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Navigation Systems in Neurosurgery

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When preparing the review, we analyzed publications available in the Medline database; a total of 1,083 publications related to the review's subject were analyzed. After more careful analysis, we selected 117 publications devoted to the development of neuronavigation in craniocerebral surgery, its historical background, current trends, and future prospects of the technique.

Keywords: neurosurgery, neuronavigation, stereotaxis, computer-assisted neurosurgery.

At the initial stage, the development of neurosurgery was limited by technical level of that time. The lack of accurate and objective anatomical assessment of the relationship between paraplasm and surrounding structures in each individual patient [1—3] was another major limitation. Fundamental studies on the functional brain mapping, which were started as early as in the XIX century by Broca, Wernicke, Exner, and Dejerine, provided data on the architectonics of the key functional systems and their topical representation in the cerebral cortex [4, 5]. W. Penfield significantly contributed to this work [6]. Nevertheless, it was difficult to assess the individual characteristic features of the anatomy and neurophysiology of each individual patient. There was an urgent need to integrate these data and present them to neurosurgeons. This problem could not be solved until 1970s due to the absence of direct brain imaging methods, possibility of mathematical processing and alignment of various data.

The instruments for frame-based stereotactic navigation laid the basis for the development of neuronavigation systems. In 1873, H. Dittmar et al. [7] used the instrument, which provided approach to the neoplasms in the medulla oblongata of laboratory animals for the first time in a neurophysiological laboratory. The pioneering work of D.N. Zernov 1889 [8] marked the beginning of stereotactic surgery on the human brain. Further development of the method was associated with the studies of Clarke and Horsley, who developed the device to study the brain of monkeys of in 1906—1908. Ranson and Ingram obtained basic information about the functions of the reticular formation, hypothalamus, and midbrain, using frame-based stereotaxis and modified Horsley-Clarke apparatus [10]. Kirshner has overcome the difficulties of the use of stereotaxis in humans associated with variability of the relationship between the skull bones and brain structures, which enabled thermal ablation of the trigeminal ganglion in a patient with trigeminal neuralgia for the first time, using originally designed stereotactic device [11]. In the second half of the 1940s, E. Spiegel and H. Wycis [12] used the stereotaxic atlas, which they previously developed, in combination with the data of contrast ventriculography and position of the pineal gland to localize intracranial anatomical structures and describe the use of frame-based stereotaxis during neurosurgery. L. Leksell significantly contributed to the development of these techniques [13]. In 1949, he developed his own construction of stereotaxic apparatus. Later on, J. Talairach, E. Monnier, T. Riechertand, and F. Mundinger [14—16] developed original stereotaxic devices for functional interventions. The articles of Russian authors E.I. Kandel and V.V. Peresedov [17—19] reported the results of the use of the original stereotaxic apparatus in the cryosurgery of the subcortical structures, as well as clipping of cerebral arterial aneurysms.

The development of X-ray diagnostic technique significantly expanded the possibilities of neurosurgical pathology diagnosis. In 1908, F. Krause et al. [20] devoted a separate chapter of their multi-volume neurosurgery guide to radiodiagnosis of neurosurgical diseases and identified characteristic features of some of them. The development of pneumoventriculography was the next milestone [21]. The capabilities of the contrast cerebral angiography proposed by E. Moniz [22, 23] greatly improved neurosurgeon's knowledge about the individual anatomy and pathological anatomy of patient's cerebral structures.

The use of metabolic navigation was based on the discovery of the phototoxicity phenomenon in the early XX century and was associated with the studies of Raab and von Tappeiner [24]. In 1924, Policard showed that some malignant human tumors fluoresce in the orange-red spectral range when irradiated with ultraviolet light [25]. This effect is due to the formation of endogenous porphyrins in tumors, which have been confirmed by fluorescence of experimental tumors in the red spectral region in animals pre-administered with hematoporphyrin [26]. The first study on the use of fluorescein dye during neurosurgical operations in patients with brain tumors was published by G. Moore in 1947 [27]. Fluorescein is not widely used in neurosurgical practice due to its toxicity and low specificity of the method. The paper of B.A. Samotokin et al. [28] reported the use of organic dyes for intraoperative imaging of brain tumors. F.A. Serbinenko et al. [29] used the technique of superselective intravascular injection of dyes in tumor-supplying vessels. However, this method cannot be used in routine practice due to insufficient specificity and reproducibility of the results and toxicity of preparations.

