electrodes as shown in Figure 2.

2. Results and discussion
In a real installation, the multi-electrode system shown in the model will be connected to two dissimilar generator leads.

![Figure 2. Alternating connection of electrodes to two terminals of the high-frequency generator](image)

The numbering of the elements in Figure 2 coincides with the numbering in Figure 1. The time for the formation of the thermal circuit was 1 minute 40 seconds. The potential on the electrodes during heating was 17.5 V. As a result, an isothermal circuit was formed for a temperature of 60 °C and above, shown in Figure 3. An isothermal circuit in this case means a heating area with a temperature of 60 °C or more.
Figure 3. Isothermal circuit appearance

The left (4a) shows the top view of the isothermal circuit, the right (4b) shows the general view of the isothermal circuit. As you can see, heating occurs only along the contour, and not inside the artery itself, which eliminates unnecessary trauma to the artery walls and blood flow. The minimum height obtained in the calculation of the thermal field is 3 mm, which is comparable to the classical method of radiofrequency denervation [12]. The effectiveness of the presented mathematical calculations is indirectly confirmed by preliminary experiments carried out by other researchers [13].

As follows from the results obtained, the proposed technique will allow refusing the cessation of blood flow during the denervation procedure. In addition, an improvement in the denervation process should be expected. The calculations were carried out to make it possible to proceed to experimental studies on animals.

3. Conclusion
Based on the results of the model obtained in this work for heating a vessel from the outside, it can be concluded that changing the approach of heating from an internal effect to an external one potentially has a number of advantages: 1. the electrodes, creating a thermal field and having the highest temperature, may not touch the surface of the vessels and disrupt them integrity; 2. The outer location of the electrodes makes it possible to regulate the temperature on the outer surface of the vessel; 3. with such heating, it is not required to cut off the blood flow; 4. due to the symmetry of the arrangement of the electrodes, it is possible to obtain continuous azimuthal heating; 5. The design of the electrodes eliminates the need to move them during the heating procedure.
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