Salud, Ciencia y Tecnología. 2025; 5:1197
doi: 10.56294/saludcyt20251197

REVIEW

The role of robotic systems in improving surgical interventions in neurosurgery

El papel de los sistemas robóticos en la mejora de las intervenciones quirúrgicas en neurocirugía

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Cite as: Burachyk A, Borysiuk I, Madinov M, Babiak V, Babiak O. The role of robotic systems in improving surgical interventions in neurosurgery. Salud, Ciencia y Tecnología. 2025; 5:1197. https://doi.org/10.56294/saludcyt20251197

Submitted: 30-03-2024 **Revised:** 10-08-2024 **Accepted:** 06-12-2024 **Published:** 01-01-2025

Editor: Prof. Dr. William Castillo-González

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ABSTRACT

Introduction: robotic systems can help to effectively perform complex tasks in neurosurgery that require high precision, but due to the difficulty of operative access and the peculiarities of the anatomy of the nervous system, their wide application is limited.
Objective: evaluate the effectiveness, economic feasibility and prospects of using frame-based and frameless stereotaxis for brain biopsy.
Method: a total of 155 patients of the neurosurgery department underwent brain biopsy procedures. Depending on the biopsy methods 2 groups were distinguished: group 1 (frameless) 71 (45,8 %) patients and group 2 (frame-based) 84 (54,2 %) patients. Positive results of biopsy, postoperative complications and operative time were recorded and compared with data from studies on similar topics. Groups 1 and 2 didn't differ in lesion localization, sex, age, length of the skin incision and diameter of the trepanation hole.
Results: the diagnostic yield was 94,4 % in group 1 and 92,9 % in group 2 (p>0,05). The frequency of hemorrhage was 7,0 % versus 3,6 %, p=0,471, the frequency of edema was 2,7 % versus 1,2 %, p=0,593. The duration of the operation was shorter in group 1 (112 ± 13,6 min versus 137 ± 17,6 min, p<0,001).
Conclusions: both frameless and frame-based systems are effective, safe, and reliable tools that has excellent diagnostic yield, above 92 % low frequency of postoperative complications and high accuracy. The main benefits of frameless stereotactic biopsy is shorter operative time, comfort for patients, and less intraoperative fatigue for surgeon.

Keywords: Frameless Stereotaxy; Frame-Based Stereotaxy; Biopsy; Brain Tumor; Robotic System; Neurosurgery.

RESUMEN

Introducción: los sistemas robóticos pueden ayudar a realizar eficazmente tareas complejas en neurocirugía que requieren gran precisión, pero debido a la dificultad del acceso operatorio y a las peculiaridades de la anatomía del sistema nervioso, su amplia aplicación es limitada.
Objetivo: evaluar la eficacia, la viabilidad económica y las perspectivas del uso de la estereotaxia con y sin marco para la biopsia cerebral.
Método: un total de 155 pacientes con diferentes enfermedades se sometieron consecutivamente a

procedimientos de biopsia cerebral y se dividieron en 2 grupos: grupo 1 (sin marco) 71 (45,8 %) pacientes y grupo 2 (basado en marco) 84 (54,2 %) pacientes. Se registraron los resultados positivos de la biopsia, las complicaciones postoperatorias y el tiempo quirúrgico, y se compararon con los encontrados en una revisión bibliográfica. Los grupos 1 y 2 no difirieron en la localización de la lesión, el sexo, la edad, la longitud de la incisión cutánea y el diámetro del orificio de trepanación.
Resultados: el rendimiento diagnóstico fue del 94,4 % en el grupo 1 y del 92,9 % en el grupo 2 (p>0,05). La frecuencia de hemorragia fue del 7,0 % frente al 3,6 %, p=0,471, la frecuencia de edema fue del 2,7 % frente al 1,2 %, p=0,593. El tiempo quirúrgico fue menor en el grupo 1 (112 ± 13,6 min frente a 137 ± 17,6 min, p<0,001).
Conclusiones: tanto el sistema sin marco como el basado en marco son herramientas eficaces, seguras y fiables que tienen un excelente rendimiento diagnóstico, superior al 92 %, baja frecuencia de complicaciones postoperatorias y alta precisión. Las principales ventajas de la biopsia estereotáctica sin marco son la reducción del tiempo quirúrgico, la comodidad para los pacientes y la menor fatiga intraoperatoria para el cirujano.

Palabras clave: Estereotaxia Sin Marco; Estereotaxia Con Marco; Biopsia; Tumor Cerebral; Sistema Robótico; Neurocirugía.

