Heat transfer in cryosurgical device with an extended applicator

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Abstract. This paper is aimed to study the prototype of cryosurgical device with an extended applicator. Three experiments were conducted. First, an experiment without heat load showed temperature distribution on extended applicator and its cooldown time. Second, an experiment with a typical heat load (when the applicator contacts the biotissue phantom) showed the impact of heat load on the surface temperature and on its cooldown time in this case, as well as the temperature at the control points inside the biotissue phantom and the dynamics of growth, shape and size of the freezing region. The third experiment was equivalent to the second, but without temperature sensors on the applicator surface for better freezing region visualization. Also, after the liquid nitrogen supply is stopped, the dynamics of thawing are considered. Data on the actual temperature during cryoexposure should help give basic recommendations for developing a cryoexposure technique with increased dosing accuracy.

1. Introduction

Currently, atrial fibrillation is one of the most common types of heart rhythm disorders and can cause stroke and heart failure. One of the surgical treatment methods of this pathology is a cryosurgical modification of the operation “Labyrinth”, which consists in creating non-conducting extended lines in the myocardium using surface freezing. The method of applying cryoexposure in this case is empirical, which may lead to the failure.

Safety and efficacy of cryoablation are determined by the dosing accuracy [1, 2]. The key to dosing is the placement of possible degrees of freedom and the consideration of limiting factors. At the same time, the effect of cryoexposure is achieved by the heat flux from biological tissue. This physical factor is unintuitive for the physician. Because of this the low correlation between the assigned and the actual dose may reduce its application area. Uncertainty as to the delivery of an “ablative dose” creates a less-than-optimal treatment paradigm, thereby limiting utilization of cryoablation for the treatment of various cardiac arrhythmias [3, 4].

To improve the accuracy of dosing, various cryoablation devices are developed and tested [3, 5-7]. From the thermal engineering point of view, investigation should involve temperature analysis of device capabilities by physical experiment and simulation of temperature fields in biological tissue. Knowledge of the expected performance of a cryosurgical probe is critical to obtain optimal outcomes [3].

One of the problems in cryoablation is the use of overcomplicated expensive disposable cryoprobes and applicators. The prototype, studied in this paper, on the contrary, uses reusable sterilized flexible applicators. This article is aimed to study the performance of this prototype to clear the potential cryoexposure dosing.
2. Materials and methods
A schematic diagram of the experimental installation is shown in Fig.1. The experimental installation consists of five parts: a gas pressurization system, a prototype of cryosurgical device (PCD) with a flexible extended applicator, a container with a biotissue phantom, a measurement data acquisition system, and a video recording system. The gas pressurization system consists of a cylinder with nitrogen gas, a pipeline and a gas pressure regulator.

The PCD with a flexible applicator is one of the modifications developed earlier [8]. The body material of the applicator is copper, the capillary tube that feeds the flow of boiling liquid nitrogen is stainless steel.

Ultrasound gel was chosen as the most appropriate biotissue phantom for in-vitro experiments (ultrasound gel "Mediagel", Geltek-Medica, Russia, high viscosity, uncolored composed of water, carborner, glycerin, propylene glycol, preserving agents) [9;10].

The data acquisition system has ICP CON I-87k9 controllers. To measure the temperature, two types of sensors are installed. The first is the RTD RT100A resistance thermometer (Heraeus Sensor Technology): electrical resistance is 100 Ohm, material – platinum, temperature coefficient of electrical resistance is 0.00385 °C⁻¹, measuring range is from minus 196 to 150 °C, class A, type – thin film. Due to the lack of a protective housing, the sensor has a low-inertia. These sensors are used to measure the temperature on the flexible applicator surface. During the experiment with heat load, sensors TR1, TR2, TR3, TR4, TR5, TR6 were located at a distance of 85, 75, 50, 40, 15 and 5 mm from the applicator tip, respectively. During the experiment without heat load, sensors T1, T2 and T3 were located at a distance of 85, 50 and 15 mm, respectively. The second is a needle-type thermocouple Single-Point 1.5 Thermal Sensor (Galil Medical). Materials: thermocouples – copper-constantan, housing – stainless steel, inside there is a tip made of bronze. These sensors are used to measure the temperature at biotissue phantom points. The measurement error of thermocouples and thermoresistors in temperature measurement is estimated to be no more than ±1°C. The system also contains a pressure sensor for measuring the pressure in the vessel of the PCD. Pressure Transmitter – HYXC-MP, output signal: 4-20 mA, accuracy is 0.5%. The video recording includes a Nikon D7100 camera and a tripod.

![Figure 1. Experimental installation.](image)
Brief exposure protocol consists of a preparatory and main parts. The preparatory part includes the biotissue phantom preparation (filling the container; with ultrasound gel and vacuuming to eliminate air bubbles inside), checking the measuring system, checking the gas pressurization system (pressure in the cylinder) and preparing the installation (positioning the applicator relative to the biotissue phantom and the sensors). The main part is a physical experiment. The compressed gas cylinder is opened. Gas is supplied to the PCD vessel with an operating absolute pressure of 1.4 – 1.8 bar, pressure increases and liquid nitrogen is pumped through the capillary tube into the annular, elongated channel of the flexible applicator, to which a heat load can be applied.

