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Determining the Law of Movement of A Surgical Instrument in the Systems of Magnetic Stereotaxis

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Abstract:- *The forces acting on the surgical instrument moving in the neural tissue are discussed and their numerical estimates are given. The analysis of motion equation of a surgical instrument is provided with the purpose of increasing the efficiency of control systems for the surgical instrument in apparatus employing the principle of contactless magnetic stereotaxis.*

Keywords:-*radiography, mathematical model, stereotactic apparatus , electromagnetic system control , algorithm control , the coordinates, predict of direction.*

Introduction:

For high-precision neurosurgical operations on deep-seated humane brain structures, stereotaxic equipment is traditionally used where principle of direct mechanical control of surgical instrument (probe, canula, or electrode) is implemented. The instrument is inserted into the brain along straight-line path. With such approach, due to location of vital centers in close proximity to the operation area a number of deep-seated neoplasms are beyond the reach of surgical intervention (some thalamus textures and subthalamic region) that does not offer the possibility for providing adequately efficient treatment of a number of diseases of extrapyramidal nervous system, localized neoplasms, etc. High traumatism of surrounding tissues in the course of multiple aiming operations causes heavy complications in a number of cases. Therefore, this technique developed in order to allow operating deep-seated brain structures along arbitrary curvilinear trajectory of reasonably complex configuration. One of them is magnetic stereotaxis.

Technique of Remote Control of Movement Contactless Surgical Instrument Movement:

The method is based on remote contactless control of a surgical instrument the moving part of which is a tip made of ferromagnetic material by means of external constant magnetic field. In this case due to possibility of optimal selection of place for application of a burr hole and less traumatic nonlinear trajectory of the surgical instrument movement minimal damage of surrounding tissues is obtained. To form the required magnetic field parameters systems for electromagnetic control of a surgical instrument contain movable [1,2] or stationary [3,4,5] electromagnetic coils with adjustable current value. Application of magnetic coils without ferromagnetic cores results in linear dependence between the values of magnetic field induction and current in coils. Moreover, the magnetic field induction created by the system of coils is the superimposition of magnetic field induction of individual coils. Control algorithm in these systems is based upon manipulating the values of current in magnetic coils (as well as coils position coordinates in case of possibility of their mechanical displacement) to create magnetic field gradient characteristics, which provide movement of a surgical instrument along the preplanned trajectory, control of its position according to data of direct visual feedback system implemented with the help of orthogonal X-ray radiography and automatic formation of controlling actions in order to eliminate mismatching between the required and actual positions of a surgical instrument. Accuracy of a surgical instrument positioning depends upon the degree of accuracy of demining magnetic field power characteristics and determining the ratio between absolute values and directions of magnetic and resulting extraneous (non-magnetic) forces. Thus, the necessity of real-time manipulation of a surgical instrument imposes heavy demands on the response speed of control system and primarily on computation algorithms of magnetic field induction [3]. Requirements to precision positioning of a surgical instrument in existing experimental magnetic stereotaxis systems includes X-ray pictures of operation area in the two mutually perpendicular views with the frequency of up to 3 times per second [5] and corresponding increase of radiation exposure. Besides, lack of information on external (non-magnetic) forces acting on a surgical instrument decreases control efficiency [8]. Therefore, development of control algorithms, which consider physical processes taking place in the process of displacement of a surgical instrument in neural tissue, is essential.

The law of movement of a surgical instrument in the coil magnetic field (in vector form, according to Newton's second law) is given by:

$$\vec{F}_{\text{р}} = \vec{F}_{\text{м}} + \vec{F}_{\text{c}} + \vec{F}_{\text{т}} + \vec{F}_{\text{A}}\ , \qquad (1)$$

where $\vec{F}_{\text{р}}$ is resultant force acting on a surgical instrument; $\vec{F}_{\text{м}}$ is mechanical force acting on a surgical instrument from the direction of external magnetic field; $\vec{F}_c$ is resistant force, which occurs during movement in viscous medium; $\vec{F}_{\text{т}}$ is force of gravity; $\vec{F}_A$ is buoyancy force.