INTRODUCTION

In recent years, robotic systems have been actively introduced into clinical practice due to minimal invasiveness, reduction of postoperative complications and increased accuracy of surgical manipulations.[1] While robotic technologies have found application in various areas of surgery, they have not gained such popularity in neurosurgery. On the one hand, fully robotic systems and instrument holders are little studied in clinical researchers, on the other hand, robotic stereotaxic, neuronavigation and endovascular systems significantly increase the accuracy of operations and, in some modifications, become the standard for neurosurgical procedures.

Literature review

Fully robotic assistants are widely used in general surgery, urology and gynecology, but they have a limited application in neurosurgery, because of the narrow operative access and delicate surrounding anatomy.[3] For instance the da Vinci system widely used in general surgery, needs to be improved according to the requirements of neurosurgery: the robotic instruments must be smaller and surgical assistance should be stable enough and powerful enough to permit drilling through bone.[4] Chauvet et al.[5] also described the lack of tactile feedback as a threatening problem for robotic surgery, on the other hand the 3D vision is useful for preventing of postoperative complications and complete removal of the tumor. Otherwise robotic surgery as it has been shown in other fields of medicine, costs the hospital 1,4–2 times more than the same, non-robotic manipulations.[6,7]

Other partially robotic assistants include instruments holders, the most common of which are endoscope holders, which make surgery easier.[4] These tools can replace surgical assistant and reduce the time of operation and operator fatigue. This robotic systems cost less than fully robotic assistants and they are more popular in clinical practice.[8]

Robotics for stereotaxis is widely implemented in neurosurgical hospitals. This systems are used in deep brain stimulation, biopsy, shunt placement and cyst drainage.[3] Stereotaxic systems are characterized by submillimetre accuracy in trajectory planning.[9,10] Moreover, recent researches have demonstrated that robotic-assisted stereotaxis can reduce aiming errors.[3,11] The main characteristics of framelessrobotic-assisted stereotaxic systems are safety, accuracy, efficiency, but require maintenance costs and additional personnel costs and additional staff training.[12]

The application of robotics in neurosurgery is revolutionary in particular due to its compatible use with medical imaging and navigation technologies.[13] During neurosurgical operations and manipulations the main problems are locating and identifying the anatomy which requires considerable experience, time, and care in order to reduce the risk of tissue damage. Neuronavigation is necessary in neurosurgery, because of the peculiarities of procedures, which are the complexity of surgical access, a large number of blood vessels and histological features of the sensitive brain parenchyma.[1,13]

Considering the high frequency of vascular pathology in neurosurgery, the development of neuroendovascular robotics is promising. The advantages of this system are the ability to perform rotational movements, reduce the fatigue of the surgeon and eliminate accumulated radiation.[14] The main disadvantage is the limited ability of tactile feedback, which can lead to vessel injury.

Robotic systems shorten the duration of procedure and provide safer, less invasive and more precise surgery, improving long term results.(1) However development of these systems requires costs, staff training and additional clinical researches in cranial and spinal neurosurgery. Despite pros and cons of robotic assistance in neurosurgery the question lies in the clinical and economic efficiency of their widespread introduction into surgical practice.

We decided to evaluate the feasibility of using robotic surgery on the example of technologies that are available in our department and are widely used around the world for biopsy. The purpose of our research was to assess the effectiveness, economic feasibility and prospects of using robotic surgery in neurosurgery based on the analysis and comparing of foreign and original researches.

METHOD

A retrospective study was conducted on the basis of the Neurological Department, which included a 15-year observation period from 2010 to 2023. One hundred and fifty five patients with brain tumors, who needs the performing of tumor biopsy were observed and treated in our department. Whole information about data on patients and specifics of the operation was extracted from case notes and operative reports. The study was conducted in accordance with ethical standards, after receiving the patient's consent to participate in the study and publication of the results. Vascular pathology, coagulopathy, local or systemic infections and decompensated concomitant diseases were the exclusion criteria. Out of the total 155 patients, 78 (50,3 %) were male and 77 (49,7 %) were female, with their mean age of 58,6 ± 12,4 years (from 42 to 77 years). The were 2 groups of patients, depending on the type of stereotactic biopsy.

The data of occurrence of postoperative complications (hematoma, infection, edema) and the frequency of positive results of the biopsy were analysed to demonstrate the efficiency of the procedure. All statistical calculations were performed in STATA version 2.0 (Stata Corporation, College Station). Among statistical methods, we used Fisher's exact test, one-way analysis of variance (ANOVA), as well as Kruskal-Wallis test and one-way variance test. We've presented results as mean and standard deviation. The measure of significant difference was p(value)<0,05.

