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An Attempt of Determining the Force Characteristics of Fields in Magnetic Stereotactic System

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***Abstract*— Method for analytical determination of the components of magnetic field induction vector and gradient characteristics of magnetic field in stereotactic magnetic neurosurgery systems has been investigated. Components of power vector acting on a surgical instrument from magnetic coil field have been determined and the analysis of topography of magnetic field power characteristics has been carried out.**

***Keywords*—Magnetic Fields, Magnetic Stereotactic System (MSS), Magnetic Controlling Surgical Instrument, Contactless Stereotactic.**

I. INTRODUCTION

Methodology of surgery of deep-seated brain structures is based on stereotactic principle that allows local access to intracerebral lesions by means of intracranial anatomic mapping and specialized surgical instrumentation. By doing so clinical effect of surgery depends upon the accuracy of hitting the assigned cerebral structure with a surgical instrument as well as a degree of traumatizing surrounding tissues.

II. STATEMENT OF THE PROBLEM AND THE TARGET

The basic component of these neurosurgical interventional systems is the device, providing precision manipulation of a surgical instrument - stereotactic apparatus. Principle of the rigid connection of intact part of surgical instrument with a guide assembly which is implemented almost in all the models of modern stereotactic apparatus permits only rectilinear insertion of a surgical instrument deep into the brain that considerably restrains the possibility of surgical approach and makes multiple aiming surgery excessively intrusive. As part of the existing approach it is extremely difficult and sometimes impossible to ensure intervention into brain stem structures and localized neoplasms of this area. Alternative to traditional stereotaxis is the radiotherapy method based on focusing ionizing radiation of the system of radioactive emitters in the area of surgery. However, these systems are able to provide only a destructive effect on the operated structures. Therefore, the actual problem is the development of a universal method of influence on intracerebral neoplasms, combining optimum access to stereotactic "target" and a wide range of remedial measures, including the introduction of drugs, biopsy, and transplantation of embryonal neural tissue, electrical and laser stimulation of abnormal structures. A promising way to affect the deep-seated brain structures is the magnetic stereotaxic. This method, which is currently at the stage of experimental studies, is based on surgical instrument control by means of external constant magnetic field. Due to the possibility of contactless control of tool tip immersed into the brain tissue, this method allows optimal access to the operated structures on curvilinear, pre-calculated trajectory, ensuring minimal trauma of vitally important centres' of neural activity.

III. THE TECHNIQUE OF CONTACTLESS STEREOTACTIC SURGICAL INSTRUMENT

Surgical instruments in magnetic stereotaxis systems is a flexible catheter or implant for the high-frequency thermal decomposition with an external diameter of about 2 to 3 mm, the operating part of which is the tip made of hard-magnetic material with high values of residual magnetic induction and coercive force, which is approximately regarded as a precision magnetic dipole [1]. Formation of an external magnetic field of assigned configuration is

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carried out by means of magnetic coils moving around the operating area [2,3] or fixed coils[1,4,5] with controllable magnitude of the current. Taking extraneous (non-magnetic) forces into account the law of surgical instrument movement in the neural tissue under external magnetic field is defined (in vector form):

$$\vec{F}_p = \vec{F}_м + \vec{F}_c + \vec{F}_m + \vec{F}_A \ , \qquad (1)$$

Where $\vec{F}_p$ the resultant force is applied to the surgical instrument; $\vec{F}_м$ is mechanical force, applied to the surgical instrument from external magnetic field side; $\vec{F}_c$ is drag force, appearing during movement in neural tissue; $\vec{F}_m$ is force of gravity; $\vec{F}_A$ is Archimedes' buoyant force. Moreover ponderomotive force which characterizes magnetic field mechanical action is defined according to [6]:

$$\vec{F}_м = (\vec{m}\nabla)\vec{B} \ , \qquad (2)$$

Where $\vec{m}$ is vector value which characterizes moment of magnet of the dimension of "active" part of surgical instrument, $\vec{B}$ is external magnetic field displacement vector? It follows from (1), that in order to move a surgical instrument in a required direction it is necessary to form nonhomogeneus magnetic field possessing adequate gradient characteristics determining module and direction of mechanical force (2) which is capable of compensating external (nonmagnetic) forces strength applied to the surgical instrument and move in neural tissue (viscous medium which is equivalent to gelatin [7] by its rheological properties) with assigned speed. For this reason a top-priority objective is to determine magnetic field power characteristics (displacement vector and derivatives of its components by the coordinates). In so doing requirement to form real-time controlling manipulations based on calculation of surgical instrument displacement equation imposes heavy demands on performance of magnetic field parameters calculation algorithm.
Thus, in mathematical description of the magnetic stereotactic system (MSS) developed by Stereotaxis Inc. [1] calculation of the total field induction generated by the magnetic coil is carried out using numerical integration of the induction produced by current elements, according to the coil winding (according to Biot – Savart Law) :

