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EXPERIMENTAL AND MATHEMATICALLY MODELLED TEMPERATURE CHARACTERISTIC OF HUMAN KNEE JOINT MEISCUS DURING RADIOFREQUENCY RESECTION

Abstract. This study investigates radiofrequency (RF) plasma temperatures around the active electrode of a bipolar arthroscopic RF resector and human knee meniscus tissue temperatures during RF resection.

The aim of this study was investigating radiofrequency (RF) plasma temperatures around the active electrode of a bipolar arthroscopic RF resector and

human knee meniscus tissue temperatures during RF resection. Knee arthroscopy knowing the optimal parameters for RF meniscus resection, such as resection temperature, mechanical stress on tissues, and process duration, is important.

The parameters for RF tissue resection, such as RF plasma temperature, meniscus heating temperature, meniscus load, and resection process duration were determined by modelling the heating process of the knee joint meniscus using special COMSOL software. A model of the heating processes of the knee joint meniscus and conductive fluid was built in the COMSOL environment. Finding safe temperature conditions for the resection process and determining its optimal parameters is necessary to improve the RF resection technology. The process of heating the knee joint meniscus and the conductive fluid that fills the joint were simulated using the real parameter values for biological tissues (Young's modulus and Poisson's ratio) and electrode characteristics (material, electrical conductivity, and thermal conductivity). The optimal experimental HF resection parameters were determined using constant values for the force applied to the electrode, HF resection duration, and electrical voltage.

This study experimentally determined the temperature characteristics of RF meniscus resection using a bipolar RF arthroscopic resector and compared the results with a mathematical model of RF meniscus resection compiled in the COMSOL environment. Discrepancies between modelling and experimental research were obtained that determine the optimal temperature parameters for RF resection of the knee joint meniscus: temperature of HF plasma, meniscus heating temperature during RF resection using a resector in a conductive fluid, and meniscus heating temperature when using analogues in a conductive fluid.

The proposed RF resection technology can be used to perform partial resection of the knee joint meniscus. Studies have shown that mathematical modelling of the knee joint meniscus and conductive fluid heating processes due to a bipolar electrode through which an HF current passes closely aligns with experimental data. The optimal conditions for RF resection obtained from thermographic studies and modelling, such as the temperature of the knee joint meniscus and conductive fluid and resection process duration, can improve meniscus injury treatment result.

Keywords: arthroscopy; COMSOL modeling; knee joint; meniscus resection (partial meniscectomy); radiofrequency; temperature.

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ЕКСПЕРИМЕНТАЛЬНО ТА МАТЕМАТИЧНО ЗМОДЕЛЬОВАНІ ТЕМПЕРАТУРНІ ХАРАКТЕРИСТИКИ МЕНІСКА КОЛІННОГО СУГЛОБА ЛЮДИНИ ПІД ЧАС РАДІОЧАСТОТНОЇ РЕЗЕКЦІЇ

Анотація. У цьому дослідженні досліджується температура плазми навколо активного електрода біполярного артроскопічного радіочастотного (РЧ) резектора та температура тканини меніска колінного суглоба людини під час РЧ-резекції.

Мета дослідження полягала в дослідженні температури плазми навколо активного електрода біполярного артроскопічного радіочастотного (РЧ) резектора та температури тканини меніска колінного суглоба людини під час РЧ-резекції.

Параметри ВЧ-резекції тканини, такі як температура ВЧ-плазми, температура нагріву меніска, навантаження на меніск і тривалість процесу резекції, визначали шляхом моделювання процесу нагріву меніска колінного суглоба за допомогою спеціальної програми COMSOL. У середовищі COMSOL побудовано модель процесів нагріву меніска колінного суглоба та провідної рідини. Знаходження безпечних температурних умов для процесу резекції та визначення його оптимальних параметрів є необхідним для вдосконалення технології ВЧ резекції. Процес нагрівання меніска колінного суглоба та електропровідної рідини, що заповнює суглоб, моделювали з використанням реальних значень параметрів біологічних тканин (модуль Юнга та коефіцієнт Пуассона) та характеристик електродів (матеріал, електро-провідність і теплопровідність). Оптимальні експериментальні параметри ВЧ резекції були визначені з використанням постійного значення сили, прикладеної до електрода, тривалості ВЧ резекції та електричної напруги.

У дослідженні експериментально визначено температурні характерис-тики РЧ-резекції меніска за допомогою біполярного ВЧ-артроскопічного резектора та порівняно результати з математичною моделлю РЧ-резекції

меніска, яку розроблено в середовищі COMSOL. Отримано розбіжності між моделюванням та експериментальними дослідженнями, які визначають оптимальні температурні параметри для РЧ-резекції меніска колінного суглоба: температура ВЧ плазми, температура нагріву меніска під час РЧ резекції резектором у провідній рідині та температура нагріву меніска при використанні аналогів у провідній рідині.