The force, which causes mechanical displacement of a surgical instrument in external magnetic field, is determined according to [6]:

$$\vec{F}_{\text{м}} = (\vec{m}\nabla)\vec{B}\ , \qquad (2)$$

where $\vec{m}$ is magnetic moment of a volume occupied by ferromagnetic; $\vec{B}$ is magnetic field induction vector. Expression (2) determines a vector, which is in opposition to the gradient of magnetic dipole potential energy in external magnetic field. The force applied to the surgical instrument from the magnetic field is directed towards the increase of magnetic field induction.

Considering neural tissue by its mechanical properties is a viscous fluid [7], according to Stokes model, surgical instrument travel resistance is determined as:

$$\vec{F}_{\text{c}} = -b\vec{v}\ , \qquad (3)$$

where b is drag factor; $\vec{v}$ is speed of surgical instrument movement.

$$\vec{F}_m = m_u g\ , \qquad (4)$$

where m_u is surgical instrument mass; g is gravity factor.

Buoyancy force applied to the surgical instrument immersed into neural tissue is determined from:

$$\vec{F}_{\text{A}} = \rho g V\ , \qquad (5)$$

where ρ =1.27·103 kg/m3 is gelatin density which is equivalent to neural tissue by its physical properties [6, 7], V is volume of ferromagnetic tip of a surgical instrument.

With provision for (2, 3, 4, 5) for forces acting on a surgical instrument according to (1), surgical instrument dynamic equation in vector form when moving in a direction opposite to force of gravity:

$$m_{\text{и}}\frac{d^2\vec{s}}{dt^2} = (\vec{m}\nabla)\vec{B} - b\frac{d\vec{s}}{dt} - m_{\text{и}}g + \rho g V\ , \qquad (6)$$

where $\vec{s}$ is radius-vector of a surgical instrument position.

By this means, resistant force with the module that linearly depends upon displacement speed and constant opposite acting forces of gravity and buoyancy force act on a surgical instrument that moves under ponderomotive force of the magnetic field.

Let us determine the numerical values of forces in equation (1), with respect to Magnetic Stereotactic System (MSS (Stereotaxis inc.)) [3], currently having the best technical performance. The system includes 6 superconducting magnetic coils shown in Fig.1 which are paired in mutually perpendicular planes (1, 2 – at right angles of axis X of the system, 3,4 –Y, 5,6–Z).

Maximum value of current in coils is 100A. Coils internal diameter range within 280 to 321mm, external: 372–411mm, length: 37.2–71mm. Coils along axis Z (which is perpendicular to the drawing plane) have a greater diameter and a smaller length.

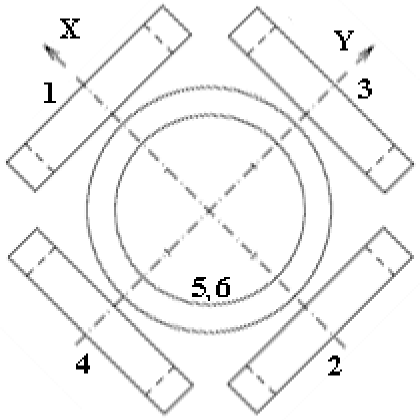


Fig.1. General schematic arrangement of magnetic coils in MSS system.

Surgical instrument for thermal destruction of surrounding tissue by means of external high-frequency external electromagnetic field (10–40 МГц) is a circular cylinder with diameter of 3mm and length of 3mm, mass m_u = 0.187g made of ferromagnetic material, magnetized to saturation with a magnetic moment module $|\vec{m}|$=0.016A·м2 .

In order to determine the coil magnetic field method of equivalent representation of coil winding in the form of an aggregate of circular windings and algebraic summation of the corresponding induction components produced by individual windings was used. For cutting computation time approximation of several coil windings by idealized loop of winding was carried out with provision for the fulfillment of the condition:

$$a_{cp} << d_{k\min},$$

where a_{cp} is average dimension of idealized winding wire cross section; $d_{k\min}$ is minimum magnetic coil diameter.

Magnetic induction of a single turn was determined using the method of vector potential that allows expressing the components in terms of complete elliptic Legendre integral. This method involves improved accuracy of computation in comparison to the method used in MSS [3], which is based on interpolation of values of magnetic field induction components found in supporting points by means of numerical integration in terms of coil volume according to Biot – Savart Law. Mechanical force acting on a surgical instrument from the direction of the magnetic field of an individual coil with winding current of 100A averages approximately 0.03 N in the operating area approximately 200 mm away from the coil. Components of magnetic induction vector are the linear functions of the coil current.