Since the mid-1990s, idocyanin green dye, which is fluorescent in the infrared range, is used for intraoperative visualization of blood vessels (both in normal brain tissue and in tumors). The possibilities of modern surgical microscopes (e.g., Zeiss OPMIpentero) enable color mapping, determining the direction of blood flow [30, 31].

Pioneering studies of the metabolism of porphyrins and visualization of leukemic cells using 5-aminolevulinic acid were reported by Z. Malik et al. [32] in 1979. It was shown that 5- aminolevulinic acid is metabolized by enzyme systems that

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are active only in tumor cells to produce protoporphyrin IX, which is fluorescent under external light source having certain wavelength [33]. In the late 1990s, the first reports on the possibility of using 5-aminolevulinic acid in neurosurgery were published [34]. Later studies showed that the use of metabolic navigation improves the extent of tumor resection and increases disease-free and overall survival of patients with malignant gliomas [35]. The studies of A.A. Potapov et al., S.A. Goryaynov et al. [36, 37] have shown that metabolic navigation using 5-aminolevulinic acid can be applied not only in gliomas, but also in meningiomas. Currently, the ways to improve sensitivity of fluorescence diagnosis in the surgery of low-grade gliomas and metastases are being investigated [36, 38]. In the absence of visible fluorescence, the authors suggested laser spectroscopy method to estimate the concentration of amino-levulinic acid in the tumor tissue and thus differentiate it from the healthy brain [24, 37, 38].

Along with fluorescence, high resolution mass spectroscopy is another promising method for ultrafast real-time intraoperative identification of tissues. The method provides molecular "fingerprints" based on the analysis of lipids and proteins produced in the ionization mass spectra, which enables characterizing various brain tumor [39].

Radioisotope-based diagnostic techniques are being used since the mid 1950s — early 1960s [40]. Various isotopes were used, such as iodine(^{111}I,^{123}I,^{125}I), bismuth, mercury, gold, technetium, copper, and labeled serum albumin [41]. In 1964, the article of E.V. Kotlyarov [42] reported the results of the use of radioactive phosphorus for intraoperative localization of brain tumors. The study of M. Fischer et al. [43] published in 1977 showed that radioangiography is more sensitive than scintigraphy, when determining the histological structure of the tumor. At the same time, the latter enables more reliable assessment of tumor vascularization. The study of A.N. Konovalov [44] published in 1980 notes very high sensitivity of perioperative beta-radiometry, which enabled tumor localization in 98% of cases. Later studies showed that positron emission tomography with 11C-methionine involved in the metabolic pathways in tumor cells is more specific for glial tumors. The data on the accumulation of methionine enable determining the degree of anaplasia, selecting the target for stereotactic biopsy, differentiating between radiation necrosis and continued tumor growth, developing a predictive model for the patient [45, 46]. F.M. Lyass and E.Ya. Shcherbakov [47—49] investigated the role of radionuclide studies in the diagnosis of CSF system diseases, intracranial inflammation, and the consequences of traumatic brain injury. Currently, single-photon and positron emission tomography are mainly used for differential and topical diagnosis of various pathological processes; these methods have significant limitations [46] in intraoperative navigation.

X-ray computed tomography (CT) is based on the studies of Oldendorf, Hounsfield, and Cormack. The first ever in vivo image of patient's brain was obtained in 1972 [50, 51]. In 1976, L. Jacobs et al. [52] compared the results of computed tomography and 79 autopsies, the accuracy of intracranial pathology diagnosis was 86.2%. Today, CT with intravenous contrast and perfusion techniques enable assessing the condition of the blood flow in the mass lesion and perifocal zone in different parts of the brain, including its deep structures and brainstem [53—57]. The study of J. Maroon et al. [58] focusing on the use of CT to navigate the puncture emptying of tumor cysts and brain abscesses was an important milestone in neurosurgery. In 1979, R. Brown [59] presented the results of successful use of CT and three-dimensional computer graphics for stereotactic localization of targets in a phantom with installed special stereotactic frame. Later on, the results of clinical application of CT to calculate stereotactic surgery (functional neurosurgery and tumor biopsy) were reported in the articles of J. Boethius, B. Czerniak, and Z. Krzystolik [60—62].

Intraoperative CT was developed in various fields of neurosurgery to specify the completeness of tumor resection, eliminate intraoperative complications, intraoperatively correct navigation information, and provide more accurate implantation of stabilization system elements in spinal neurosurgery [63—66].