Запропонована технологія РЧ-резекції може бути використана для часткової резекції меніска колінного суглоба. Дослідження показали, що математичне моделювання меніска колінного суглоба та кондуктивних процесів нагрівання рідини за рахунок біполярного електрода, через який проходить високочастотний струм, повністю узгоджується з експериментальними даними. Оптимальні умови для радіочастотної резекції, отримані в результаті термографічних досліджень і моделювання, такі як температура меніска колінного суглоба і провідної рідини та тривалість процесу резекції, можуть покращити результат лікування травми меніска.

Ключові слова: артроскопія; моделювання у COMSOL; колінний суглоб; резекція меніска (часткова меніскектомія); радіочастота резекція; температура.

Problem statement. Meniscal injury accounts for 75% of all knee injuries, with an incidence of 60–70 per 100,000 population and a prevalence of 12%–14% [1]. Arthroscopic repair of a damaged meniscus is common in surgery, ranging from 10%–20% [1, 2]. Mechanical resection has been the gold standard for treating knee injuries for years [3, 4]. However, preserving as much meniscal tissue as possible is vital. The meniscus is important for shock absorption, knee stability, and load distribution. During arthroscopy, it is necessary to determine how much meniscal tissue to resect and how much is suitable for repair. The key disadvantages of mechanical resection are the low ability to control the resection volume and the high risk of damage to non-target tissue [3, 5, 6]. The mechanical method may have low control over meniscus resection volume because, after completing one resection cycle, the next, cycle starts elsewhere on the meniscus tissue. For example, when using a puncher to release the blades from the previous meniscus tissue fragment in the interval between resection cycles, it must be moved relative to the meniscus surface. In addition, special milling cutters and shavers are used in the mechanical resection process, which use a powered motor to reduce time loss when repeating resection cycles, increasing the mechanical stress on the meniscus tissue. This stress increases the risk of additional damage to the meniscus tissue and deformation of its surface. Various high-frequency (HF) arthroscopic ablators eliminate this disadvantage.

Analysis of recent research and publications. Radiofrequency (RF) energy is widely used in modern medicine for cutting, coagulation, or tissue ablation, including in orthopaedics and traumatology [4, 7, 8]. The basis of its effect is heating

the target tissue with the help of plasma, leading to its molecular dissociation. There are two electrode configurations for forming plasma: monopolar and bipolar. In the first case, relatively high temperatures are used, which can reach ≥100°C, which is destructive for joint tissues [3, 5]. Studies have shown that for effective treatment, the temperature should not surpass 52°C [9, 10, 11]. This limit is achievable using a bipolar electrode configuration [12-14].

There are many electrode types for treating knee injuries, with average operating temperatures of 30°C–50°C [7]. However, while treating injuries using RF energy provides good clinical results in the early and middle postoperative period, in the long term, treatment results do not differ greatly from mechanical resection and are sometimes worse [3]. This observation may be due to coagulative necrosis of the meniscus tissue, which occurs with RF energy when using an RF multielectrode ablator. The electrode configuration implies the appearance of a steam pop [8, 13], which destroys a relatively large amount of tissue. Therefore, there is a risk of damage and deformation of non-target meniscus tissue, leading in the long term to the destruction of the knee joint meniscus, increasing postoperative arthrosis and meniscus re-rupture risks [4].

Deformation of the meniscus surface can reduce its biomechanical properties, such as resistance to circumferential cylindrical stress, increasing the likelihood of further loss of meniscus tissue volume. Researchers have been investigating ways to solve the issue of selecting the best tool for treating a damaged meniscus [15-18], which remains an open question.

In search of the most effective treatment method, we hypothesize that the optimal choice of active electrode shape and configuration for resection of the knee joint meniscus could reduce the thermal burn risk of non-target tissue, improving treatment outcomes. A bipolar arthroscopic RF instrument with an active loop electrode should optimize the performance of RF resection of the knee meniscus, making the study of RF resection methods relevant and appropriate.

This study aimed to determine the temperature parameters of RF plasma around the active electrode and the human knee joint meniscus tissue temperature during RF resection. In addition, it aimed to improve the RF resection technology, which can be successfully used to perform partial resection of the knee joint meniscus. In particular, it is necessary to experimentally determine the temperature indicators (characteristics or properties) of RF resection of the meniscus.