$$\vec{B} = \frac{\mu_0}{4\pi}\int_V \frac{[\vec{j} \times \vec{r}]}{r^3} dV \ , \qquad (3)$$

Where $\vec{j}$ is bulk current density, $\vec{r}$ is distance vector from current element to the point where estimation of magnetic induction is carried out. Absence of magnetizable media enables the application of the principle of superimposition in calculating a complete field produced by the system of the six toroidal coils paired in orthogonally-related planes. Considering computation-intensive task MSS mathematic model employs combined method of magnetic field characteristics computation which is based on accurate determining of induction (according to Biot – Savart Law) in supporting points matrix with further interpolating[1].
This paper provides the method of representation of a magnetic coil as a set of series-connected circular current loops having common axis and algebraic summation of corresponding components of induction produced by individual coils. Determining magnetic induction of an individual coil is carried out by means of vector potential method [6]:

$$\vec{A} = \frac{\mu_0}{4\pi}\oint_l \frac{I}{r'} d\vec{l} \ . \qquad (4)$$

Where r′ is distance from current element $Id\vec{l}$ to point M.
Due to axial symmetry of the system calculation of magnetic field characteristics is carried out in cylindrical coordinates system. Keeping in mind current flow direction in the cylindrical coordinates system, only angular component A_α of the vector potential would be other than zero and using vector analysis formulas for transition to magnetic field induction (according to vector potential definition):

$$\vec{B} = rot\vec{A} \ , \qquad (5)$$

We obtain axial B_z and radial B_r components of magnetic induction vector:

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$$B_z = \frac{\mu_0}{4\pi} \cdot 2I \cdot \frac{1}{\sqrt{(a+r)^2 + z^2}} \cdot \left[K(k) + \frac{a^2 - r^2 - z^2}{(a-r)^2 + z^2} E(k) \right], \quad (6)$$

$$B_r = \frac{\mu_0}{4\pi} \cdot \frac{2Iz}{r\sqrt{(a+r)^2 + z^2}} \cdot \left[\frac{a^2 + r^2 + z^2}{(a-r)^2 + z^2} E(k) - K(k) \right], \quad (7)$$

Where I is value of current flowing along the winding, a is the radius of the winding, r, z are cylindrical coordinates of the point, where magnetic induction vector is located, $K(k)$ and $E(k)$ are complete Legendre elliptic integrals of the first and second kinds [8]. Due to axial symmetry of the system magnetic field vector angular component is equal to zero.

In the process of determining complete induction of magnetic field created by the coil for calculation time reduction approximation of several winding turns is carried out with an equivalent turn (with consideration of the fulfillment of the model perfection condition):

$$a_{cp} << d_{k\min}, \quad (8)$$

Where a_{cp} an average equivalent winding turn is cross section; $d_{k\min}$ is minimum magnet coil diameter.

From expressions (6) and (7) it follows that magnetic field induction is the linear function of current flowing along the coil winding. On the coil axis magnetic field induction vector is determined by axial component only. The following continuous-tone illustrations of distribution of components and module of magnetic induction vector value (see Fig. 1), make it possible to predetermine absolute value and the degree of nonuniformity of the field in the operating area (dotted), which is a cube with the side of 200 mm, where surgical intervention area is located.