The studies of F. Cope and R. Damadian [67], who used magnetic resonance to determine the concentration of potassium ions in a bacterial cell in 1970, provided the basis for magnetic resonance imaging (MRI). Obtaining information about tumors in vivo was made possible through the use of a field-focusing nuclear magnetic resonance, FONAR [68]. The first magnetic resonance image of the human chest was obtained in 1977 [69]. The first commercially available magnetic resonance imager (MRI) was produced in 1980 [70]. When comparing CT and MRI for stereotactic interventions, W. Birg et al. [71] noted high accuracy of the latter, better visualization of brain structures located close to the bone tissue, as well as the absence of necessity for contrast ventriculography during functional operations.

Intraoperative MRI also enables intraoperative correction of navigation data and improves the completeness of surgery. However, it requires special equipment in the operating room, non-magnetic devices and instruments [72]. Low-field portable MR scanners require longer scan time due to low resolution, which lengthens the operation time and does not enable perfusion or spectroscopic studies during the operation. High-field MRI scanner, providing better image quality and wider visualization capabilities due to larger number of sequences, are difficult to integrate into existing operating rooms, requiring either major modernization of the operating unit or its reconstruction with allowance for MRI placement. In addition, the use of high-field scanners is associated with image artifacts and requires long-term personnel training.

Furthermore, intraoperative use of CT and MRI is very expensive and it is not available in all hospitals.

Intraoperative use of ultrasound (US) is the most available and simple method for navigation and localization of neoplasms and correction for brain displacement [73]. Application of three-dimensional US-navigation, such as Sonowand Invite system, improved surgeon's orientation, provided adequate assessment of the completeness of paraplasm resection and identification of intraoperative complications, including those in ventriculoendoscopic surgery [74—76]. Along with Sonowand system, a combination of a separate expert-level ultrasonic scanner, control computer, and neuronavigation system were used for intraoperative three-dimensional US-scanning and navigation [77, 78].

The effect of brain displacement reduces the accuracy of intraoperative navigation [79, 80]. Reliable prediction of the magnitude and direction of brain displacement is not possible [81]. Correction for brain displacement can be achieved using intraoperative computed tomography or MR imaging, as well as ultrasound study.

The development of neuronavigation systems, which made all of the above methods as much applicable as possible from the neurosurgeon's viewpoint, was the logical

continuation of the studies of intraoperative visualization of paraplasms and other brain lesions. Currently, the most accurate and sparing approach to the pathological lesion is possible in each particular patient.

Since the inception of neuronavigation systems, they developed along two parallel lines determined by the used monitoring techniques, optical (active or passive) or electromagnetic.

In the first report of A. Kato et al. [82] on the frameless electromagnetic navigation, the system which enables monitoring of inclination and spatial arrangement of the surgical instrument equipped with electromagnetic sensor to within 4 mm was described. ISG Magic Wand system produced in 1992 was the first commercially available neuronavigation system. It was a manipulator consisting of six segments, where a special pointer, rigid endoscope, or biopsy needle can be installed. This system was used for navigation in brain tumors, epilepsy surgery, ventriculoscopic operations, stereotactic biopsies, pathology of the skull base, posterior fossa, clivus, and superior cervical vertebrae [83—85]. This system could not be used for functional neurosurgery due to inability of rigid fixation of navigation manipulator and relatively high error (>2.2 mm) [86].

The operation principle of electromagnetic navigation systems is based on the fact that a special generator (running on DC or AC) creates an electromagnetic field around the patient's head, which is the coordinate system where the reference and surgical instrument equipped with a built-in electromagnetic sensor or special adapter are positioned. Spatial movement of the sensor changes the characteristics of the field at this point, which allows the navigation system to determine the coordinates of the instrument. The dimensions and placement of the sensor on the instrument may vary, affecting the functionality of the system: for example, Medtronic Stealth Station 7 navigation system (Medtronic, USA) incorporates a separate external electromagnetic navigation module and DC electromagnetic field generator; sensors in disposable instruments are located in the handle, which prohibits changing the length of the instrument during the operation or its bending. At the same time, Fiagon navigation system (Fiagon GmbH, Germany) include electromagnetic field generator operating on alternating current, and instruments contain two sensors: one of them is located on the working end of the instrument and the other is located on the handle, which allows the surgeon to model (bend) the instrument depending on the operating situation, while preserving navigation accuracy. Application of direct current to generate electromagnetic field is an earlier technology. It requires the use of larger sensors and the resulting field is more vulnerable to various factors that can change its shape, such as the presence of large quantities of metal or a source of electromagnetic interference near the patient's head [87]. Using AC overcomes these limitations [88]. Electromagnetic field generator can be fixed to the operating table using a special bracket (Stealth Station 7, Fiagon), as well as integrated into the universal head support for an operating table (Fiagon). A separate module for electromagnetic navigation that requires connection to the main system increases the overall size and floor space occupied by the system. The advantages of the last generation electromagnetic navigation system include their portability and compactness, the possibility of integration into existing operating room system, very small sensor, which enables its integration into an instrument without increasing its size and, more importantly, changing tool geometry during operation without loss of navigation accuracy. According to C. Hayhurst et al. [89], the use of electromagnetic navigation in most cases enables avoiding rigid fixation of patient's head, for example, during neuroendoscopic interventions, bypass surgery, awake craniotomy. Compatibility with intraoperative neurophysiological monitoring is an important factor.