The **aim** of this study was investigating radiofrequency (RF) plasma temperatures around the active electrode of a bipolar arthroscopic RF resector and human knee meniscus tissue temperatures during RF resection. Knee arthroscopy knowing the optimal parameters for RF meniscus resection, such as resection temperature, mechanical stress on tissues, and process duration, is important.

Materials and methods. The study of RF resection was conducted on 30 macropreparations of meniscus removed during total human knee arthroplasty. Gross preparations of the meniscus were placed in a solution of 0.9% sodium

chloride (NaCl) at 18°C–21°C during the operation. In a laboratory at the State Institution of Science, Research and Practical Center of Preventive and Clinical Medicine (Kyiv, Ukraine), their laboratory conditions were maintained as close as possible to those when performing joint arthroscopy. RF resection of the meniscus was performed using a bipolar RF arthroscopic meniscus resector (LLC Gryshchuk Medical Devices, Ukraine) [19]. This study was conducted according to the Declaration of Helsinki of the World Medical Association, "Ethical Principles of Medical Research Involving Human Subjects" (1964, updated in 2013). The patient or his legal representative completed the informed consent document (approved by the Ethics Commission: State Institution of Science "Research and Practical Center of Preventive and Clinical Medicine" Ukraine), 04.07.22, protocol N. 03).

It is important to know the optimal exposure parameters, such as RF plasma temperature, meniscus heating temperature, meniscus load, and resection process duration, to determine the optimal conditions for RF tissue resection. These parameters were determined by modelling the heating process of the knee joint meniscus using special COMSOL software [20]. A model of the heating processes of the knee joint meniscus and conductive fluid was built in the COMSOL environment. Finding safe temperature conditions for the resection process and determining its optimal parameters is necessary to improve the RF resection technology. Studying the optimal RF resection parameters may improve future meniscus injury treatment results.

The process of heating the knee joint meniscus and the conductive fluid that fills the joint were simulated using the real parameter values for biological tissues (Young's modulus and Poisson's ratio) and electrode characteristics (material, electrical conductivity, and thermal conductivity). In the model, energy was transferred to the meniscus tissue during its interaction with the electrode. A specific pressing force was applied to the electrode. The optimal experimental HF resection parameters were determined using constant values for the force applied to the electrode, HF resection duration, and electrical voltage.

For example, the safe temperature for non-target tissue on the knee joint's cartilaginous surface is described differently in different sources, ranging from 10°C to 50°C. The cartilaginous surface was chosen because its integrity may be compromised when RF energy is applied to the knee joint. Among the in vivo temperatures described [21, 22, 23, 24, 25], the range in which significant tissue changes occur is from 65°C to 75°C. For example, One study noted that significant morphological surface changes in the degeneratively affected cartilage require a temperature of 56.5°C [26]. Another study [27] showed that non-degeneratively affected cartilage did not change up to 60.9°C, and chondrocyte viability was threatened at a temperature of ~55°C. Therefore, this study considered temperatures ≥50°C as potentially hazardous.

The optimal parameters for RF meniscus resection were determined by studying the temperature parameters of RF plasma around the active electrode and

the temperature of the human knee joint meniscus tissue during the RF resection procedure. Knee meniscus and conductive fluid temperatures during HF resection were measured using a FLIR i7 thermograph (FLIR Systems AB, Sweden), with a temperature sensitivity of $0.1°C$ and a measurement error of 2% of the measured range. The thermograph's technical capabilities make it possible to determine the minimum temperature difference between adjacent tissues from $0.5°C$. An MS Plus pyrometer (Optris, Germany) was used to measure the meniscus's heating temperature at the site of electrode application, with a temperature sensitivity of $0.1°C$ and a measurement error is $±1\%$.

An arthroscopic meniscus resector (LLC Gryshchuk Medical Devices, Ukraine) [19] was used to perform RF resection. It comprises a handle and internal (contains a loop electrode and aspiration channel) and external (designed to protect the inner tube and its contents from damage when immersed in the joint) tubes) (Figure 1).
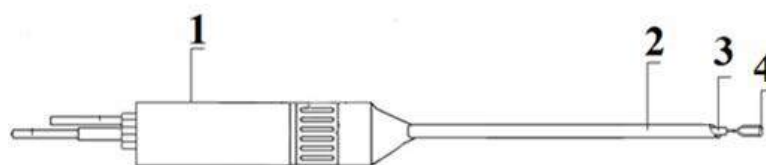

Fig. 1. Schematic of an arthroscopic instrument for RF resection: 1 – handle with a manipulator for linear movement of the outer tube; 2 – outer tube designed to protect the inner tube; 3 – inner tube containing the loop electrode and the aspiration channel; 4 – bipolar electrode-loop, which is attached to the inner tube.