RESULTS

All patients who took part in our study were divided into two groups: the group 1 included 71 (45,8 %) patients, who underwent frameless intracranial brain biopsies from 2017 to 2023 year. The group 2 included 84 (54,2 %) patients who underwent frame-based intracranial biopsy from 2010 to 2023 year. Patient characteristics of both groups are shown in table 1.

Table 1. Patient and perioperative characteristics in group 1 and 2

	Group 1, n = 71	Group 2, n = 84
Male %	52,1 %	48,8 %
Age (years±SD)	56,7 ± 11,4	60,2 ± 13,1

The complex of examination of patients of both groups before biopsy included an ophthalmological and neurological examination, computed tomography (CT) and magnetic resonance imaging MRI of the brain. The size of the lesion measured from 2,4 to 3,6 cm in diameter, on average (2 85±0,43) cm. The single lesion was found in 144 (92,9 %) patients, while in 11 (7,1 %) patients the multiple lesions was diagnosed.

The coordinates of the entry point, the trajectory of the biopsy needle, and the location of the biopsy in all patients were determined, based on the data processing of the mathematical spiral computed tomography angiography (SCTA) of the brain. We chose the most contrasted tumor areas for biopsy. After comparing the SCTA and MRI results, we modeled the entry point for trepanation and entered all coordinates into the stereotactic system. During the biopsy, the fixation position of the head was chosen according to the entry point, which was the upper part of the head in order to obtain quality material for histological examination. In group 2 the position of the frame was chosen according to the results of examination, this process required some additional time.

Operative interventions were performed under general anesthesia in 50 (70,4 %) patients in group 1 and in 55 (65,5 %) patients in group 2 (p>0,05). Throughout the entire intake process the blood pressure, heart rate, breathing, neurological changes were monitored. Firstly, we determined the entry point, then treated the operating field with antiseptic solution and covered it with sterile napkins. After cutting the skin, we installed the wound expander and determined the entry point. The length of the skin incision did not differ in both groups and was 2,2 ± 0,26 cm in frame-based group and 2,3 ± 0,21 cm in frameless group (p>0,05). The diameter of the trepanations hole wasn't different in both groups, in group 1 the average diameter was 8,2 ± 0,1 mm, in group 2 – 8,5±0,2 mm (p>0,05). The procedure was performed with passive biopsy needle 2×10 mm in both groups. After biopsy all patients underwent CT scan to control postoperative complication.

The localization of the lesions in both group is shown in table 2. Pathological lesions were found mostly in corpus callosum (12,9 %), medial sections of the frontal lobe (21,9 %), subcortical ganglia (10,9 %), occipital (17,4 %) and parietal lobes (14,2 %).

Table 2. Distribution of patients according to the localization of the pathological formation

Localization	Frameless group 1		Frame-based group 2	
	n = 71	%	n = 84	%
Corpus callosum	11	15,5 %	9	10,7 %
Medial sections of the frontal lobe	14	19,7 %	20	23,8 %
Subcortical ganglia	7	9,8 %	10	11,9 %
Thalamus	3	4,2 %	4	4,7 %
Medial divisions of the occipital lobe	12	16,9 %	15	17,9 %
Parietal lobe	11	15,5 %	11	13,1 %
The area in front of the central gyrus	7	9,9 %	11	13,1 %
Cellar site	3	4,2 %	2	2,4 %
Section III ventricle	2	2,8 %	2	2,4 %

As can be seen from the table, both groups didn't differ in the localisation of the lesion, sex, age, length of the skin incision and diameter of the trepanation hole.

Positive biopsy results were obtained in 67 (94,4 %) observations in group 1 and in 78 (92,9 %) patients in group 2 ($p>0,05$). A glioma was diagnosed in 79 (50,9 %) patients, lymphoma in 19 (12,3 %), astrocytoma — in 7 (4,5 %), glioblastoma in 10 (6,5 %), metastases in 13 (8,4 %), abscess in 11 (7,1 %) (table 3).

Table 3. Shows the distribution of patients according to the histological results of the pathological formation

Histological results	Group 1 n = 67	Group 2 n = 78
Nondiagnostic malignant glioma	30	35
Low-grade glioma	8	6
Lymphoma	7	12
Metastasis	7	6
Glioblastoma	5	5
Abscess	4	7
Medulloblastoma	1	0
Ependymoma	2	3
Anaplastic astrocytoma	3	4

The lesion locations of nondiagnostic biopsies were frontal (n=1), frontotemporal (n=1), parietooccipital (n=2) for frameless biopsies and frontoparietal (n=3), temporal (n=2), and thalamus (n=1) for the frame based biopsies.