The use of the most portable and mobile electromagnetic navigation systems, which are not only a module in the basic optical navigation system, but rather can be effectively integrated into the workspace of the operating room, do not require any special infrastructure owing to full compatibility with existing equipment and instruments, and are easy to master for the staff, is the most promising direction.

Most neuronavigation systems developed in the 1990—2000s were based on optical monitoring technique. Historically, its earlier version involves the use of diodes emitting light in the IR range, which is detected by the receiving camera of the system. The LEDs are located on the reference, which is placed as close to the patient's head as possible. They form the basis of the coordinate system and can also be placed on the instruments using special adapter or directly integrated into the instruments. Passive techniques involve the installation of reflective spheres, which are located in the field of view of the camera equipped with an infrared light source, on the reference, instruments, and adapters. The article of K. Roessler et al. [90] describes the results of clinical application of this system in spinal and cranial neurosurgery. System accuracy averaged 3.4 mm in 36 craniotomies and 11.3 mm in 4 cases of spinal operations. The large error during spinal operations was associated with difficulties in the registration of images and the use of cutaneous registration markers. The development of computer graphics and new data processing capabilities have led to the use of "augmented reality" concept in neurosurgery, which enabled direct real-time alignment of paraplasm modeling results, functional areas, and anatomical landmarks (based on CT or MRI data) with the surgical field [91].

New features of intraoperative neuronavigation were associated with combining different modalities of neuroimaging: CT, conventional MRI, diffusion-tensor and functional MRI, as well as magnetoencephalography and electrophysiological mapping of speech, sensory, and motor areas of the cerebral cortex [92]. This improved the results of surgical procedures for pathological processes at the functional areas, hydrocephalus, ventriculoendoscopic interventions, and epilepsy [93, 94]. Many authors noted a positive effect of intraoperative navigation on completeness of paraplasm resection, duration of hospital stay, overall survival, and functional outcome [95—97].

The use of data provided by diffusion-tensor MRI, magnetoencephalography, functional MRI in a navigation system with simultaneous recording of cortical somatosensory evoked potentials enabled successful reconstruction of conductive paths of the brain at different levels and assessing the impact of the pathological process on these pathways [98, 99]. Computer modeling facilitated understanding of the anatomical relationships between the paraplasms and intact structures of the brain [100]. The use of neuronavigation significantly improved the resolution of transcranial magnetic stimulation [101].

Comparative analysis of various neuronavigation system (ISG Magic Wand, Cygnys PFS, SMN) by E. Benradette et al. [102] in the laboratory showed that, regardless of the used technique (mechanical manipulator, electromagnetic or

optical monitoring, respectively), the average precision of the systems did not differ significantly and ranged 1.67 to 2.6 mm. According to the authors, selection of navigation system was mainly determined by portability, ease of use, and compatibility with the operating microscope. The study of M. Cartellieri et al. [103] comparing six different navigation systems also showed no fundamental difference between the systems, since their precision was comparable (error ranged 0 to 6.7 mm). For a long time, precision of neuronavigation systems compared to conventional frame-based stereotactic devices was the subject for discussion. R. Steinmeier et al. [104] analysed the factors (technical precision of the system, registration process, voxel size and/or the presence of images distortions, intraoperative situation) that have a direct impact on navigation precision. It has been shown that imaging modality has minimal effect on the accuracy of navigation. The number of registration markers and the nature of their placement are the most important factors. The authors concluded that the accuracy of neuronavigation systems (as exemplified by a robotic microscope MKM Carl Zeiss and optical system Stealth Station Sofamor-Danek) is comparable to that of conventional stereotactic frame-based devices. Particular attention was paid to the fact that registration error calculated by each navigation system does not reflect the real error. U. Spetzger et al. [105] analyzed 10 years of experience in the application of neuronavigation and came to conclusion that system accuracy is mainly affected by the human factor. At the same time, S. Poggi et al. [106] concluded that the parameters of CT or MRI images also have an impact on the accuracy of neuronavigation. The accuracy of target localization based of CT data was higher than when using MRI data; the presence of image distortions was an important parameter that reduces the accuracy of MRI navigation. At the same time, Y. Enchev et al. [107] found no statistically significant differences in accuracy of neuronavigation with CT and MRI. There was also no significant differences in the navigation accuracy when using registration based on anatomical landmarks or fiducial markers. For this reason, W. Pfisterer et al. [108] recommended to use registration based on anatomical markers as more economic and less costly.