The instrument is connected to an RF power generator controlled using a foot switch. When RF energy is applied to the loop electrode close to the target tissue, it molecularly dissociates. The aspiration channel removes bubbles and small molecular dissociation products from the surgical field [19].

In the performed experiments and models in the COMSOL software environment, RF resection of the knee joint meniscus used a bipolar loop electrode (Figure 2).

Fig.2. Bipolar electrode-loop for an electrosurgical instrument

The conditions used to conduct clinical experiments were as follows: the surfaces of the joint meniscus were contained in the conductive fluid (0.9% NaCl);

the initial meniscus temperature was 24°C–26°C; the operating temperature of the RF resector electrodes was 10°C–40°C; the duration of a single RF resector cycle was 1 s; the maximum HF duration on the meniscus was 3 s.

The RF energy generator's parameters in the cutting mode were a current strength of ≤10A, current frequency of 100 kHz, maximum output power of 400 W at a load of 217 Ohm, and voltage range of 0–340 V [7, 28, 29]. The menisci of the human knee joint, which were removed during total knee arthroplasty and placed in a 0.9% NaCl solution at a temperature of 18°C–21°C during the operation, were placed in an experimental 0.75L container filled with a 0.9% NaCl solution. A block diagram of the experimental setup is shown in Figure 3. The Meniscus Resector was connected to a Quantum 2 RF Power Generator. A Quantum 2 System generator (ArthroCare, USA) was used as part of surgical arthroscopy and orthopaedic equipment to power the HF instruments. Adjustable coagulation and ablation enable separate regulation of coagulation and ablation modes during surgery
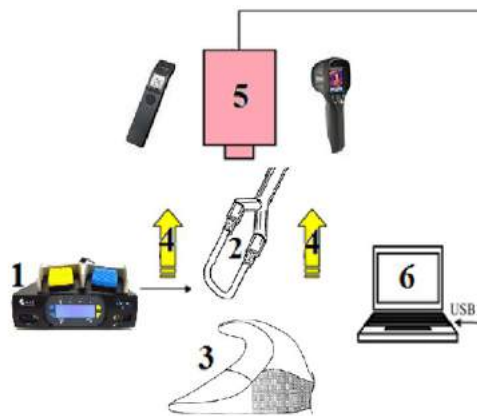

Fig. 3. Block diagram of the experimental setup: 1 – Quantum 2 System power supply; 2 – bipolar electrode-loop; 3 – the research object (knee joint meniscus); 4 – infrared radiation; 5 – a thermographic system using a FLIR i7 thermal imager and Optris MS Plus pyrometer; 6 – a personal computer with specialized software.

To determine the confidence interval and the probability with which the absolute error of a series of measurements lies within the allowable temperature range, the hypothesis was accepted that the measured temperatures in the meniscus follow the Student's distribution. Since the measurement errors that are caused by temperature measurement tools (FLIR i7 thermal imager, Optris MS Plus pyrometer) cannot be eliminated, after performing several temperature measurements in the meniscus in the area of application of the loop electrode, it can be argued that its true values are statistically obtained.

A confidence interval of 1°C determines the temperature range at the points of average temperature changes in the meniscus, within which the true value of the measured value lies with a given probability $p < 0.001$.

It is important to know the optimal exposure parameters, such as RF plasma temperature, meniscus heating temperature, meniscus load, and resection process

duration, to determine the optimal conditions for RF tissue resection. These parameters were determined using a simulation of the heating process of the knee joint meniscus and conductive fluid.

The simulation used the finite element method in the COMSOL Multiphysics 5.1 software. The maximum resection temperature was 40°C–50°C, corresponding to clinical experimental data. The optimal temperature for HF resection of the knee joint meniscus was determined based on various research parameters (electrode current, electrical voltage, and temperatures of knee joint tissues).

The RF resection process model built in COMSOL Multiphysics 5.1 used a constant value for the force applied to the loop electrode, resection time, and electric potential on the electrode's surface. A mathematical model of a resection process involving a loop electrode immersed in the tissue of the knee joint meniscus during RF resection was built in COMSOL (Figure 4).
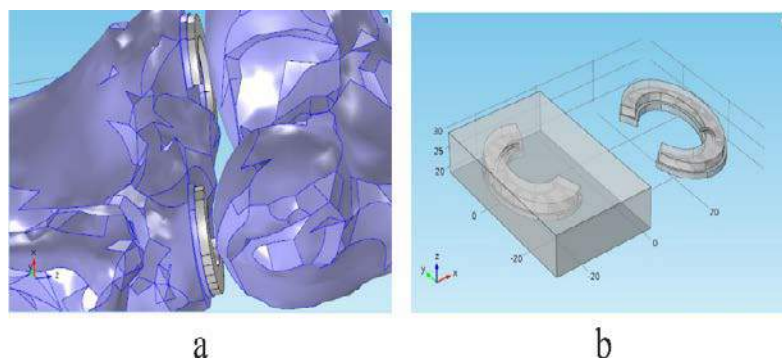

Fig.4. The RF resection process model: (a) knee joint model with meniscus; (b) model of an electrode immersed in the meniscus tissue in a conductive liquid (0.9% NaCl).