Among postoperative complications we observed symptomatic hemorrhage which was diagnosed in 5 (7,0 %) patients of group 1 and in 3 (3,6 %) patients in group 2. Postoperative edema was observed in 2 (2,7 %) patients in frameless group and 1 (1,2 %) patients in frame-based group. There was no infection in patients of group 1 and group 2 (table 4).

The duration of biopsy was less in group 1 compared with group 2 and lasted 112 ± 13,6 minutes against 137 ± 17,6 minutes ($p<0,001$).

Table 4. Postoperative complications and operation time in both groups

	Group 1 n = 71	Group 2 n = 84	p - value
Hemorrhage n (%)	5 (7,0 %)	3 (3,6 %)	0,471
Perilesional edema n (%)	2 (2,7 %)	1 (1,2 %)	0,593
Infection n (%)	0	0	-
Operative time (min), Mean ± SD	112 ± 13,6	137 ± 17,6	p < 0,001

The obtained results of the biopsy were later used by neurosurgeons for choosing the further treatment technique and by radiologists for more accurate planning of the irradiation area. All patients are alive after surgery. According to control SCT was noted in all observations pneumocephalus in the projection of the biopsy target, in 4 — by biopter movement. In a patient with multiforme glioblastoma occurred during material selection bleeding from the biopsy needle. Collection of material stopped, and the biopter was not removed until the bleeding stopped. According to CT data, tissue imbibition was noted tumors with blood up to 2 cm in diameter. This is a complication did not worsen the general condition of the patient and did not require performance of repeated surgical intervention.

DISCUSSION

Robotic technologies are rapidly developing and being implemented in neurosurgery.[4] Note that robotic systems are characterized by greater maneuverability and 3D visualization, but the large size of the equipment and a limited number of specific tools for brain interventions explain its low applicability in practice. Ball et al.[3] describe promising technological capabilities of robots and believe in their development which will provide safer, more efficient surgery, but even nowadays they show the importance and benefits for robotics in frameless stereotaxis, stereoelectroencephalography and endoscopy.

Girishan et al.[15] and Chumnanvej et al.[16] demonstrate the benefits of robotic arm in endoscopic neurosurgery like ensuring endoscope stability, enabling tactical feedback to improve manipulation on sensitive brain tissue in complex localization, and optimizing visualization. Although most researches are cadaveric, we may understand the possibilities which can neurosurgery get from this new technology. There is also a problem of the economic feasibility of robotic systems in neurosurgery, taking into account all the advantages and disadvantages of technologies.

Robot-assisted neuronavigation and stereotaxis reduces errors in the projection of precise coordinates, which is important for asleep implantation of deep brain stimulators and differential brain biopsy, since the accuracy of results of this interventions help to choose further treatment tactics. Another advantage of intraoperative visualisation is the ability to change the tactics of the surgical procedure in real time when individual characteristics are detected.[17] Moreover, due to autonomous capabilities robotic neuronavigation can reduce human error.[18]

In our research we decided to analyse the efficiency of robotic technology available in our country such as stereotactics assistance which is widely used all over the world. In recent years the frame-based stereotaxis became the gold standard for brain biopsy.[19] Gessler et al.[20] compared stereotactic brain biopsy and open craniotomy in their study. They found no difference in the accuracy of molecular tumor markers for both procedures, while they also described more benefits of stereotactic biopsy. However this technology has disadvantages such as the complexity of frame maintenance, additional time for overlaying the frame relative to the visualization coordinates before the operation, which causes patient discomfort and fatigue of the medical staff. Although Qin et al.[21] describe that the CT/MRI-guided stereotactic brain biopsy has an error of <0,7 mm for locating lesions in the brain, the wrong position of the frame affects the positioning accuracy. In addition the frame stereotactic system requires the adjustment of frame coordinates, which are prone to errors.