Drag factor normalized to the unit of surgical instrument length gives: $b = 2.56\text{Н}\frac{\text{с}}{\text{м}\cdot\text{мм}}$ [7].

Absolute value of the force of gravity is determined according to (4):

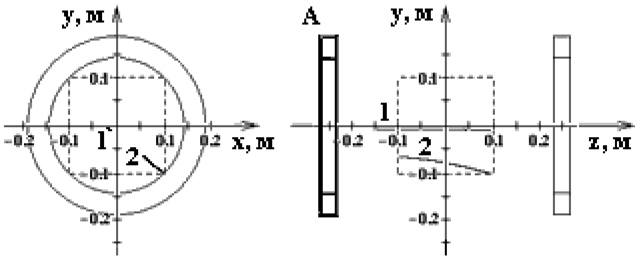
$$|\vec{F}_m|=1.83 \cdot 10{-}3 \text{ Н}.$$

Buoyancy force module directed in opposition to the force of gravity is determined from (5): $|\vec{F}_A|$=0.261 · 10–3H.

Solution of differential equation (6) of the second order was carried out by Runge-Kutta numerical technique . Fig.2 shows trajectory of the surgical instrument movement in the magnetic field of a single coil with internal diameter of 0.28 mm. The coil with a current of 100A in the winding is denoted as A. Operating area in MSS is a cube 200 mm on a side. Initial points of trajectory 1,2 of the surgical instrument movement is at a distance of 320 mm in the axial direction of the first turn of coil A. From the analysis of trajectories 1,2 of the movement it follows that at a distance of approximately 200 mm in the axial direction from the plane of the first turn of the coil radial component of the power vector acting on a surgical instrument reverses sign: at a long distance from the plane of the first coil turn the surgical instrument moves in a radial direction to the coil axis, at a shot distance it moves from the coil axis. Moreover, the value of the radial component of magnetic field ponderomotive force increases with moving away from the coil axis. In the axial direction the surgical instrument moves to the plane of the first coil turn regardless of the polarity of the flowing current – towards the increase of the magnetic field induction. Maximum travel speed in the operating area makes approximately 3 mm/s in the field of a single coil.

The results of the analysis of the law of the surgical instrument movement in the field of magnetic coil make the principle of formation of controlling action in MSS apparent: displacement along each coordinates axis should be carried out by coils which axis matches the direction of movement. Lateral coils (located at right angles of the given coordinate axis) are used to compensate lateral misalignment of the surgical instrument. By gravity, the surgical instrument moves in the neural tissue in steady state at a constant speed of approximately 0.2 mm/s, which should be counterbalanced by forming corresponding control actions. When using flexible catheter with ferromagnetic tip as a surgical instrument [4,9], displacement by gravity when inserting catheter approximately 50 mm deep is next smaller that allows implementing pulse control of a surgical instrument.

Determination of the law of movement allows creating mathematical model of the stereotax system based on determining the coordinates and the speed of movement of a surgical instrument at an arbitrary point of time by known initial data. Use of this mathematical model offers the possibility of predicting the direction and speed of the surgical instrument movement with arbitrary magnetic field parameters with consideration of external non-magnetic forces.



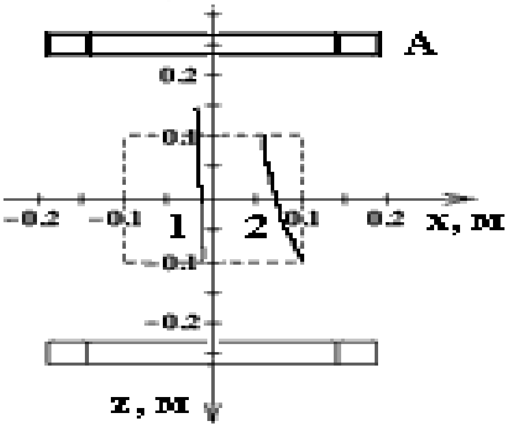


Fig. 2. Mapping of trajectories 1,2 of the surgical instrument movement in magnetic field of Coil A.

Conclusions:

This allows direct visual X-ray control in the trajectory supporting points that results in the decrease of ionizing radiation dose by several times. Formation of control actions based on simulation modeling data allows increasing accuracy and efficiency of the systems for surgical instrument magnetic control.

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