Mathematical modelling of the stationary temperature distribution in a two-phase medium at a frequency of 400 kHz has been previously considered [30]. Modelling the temperature distribution in a three-phase medium (electrode–meniscus and electrode–liquid) at a frequency of 100 kHz allowed us to study the non-stationary distribution of the temperature field during RF resection using an infrared thermograph and a pyrometer.

The physical parameters of the knee joint meniscus applied to the model in COMSOL Multiphysics were:

- Thermal conductivity = 0.5 W/m·K;
- Density = 30.9 kg/m^3;
- Heat capacity = 60 J/kg·K;
- Emissivity = 0.96 W/m^2

The meniscus's emissivity is the ratio of the energy flux emitted by a given cartilaginous surface to the energy flux emitted by an entirely black body at the same temperature. The temperature distribution of the material is described by the heat conduction equation, which has the form:

$$\rho C \frac{\partial T}{\partial t} - \nabla(k\nabla T) = Q, \qquad (1)$$

where ρ is the density, C is the specific heat, k is the coefficient of thermal conductivity, $\tilde{N}$ is the Nabla operator, Q is the heat source distribution function, T is the temperature, and t is the process duration (time).

To solve heat transfer Equation (1), it is necessary first to solve the electromagnetic problem for a bipolar loop electrode and, as a result, find the distribution function of heat sources Q in a two-phase medium (electrode–meniscus).

Maxwell's equations [31] can be used to derive an equation describing electromagnetic processes in conducting media:

$$-\nabla\left(\frac{1}{\mu}\nabla E\right) + (j\omega\sigma - \omega^2\varepsilon)E = 0, \qquad (2)$$

where E is the electric field strength, μ is the magnetic permeability of the conducting medium, j is the imaginary unit, ω is the angular frequency, σ is the electrical conductivity, and ε is the permittivity of the conducting medium.

Equation (2) makes it possible to determine the electric field strength E and the distribution of heating sources Q when an HF current flows in a conductive two-phase medium (electrode–meniscus):

$$Q = \sigma \cdot E^2. \qquad (3)$$

In surgical practice, the thermal effect should be minimal but sufficient to effectively cut biological tissues to avoid excessive destruction of the meniscus tissue during RF resection, potentially leading to post-surgery complications.

Presentation of the main material.

Temperature gradients during RF meniscus resection

The research object was the change in temperature of the knee joint meniscus and conductive fluid during HF resection (Figure 5).
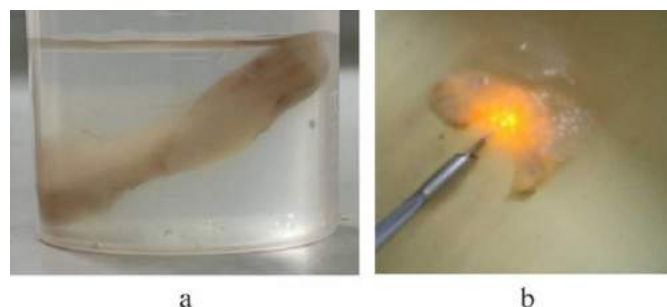

Fig. 5. Research object: (a) knee joint meniscus in conductive fluid; (b) meniscus of the knee joint during HF resection.

The initial data for modelling the tissue heating and cooling processes of the knee joint meniscus during HF resection are images showing the temperature distribution on the meniscus surface recorded with a FLIR i7 and a 1 s time interval from which temperature data can be obtained (Figure 6).
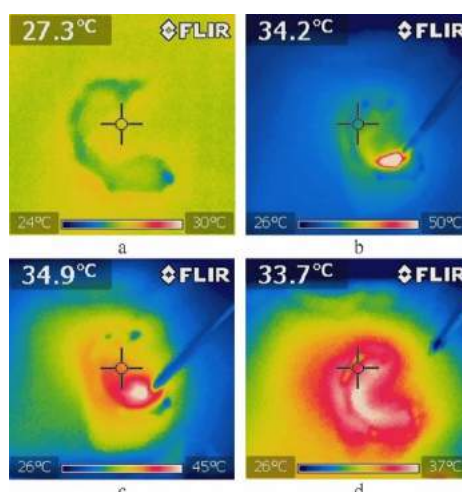
Fig. 6. Infrared images show the temperature of the isolated knee joint meniscus during RF resection: (a) 27.3°C; (b) 34.2°C; (c) 34.9°C; (d) 33.7°C