On the other hand frameless is more comfortable for patients, less fatiguing for neurosurgeons, safer and more accurate. Frameless neuronavigation systems for the purpose of accurate placement of coordinates in the arsenal of tools have pointers, a digitizer, a work station and fiducials. Fiducials are sensors fixed to the scalp as pre-procedural landmarks to define a precise needle trajectory and project the operating space relative to the patient's head. The resulting spatial visualization is registered using a digitizer, which is then read by a workstation. The accuracy of intraoperative navigation consists in comparing and matching the coordinates of the preoperative images and the expected trajectory of the biopsy needle.[9] The procedure for taking biopsy material can be carried out both under general and local anesthesia, depending on the state of consciousness, the patient's wishes and the complexity of localization of the lesion, which is assessed by the neurosurgeon. Moreover neuronavigation systems help in visualization and planning, which can be done without time limitation. Since MRI or CT can be performed a day or hours before the biopsy, due to the fact that fiducials do not cause discomfort to the patient and ensure his mobility. In turn, the frames require the constant presence of the patient in the hospital office. This fact allows reduce the procedure and make biopsy planning more flexible.[9]

The results of our research haven't shown the efficiency difference between frame-based and frameless stereotactics assistans for performing the brain biopsy. The positive results were observed in 94,4 % of patients of frameless group and in 92,9 % of patients in frame-based, which wasn't significantly different. According to authors[22] the positive results did not differ from the data given in the literature for frameless systems, an overall diagnostic yield was 94,6 %. Qin et al.[21] also describe positive results of frame-based stereotaxis biopsy in over 95,2 %. Althought there are some authors who gives the measures of positive results from 73 to 97 % which can be observed in the absence of standardization of the study, characteristics of the sample and unclear criteria of effectiveness.[23,24] Bai et al.[2] and Nishihara et al.[25] declare that in the diagnosis of atypical location, diffuseness of the structure, small size and multiple lesions of the brain, the correspondence of imaging results to pathological diagnoses remains low for both frameless and frame stereotaxic biopsies.

During our research we found the difference between operative time, which was 112 ± 13,6 minutes in group 1 versus 137 ± 17,6 minutes in group 2 (p<0,001). The time of operation of frameless stereotaxis brain biopsy was similar as described for frameless stereotaxis by authors (from 108 - 120 min).[22] Partially, this can indicates a learning curve as frame-based stereotactic biopsy was performed 5 years earlier than frameless biopsy. But the main reason of longer operative time of frame-based stereotactis biopsy seems to be the process of positioning the frame according to the CT or MRI coordinates.

Another benefit of frameless stereotactic biopsy was the ability to stop hemorrhage during biopsy, which is important for asymptomatic bleeding.[21] As in our research we didn't observe asymptomatic bleeding, we couldn't confirm or deny this fact. While observing the postoperative complications we didn't found the difference between framebased and frameless stereotactics biopsy. Although the frequency of hemorrhage and perilesional edema was higher in group 1 (5 (7,0 %) cases versus 3 (3,6 %) cases, p=0,471: and 2 (2,7 %) versus 1 (1,2 %), p=0,593), the difference wasn't significant.

Nishihara et al.[25] describe the feasibility of frame-based stereotactic biopsy under local anesthesia in more than 50 % case, what should be a big advantage for cost effectiveness and postoperative recovery. In our study we observed that stereotactic biopsy was performed under local anesthesia in 50 (32,3 %) patients (29,6 % versus 34,5 % in groups 1 and 2). This fact was mostly connected with the choice of the surgeon, and the wishes of the patients.

If talking about the accuracy difference although[25] claim that neuronavigation stereotactic biopsy is preferable to CT – stereotactic biopsy to reduce morbidity when the target is basal ganglia (putamen, globus pallidus) or thalamus, we cannot confirm this hypothesis, due to a small amount of patients with postoperative complications.

In conclusion there is no significant difference between frameless and frame- stereotactic biopsy in postoperative complication, accuracy and positive results of biopsy. However we found the difference between operative time in frameless group. After observing other researches we can make a conclusion that frameless biopsy is more comfortable for patients and less tiring for neurosurgeons, although this technology is more expensive and requires long staff training.

Due to limited economic resources, new robotic technologies have very limited prospects in our country. However, the feasibility of implementing robotic technologies has been established on the example of frameless stereotactic biopsy. As for more expensive and autonomous robotic systems, they should be implemented after being refined according to the requirements of neurosurgery.

CONCLUSIONS

Both frameless and frame-based systems are effective, safe, and reliable tools that has excellent diagnostic yield, above 92 %, low rate of postoperative complications and high accuracy. The main benefits of frameless stereotactic biopsy is shorter operative time, comfort for patients and less intraoperative fatigue for surgeon. Although the medical application of some robotic systems in neurosurgery is limited, and economic feasibility has not been proven, the prospects for their development and improvement in accordance with the requirements of neurosurgery seem promising.

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FINANCING
The authors did not receive financing for the development of this research.

CONFLICT OF INTEREST
The authors declare that there is no conflict of interest.

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