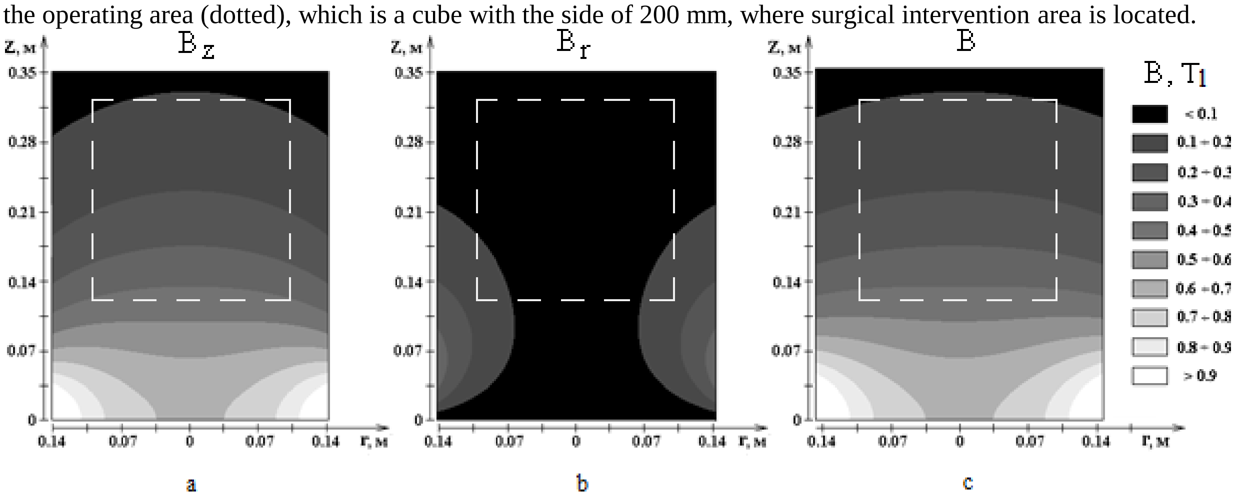

Fig.1: Halftone Illustrations Distribution of Magnetic Induction in the Coil:
A - Axial Component, B - Radial Components, C - The Absolute Value of the Magnetic Induction

Pictures have been made for toroidal-core superconducting magnet coil with internal diameter of 280 mm and external diameter of 372 mm and 70,1 mm long, specific coil turns per window square centimetre of 207.2, with winding amperage of 100A. In the specified operating area axial component of induction vector of magnetic field generated by the coil (Fig.1.a), increases on approaching to the plane of the first coil turn, while the field nonuniformity in axial direction is several times greater than its nonuniformity in radial direction, which is also observed for induction vector absolute value (Fig.1.c). Radial component of magnetic field induction value (Fig.1.b) is 5 to 6 times less than the axial one and is relatively uniform along all directions in the operating area. Calculation of the force acting on the surgical instrument from external magnetic field is carried out according to formula (2) by numerical determination of derivative components of magnetic induction vector with respect to the coordinates. Fig 2. Shows continuous-tone illustration of axial and radial components as well as the module of magnetic induction vector. Hard-magnetic alloy (Nd–Fe–B) permanent magnet with magnetic moment of 0.016 A·м2 [1] is used as a surgical instrument tip.

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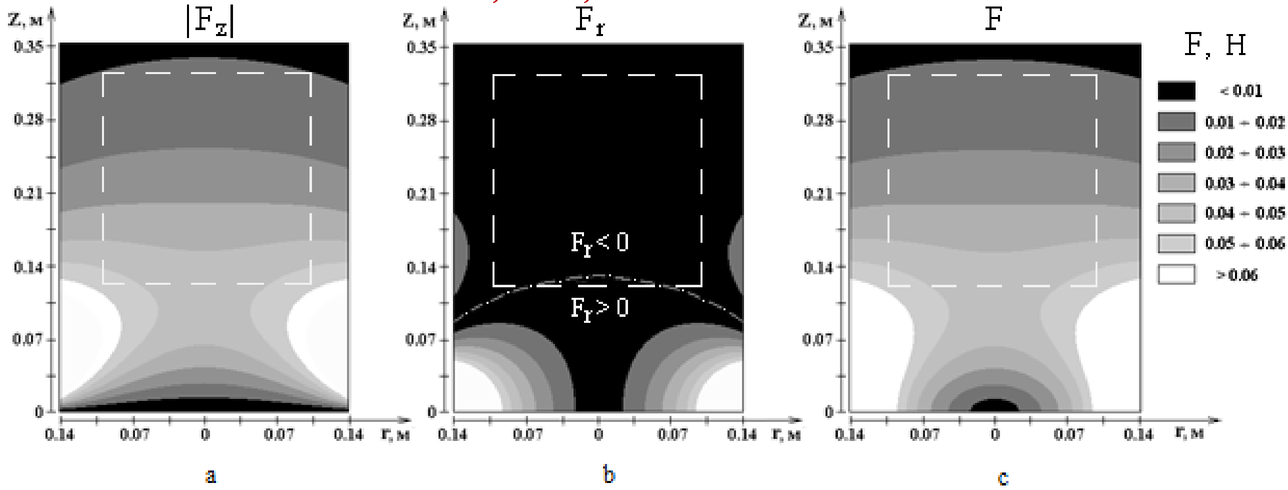