Non-contact temperature control in the isolated meniscus, HF plasma, and conductive fluid used a FLIR i7 thermograph in RF resection mode with a current frequency of 100 kHz. The tissue temperature between the electrode and the meniscus was measured using an Optris MS Plus pyrometer. The spectral range of the infrared thermograph was 75–13 µm. The distance between the object (meniscus) and the thermograph lens was 0.1–10 cm. The FLIR i7 thermograph measures the thermal energy flux in the infrared spectrum emitted from the surface of the examined meniscus tissue at a specific temperature from a unit surface area (cm^2). The thermal imager's 140×140-pixel resolution in the studied temperature range of 0°C–90°C ensured the measurement error of the meniscus and conductive liquid temperature was no more than $\pm2\%$ of the measurement range, as set in the device settings.

Ten meniscus and RF plasma temperature measurements were made per experiment. The change in temperature of the isolated meniscus and nearby tissues in the centre of a loop electrode applied three times (inclusions) during HF resection with the Quantum 2 generator is shown in Figure 7.
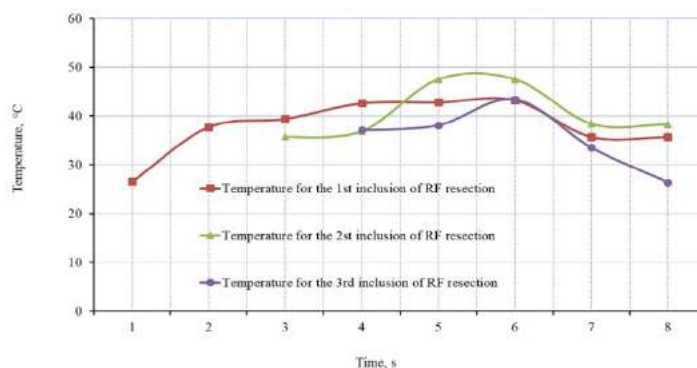

Fig.7. Changing in temperature of the isolated meniscus and nearby tissues in the centre of the applied loop electrode: (a) the first 8-second RF resection inclusion; (b) the second 5-second RF resection inclusion; (c) the third 3-second RF resection inclusion.

Data on temperature changes of the isolated meniscus and nearby tissues in the centre of the loop electrode applied during RF meniscus resection (Figure 7) are averaged for 10 RF resector experiments, each with three inclusions (first, second, and third; measurement error $p < 0.001$ for the data). The correlation between the 10 temperature measurements was 0.57–0.85 units, confirming the reliability of the experimental data. The temperature dispersion in time readings for each temperature measurement was ±1°C, corresponding to an instrument error for temperature measurement of no more than ±2% in the range 0°C–90° C.

Simulation results

During RF meniscus resection at temperatures >46.7°C, labile globular proteins can experience thermal denaturation since an increase in temperature causes a structural transition, resulting in the formation of adhesive substances. This process is not desirable for the RF resection process. Since the course of tissue thermal denaturation processes depends on temperature penetration deep into the tissue, this temperature value was determined by the RF resection simulation results in the COMSOL environment (Figure 8).
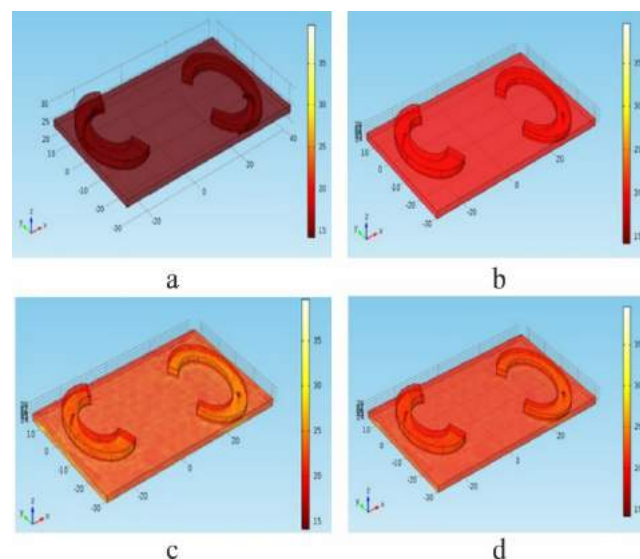

Fig.8. COMSOL model of the temperature distribution in the meniscus: (a) after 0.1 s at a conductive fluid temperature of +18°C; (b) after 0.3 s at a conductive fluid temperature of +20°C; (c) after 0.6 s at a conductive fluid temperature of +25°C; (d) after 0.9 s at a conductive fluid temperature of +30° C.