Due to the flow of boiling liquid nitrogen, the applicator begins to cool down and take heat from the biotissue phantom. Biotissue phantom is freezing. The measurement data system records the temperatures on the applicator surface and at the biotissue phantom control points, as well as the pressure above the surface of the liquid nitrogen in the PCD vessel. Three experiments were conducted. The first one demonstrates data on the applicator surface temperature without heat load – in the air. The experiment duration was 10 minutes. The second shows applicator surface temperature with a heat load - in contact with the biotissue phantom, as well as the biotissue phantom temperature at control points (sensors TC1, TC2, TC3) of the 5 mm distance from the applicator surface and at a distance of 85, 50 and 15 mm from the applicator tip, respectively. The experiment duration was 10 minutes. The third experiment was equivalent to the second, but without temperature sensors on the applicator surface for better freezing region visualization.

3. Results & Discussion
Data on the applicator surface temperature without heat load are shown in Figure 2. The minimum achievable temperature was minus 190 °C for about 1 minute from the moment of gas supply start. The indicator for cooldown time was a steady temperature plateau.

![Figure 2. The applicator surface temperature without heat load.](image-url)
Figure 3 shows the applicator surface temperature with a heat load with a biotissue phantom, and it shows the pressure values in the PCD vessel.

![Figure 3. Temperature and pressure in the experiment with heat load.](image1)

**Figure 3.** Temperature and pressure in the experiment with heat load.

![Figure 4. The dynamics of the freezing region growth.](image2)

**Figure 4.** The dynamics of the freezing region growth.
At the same time, the pressure changes in the PCD vessel, the temperature changes and the conditional output to the mode. At the beginning of the experiment, there is a gradual gas supply to the PCD vessel, then increase to 1.8 ATM. with a gradual value of 1.4 ATM. Then there is a monotonous decrease in pressure and temperature. If the temperature changes by less than 1–2 °C for 10 seconds, we accept the conditional output to the prototype at 6 minutes and stop the gas supply.

Figure 4 shows the dynamics of the bio-tissue phantom freezing depending on the time. At the initial moment after applying pressure, a cold wave starts on the applicator surface after ~8 seconds from a point 20 mm away from the tip. Next, the bio-tissue phantom is frozen along the entire applicator length. Inside the applicator, there is a flow of boiling liquid nitrogen, i.e. two-phase. At the beginning of the process, the heat load causes more intense vaporization, which decreases as the bio-tissue phantom and the cooldown PCD.

Based on the conducted experiments, the average difference in the applicator surface temperature without and with a heat load was revealed, which was 35 °C. It is shown that it is possible to create extended freezing regions using an applicator, which is relevant for the atrial fibrillation treatment. It is also possible to use the results obtained as a source for the development and verification of calculation programs.

4. Conclusions
A study of heat transfer in an extended applicator, cooled from the inside by a flow of boiling liquid nitrogen, was carried out to determine the cryoexposure rational modes. The applicator surface temperature (without and with heat load), the cooldown time, the dynamics of growth, shape and size of the freezing region were determined. Based on the results obtained, it is possible to give basic recommendations for developing a cryoexposure technique with increased dosing accuracy [1]. This will be helpful for the atrial fibrillation treatment.

5. References
[1] Shakurov A V, Pushkarev A V, Pushkarev V A and Tsiganov D I 2017 Prerequisites for developing new generation cryosurgical devices (review) Sovremennye tehnologii v medicine vol 9(2) pp 178–189 https://doi.org/10.17691/stm2017.9.2.23
[2] Goff R P, Quallich S G, Buechler R A, Bischof J C and Iaizzo P A 2017 Determination of cryothermal injury thresholds in tissues impacted by cardiac cryoablation Cryobiology vol 75 pp 125–133
[3] Baust J M, Robilotto A, Snyder K, Van Buskirk R and Baust J G 2018 Evaluation of a new epicardial cryoablation system for the treatment of Cardiac Tachyarrhythmias Trends Med 18 DOI: 10.15761/TiM.100012
[4] Shakurov A V, Pushkarev A V, Zherdev A A and Tsiganov D I 2018 Target region temperature history approach for increasing accuracy of cryoexposure dose providing Refrigeration Science and Technology 3 (3rd IIR Conference on Cold Applications in Life Sciences - and Cryotherapy and Cryopreservation, Proceedings) pp 3–7
[5] Schill M R, Melby S J, Speltz M, Breitbach M, Schuessler R B and Damiano R J Jr 2017 Evaluation of a Novel Cryoprobe for Atrial Ablation in a Chronic Ovine Model Annals of Thoracic Surgery vol 104 (3) pp. 1069–1073
[6] Xia Y, Liu B, Ye P and Xu B 2018 Thermal field and tissue damage analysis of cryoballoon ablation for atrial fibrillation Applied Thermal Engineering vol 142 pp 524–529
[7] Berte B, Sacher F, Wielandts J-Y, Mahida S, Pillois X, Weerasooriya R, Bernus O and Jais P A 2017 A new cryoenergy for ventricular tachycardia ablation: A proof-of-concept study Europace vol 19 (8) pp. 1401–1407
[8] Gasangusenov M G, Malyshenko E S, Ponomarev D E and Tsiganov D I 2018 Development of a cryosurgical device for the treatment of atrial fibrillation Refrigeration Science and Technology 3 (3rd IIR Conference on Cold Applications in Life Sciences - Cryotherapy and Cryopreservation, Proceedings) pp 21–24
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