Comparative analysis of systems with active (Stryker) and passive (BrainLab Vector Vision) tracking technology conducted by D. Paraskevopoulos et al. [109] at the anthropomorphic model of the head showed that the accuracy was similar for both systems (<1.5 mm), and accuracy data calculated by the systems do not always fit the actual values and always require rechecking by surgeon. In all options, optical technique is characterised by following limitations: a) the need for placing the camera at a distance of at least 1 meter from the spheres or diodes; b) placing the camera on a separate bracket or stand, increasing the size of the system and reducing its portability and mobility; c) dependence of navigation accuracy on the state of reflecting spheres or diodes; d) "visions line" problem of the camera, leading to cessation of navigation when closing diodes or spheres with some object; e) bulky adapters for reflective spheres or diodes to be mounted on surgical instruments; e) inability to provide navigation of instrument with variable length, curvature, or made of soft materials (silicone catheters); f) the need for rigid fixation of patient's head, which limits the use of navigation in children [110]. It was also shown that infrared radiation from the optical navigation system tracker camera can substantially affect the performance of pulse oximeters, causing errors in the quality of signal and assessment of saturation level [111]. In 2001, M. Zaaroor et al. [110] published the paper, where the experience with electromagnetic navigation system Magellan (Biosense Webster) was analyzed. The electromagnetic sensor was located at the working end of the instrument, which enabled using the system for installation of flexible catheters, navigation of endoscopes and other instruments.

The advantages of the use include high operation speed, high precision, small size, the possibility to navigate flexible instruments, greater freedom of movement of the surgeon, which does not depend on the viewing field of the recording camera, no need for rigid fixation of the head, which enables operating children from the second week of life [110, 112, 113]. At the same time, T. Rodt et al. [114] noted that the interference of the magnetic field might affect the performance of the navigation system.

Comparative analysis of the accuracy of optical and electromagnetic navigation systems conducted by J. Rosenow et al. [115] revealed no significant differences (the target point location error ranged 0.71 to 3.51 mm). A. Sieskiewicz et al. [116] also compared optical and electromagnetic navigation systems (Medtronic Stealth Station and Digipointeur, respectively) and concluded that electromagnetic navigation is faster and easier to configure, provides greater freedom of surgeon's hands, and its accuracy is similar to that of the optical system; the small number of instrument supported for navigation was the imitation of that specific electromagnetic system.

Recently, intraoperative robot assistance became one of the main trends in surgery, improving safety and accuracy of surgery due to high-precision intraoperative navigation. In neurosurgery, such systems have been tested in preserving craniotomy, precise approach to deep brain structures for the purpose of biopsy of tumors, inflammatory and other lesions, implantation of shunt systems, electrodes and others. [117, 118]. Robotic systems are essentially a further option of the development of navigation systems.

Conclusion

The analysis of the literature over the past 100 years revealed preconditions for the development of neuronavigation and traced the evolution of this trend from both technical and clinical point of view. The advantages of using navigation systems in modern neurosurgery are obvious. Neuronavigation is one of the most popular high-tech methods, which enables combining various studies to evaluate the anatomical and functional situation in the preoperative and intraoperative periods. All this enables conducting highly accurate and safe surgical procedures much faster than conventional methods. Application of neuronavigation systems is highly valuable from both clinical and scientific viewpoint. Integrative nature of neuronavigation enables combining different modalities of data, including anatomical, neuroimaging, molecular, and neurophysiological, which improves the efficiency, effectiveness, and conclusiveness of clinical studies carried out using this technique. Furthermore, it is undoubtedly highly promising as an educational method. Currently, neuronavigation should not be a luxury for neurosurgical clinics; its application should be as widespread and routine as possible. We believe that, although neuronavigation does not replace the expertise and clinical thinking of neurosurgeon, it is a necessary complement, which enables neurosurgeons to maximize the use of their skills.

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