In the model in the COMSOL software environment, the following initial conditions were used: the temperature of the conductive fluid surrounding the meniscus was 15°C, the current strength was ≤10 A, the frequency was 100 kHz, the maximum output power was 400 W, and the resection process time was 3 s. Temperature changes in the meniscus in the bipolar electrode's application area based on the COMSOL temperature distribution model are shown in Figure 9.
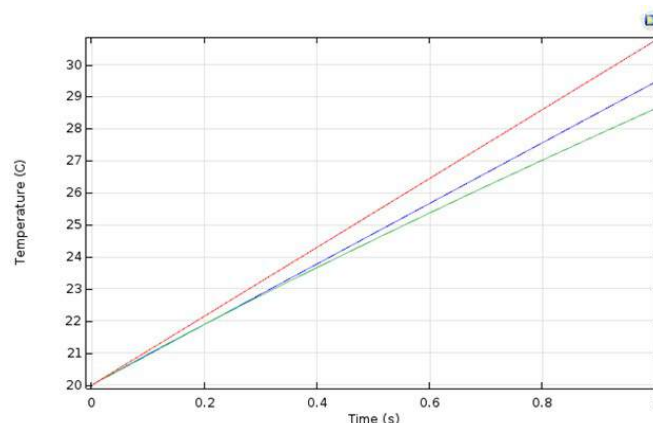
Fig. 9. Maximum temperature changes in the meniscus in the loop electrode's application area based on the COMSOL temperature distribution model: red curve – *31.0°C at the grid node on the meniscus surface; green and blue curves – 28.5°C and 29.5°C at the grid nodes in the depth of the meniscus tissue, respectively.*

The RF resection process simulation shows simultaneous and uniform heating of the knee joint meniscus and conductive fluid (0.9% NaCl) to 36°C. The simulation results in COMSOL agree with the experimental data obtained during the RF resection of an isolated meniscus (Figure 10).
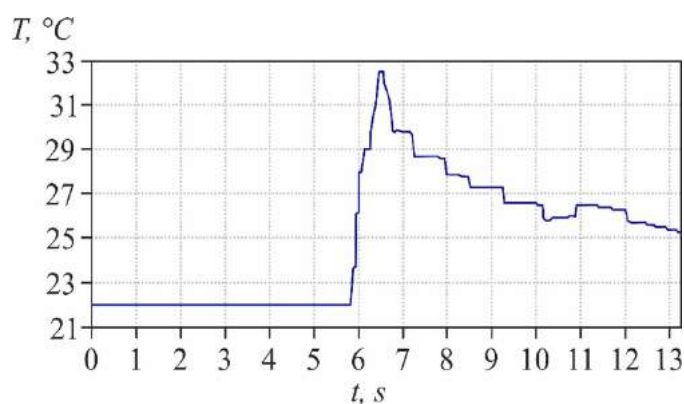

Fig.10. Average temperature changes in the meniscus in the loop electrode's application area using conductive liquid (0.9% NaCl) in the experimental data (confidence interval = 1°C; p < 0.001 for the data).

Observed average temperature changes in the meniscus in the loop electrode's application area were obtained based on 10 meniscus surface and RF plasma temperature measurements with 0.9% NaCl as the conductive fluid. In the model, the maximum temperature (31.0°C) on the meniscus surface was reached after 0.9 s. In the experiment, while 31.0°C was reached after 0.6 s, the maximum temperature (32.5°C) was reached after 0.9 s (confidence interval = 1°C, $p < 0.001$ for the experimental data). The maximum temperature difference between the experiment and the model was 1.5°C, comparable to a 1% measurement error in the temperature range 10°C–50°C. If the RF resection process model accounts for the convection