Fig.2: Halftone Illustrations Distribution Of Mechanical Forces Acting On The Surgical Instrument

A - Axial Component, B - Radial Components, C - The Absolute Value Of The Vector Of Mechanical Force

Absolute value of axial component (Fig.2.*a*) and power vector module (Fig.2.*c*) increase with approaching to the plane of the first coil turn with the axial component directed at reducing coordinate z. This means that the surgical instrument will be drawn to the coil irrespective of direction of current flowing along its winding, moving towards the increase of magnetic field induction (See Fig.1) – to the minimum of magnetic dipole potential energy in external field which is determined as:

$$W = -(\vec{m} \cdot \vec{B})\,. \qquad (9)$$

Power radial component (Fig.2.b) which in the major part of operating area is directed to the coil axis reverses sign. In the lower zone of the operating area it is directed towards the increase of the coordinate r. Due to a lack of magnetizing media, determining of the resultant field and the ponderomotive force is carried out on the principle of superimposition. Analysis of topography of the coil magnetic field and its power characteristics in MSS system shows that bidirectional movement of the surgical instrument along axis z is possible exclusively by means of two coils located symmetrically with respect to operating area center. In this case compensation of power radial component which causes lateral displacement of the surgical instrument should be provided by means of two pairs of coils located in perpendicular planes.

IV. Conclusion

Computational advantages of the method include its rapid response (order of magnitude greater than a similar indicator for magnetic field calculation numerical technique according to Biot–Savart Law) and improved accuracy (when reducing computation speed approximately four-fold), as compared with interpolation method of inductance computation by predetermined supporting points matrix. This makes possible to drop tedious method of magnetic field combined calculation suggested in [1], and to carry out direct calculations of magnetic field power characteristics in arbitrary point of operating area with minimum computer time which is a relevant issue when developing new and investigating existing systems of contactless stereotactic magnetic control of a surgical instrument.

REFERENCES

[1] Meeker .D.C., Maslen .E.H., Ritter R.C., Creighton F.M, “Optimal realization of arbitrary forces in a magnetic stereotaxis system,” IEEE Transactions on Magnetics. - 1996.V.7. - P. 320–328. 2.

[2] Howard .M.A. 3d, Grady M.S., Ritter R.C et al, “Magnetic movement of a brain thermometers,” Neurosurgery.-1989.V.24.-№ 3.– P. 444–448.

[3] Quate .E.G., Wika K.G., Lawson M.A. et al, “Goniometric motion controller for the superconducting coil in a magnetic stereotaxis system,” IEEE Trans. Biomed. Eng.-1991. V. 38.- № 9. P.899–905.

[4] Grady .M.S., Howard .M.A.3d, Dacey .R.G. et al, “ Experimental study of the magnetic stereotaxis system for catheter manipulation within the brain ,” J. Neurosurg.2000.-№ 93(2). P.282–288.

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[5] Howard .M.A. 3d., Grady .M.S., Ritter .R.C. et al, " Magnetic neurosurgery ," Stereotact. Funct. Neurosurg.- 1996.Vol. 66.- № 1–3. P.102–107.

[6] Ye Bai; Qiuliang Wang; Ming Yang; Yunjia Yu; Hongwei Liu; Keeman Kim " Characteristics of an Improved Coil Structure for the Magnetic Stereotaxis System," IEEE Transactions on Applied Superconductivity, ISSN 1051-8223, 2005, Volume 15, Issue 2, pp. 2344 - 2347

[7] Benjamin," neurosurgery," 01/2010, 1st Edition. European Manual of Medicine, ISBN 9783540795643, p.665.

[8] Tamm. I.E, "Fundamentals of theory electricity Moscow. Scientific.-1976.-616 c.

[9] Ritter .R.C., Quate E.G., Gillies G.T. et al, "Measurement of friction on straight catheters in vitro brain and phantom material," IEEE Trans. Biomed. Eng.- 1998. Vol. 45.- № 4: P.476–485.