exchange between the two-phase medium (electrode–meniscus) and the surgical field, the problem becomes multifactorial. Such multifactorial mathematical problems require significant computational resources. In addition, a comparison of simulation and experimental results allows us to determine the physical characteristics important for RF resection technology. For example, 3D modelling confirms the need to use conductive fluid (0.9% NaCl) to prevent thermal tissue denaturation (Figure 11).
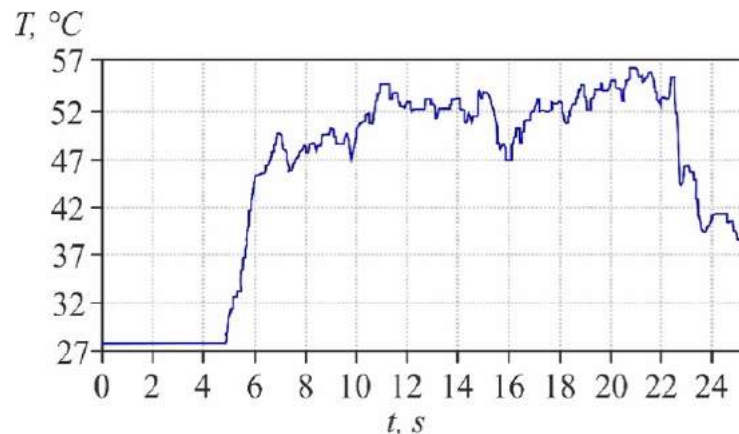

Fig. 11. Average temperature changes in the meniscus in the loop electrode's application area without using conductive fluid (0.9% NaCl) in the experimental data (confidence interval = 1°C; p < 0.001 for the data).

For the experimentally-determined average temperature changes in the meniscus in the loop electrode's application area without using conductive fluid (0.9% NaCl), the probability of the statistical model was $p < 0.001$. The confidence interval for the experimental data did not exceed 1°C. The meniscus's heating temperature during RF resection with a meniscus resector averaged 31°C–37°C with a conductive fluid and 45°C–55°C without a conductive fluid.

Tissue temperature during diathermy using a bipolar arthroscopic RF ablator ranged from 21.8°C to 39.4°C [32]. According to the user manual, the operating temperature for this electrode type ranges from 10°C to 40°C [7].

The optimal conditions for RF resection were determined based on the experimental and modelling data: (1) the meniscus's heating temperature during RF resection using a meniscus resector in a conductive fluid was 31°C–37°C; (2) the meniscus's heating temperature when performing RF resection using a meniscus resector without a conductive fluid was 45°C–55°C; (3) the temperature of the HF plasma was >37°C. Using these parameters for RF resection with the described arthroscopic instrument and a loop electrode will predictively improve the meniscal injury treatment results, confirmed by 10 clinical experiment results. Evidence supporting the efficacy of RF resection in treating meniscal injuries will be validated in future laboratory and clinical studies. The long-term postoperative effect of RF resection on the tissues surrounding the meniscus will be investigated in future studies.

Conclusions. The proposed RF resection technology can be used to perform partial resection of the knee joint meniscus. When arthroscopy is performed under conditions of a conductive fluid-filled (0.9% NaCl) knee joint, the meniscus tissue's heating temperature will not exceed the limit at which damage (denaturation) of non-target tissue occurs.

Using a pyrometer and an infrared thermograph to monitor the non-stationary temperature distribution of the meniscus is a practical example of using non-contact temperature control with RF tissue resection technology in orthopaedics and traumatology.

Studies have shown that mathematical modelling of the knee joint meniscus and conductive fluid heating processes due to a bipolar electrode through which an HF current passes closely aligns with experimental data.

This approach made it possible to develop an arthroscopic joint meniscus resector and improve arthroscopic electrosurgical instruments. The optimal conditions for RF resection obtained from thermographic studies and modelling, such as the temperature of the knee joint meniscus and conductive fluid and resection process duration, can improve meniscus injury treatment result.

Declarations
Funding and/or Competing interests
The authors declare no conflict of interest.
No funding was received for conducting this study.

Ethics approval
This study was conducted according to the Declaration of Helsinki of the World Medical Association, "Ethical Principles of Medical Research Involving Human Subjects" (1964, updated in 2013). The patient or his legal representative completed the informed consent document (approved by the Ethics Commission: ДНУ «НПЦ ПКМ» ГУД (State Institution of Science ″Research and Practical Center of Preventive and Clinical Medicine″ Ukraine), 04.07.22, protocol N. 03).

Author Contributions: Conceptualization: Bogdan Gryshchuk and Igor Boiko; methodology: Vladyslav Shlykov; software: Vladyslav Shlykov.; validation: Bogdan Gryshchuk, Igor Boiko and Nikolaj Višniakov.; formal analysis: Bogdan Gryshchuk.; investigation: Igor Boiko.; resources, Andžela Šešok.; data curation, Bogdan Gryshchuk; writing–original draft preparation, Andžela Šešok; writing–review and editing, Bogdan Gryshchuk and Vladyslav Shlykov. All authors have read and approved the published version of the manuscript. All authors agree to be accountable for all aspects of the work.

Data Availability. The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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