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REVIEW

Automated neurosurgical stereotactic planning for intraoperative use: a comprehensive review of the literature and perspectives

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Abstract

The creation of intracranial stereotactic trajectories, from entry point to target point, is still mostly done manually by the neurosurgeon. The development of automated stereotactic planning tools has been described in the literature. This systematic review aims to assess the effectiveness of stereotactic planning procedure automation and develop tools for patients undergoing neurosurgical stereotactic procedures. PubMed/MEDLINE, EMBASE, Google Scholar, CINAHL, PsycINFO, and Cochrane Register of Controlled Trials databases were searched from inception to September 1, 2019, at the exception of Google Scholar (from 1 January 2010 to September 1, 2019) in French and English. Eligible studies included all studies proposing automated stereotactic planning. A total of 1543 studies were screened. Forty-two studies were included in the systematic review, including 18 (42.9%) conference papers. The surgical procedures planned automatically were mainly deep brain stimulation (n = 14, 33.3%), stereoelectroencephalography (n = 12, 28.6%), and not specified (n = 10, 23.8%). The most frequently used surgical constraints to plan the trajectory were blood vessels (n = 32, 76.2%), cerebral sulci (n = 27, 64.3%), and cerebral ventricles (n = 23, 54.8%). The distance from blood vessels ranged from 1.96 to 4.78 mm for manual trajectories and from 2.47 to 7.0 mm for automated trajectories. At least one neurosurgeon was involved in 36 studies (85.7%). The automated stereotactic trajectory was preferred in 75.4% of the studied cases (range 30–92.9). Only 3 (7.1%) studies were multicentric. No study reported prospective use of the planning software. Stereotactic planning automation is a promising tool to provide valuable stereotactic trajectories for clinical applications.

Keywords Automation · Software validation · Surgery, Computer-assisted · Stereotaxy · Deep brain stimulation

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Introduction

The word "stereotaxis" stems from the union of two ancient Greek roots, "stereós" (στερεός) meaning a solid, three-dimensional, object, and "taxis" (τάξις) meaning arrangement. Stereotactic neurosurgery aims to target any intracerebral structure with precision and accuracy [55]. In the classic "frame-based" stereotaxis, the required precision rests upon the use of a stereotactic frame that maintains the head steady, enabling definition of the surrounding stereotactic space and allocation of stereotactic coordinates to any given point within this space. Preoperative brain images are matched to those acquired intraoperatively with the stereotactic frame and dedicated localizers. The stereotactic planning per se merely corresponds to the design of a straight-lined trajectory from a cortical entry point to a usually deep-seated target point [18]. During the past three decades, the advent of neuronavigational tools to register preoperative brain images to a patient's head has drastically altered the historical vision of stereotaxis [11]. It is now possible to perform a wide range of interventions using neuronavigational systems, and systems dedicated to deep-brain stimulation procedures are currently in development [39]. These advancements led to rapid development of frameless stereotaxis. Contrary to the historical gold-standard "frame-based stereotaxis" using an invasive frame, "frameless stereotaxis" relies on image-based neuronavigational systems or robotic arms.

Beyond technological advances, the most difficult part of stereotactic neurosurgery—the creation of the optimal stereotactic trajectory in terms of safety-accuracy—remains empirical in most cases and classically chosen by a single senior neurosurgeon. The use of MRI and CT-scan allows creation of an image-based stereotactic trajectory according to the patient's individual anatomy but still requires the neurosurgeon to manually and somewhat arbitrarily choose the target point, the entry point, and the connecting trajectory [27, 28]. Hence, the definition of the trajectory is highly neurosurgeon-dependent [40]. In the particular case of stereoelectroencephalography, the definition of multiple trajectories to insert up to 18 brain electrodes often proves to be a long and challenging task [3]. This current modus operandi requires a learning curve, and leads to a lengthy preoperative and intraoperative planning process, possibly increasing the risk of infective complications; hemorrhagic complications can occur as a result of inaccuracy [16, 21, 36].

To overcome the limitations induced by manual stereotactic planning, pioneer studies have addressed its automation with promising results [6, 8–10, 12, 13, 15, 25, 49, 54]. However, routine use of these proposed automated planning tools has not been incorporated into the clinical practice in the vast majority of neurosurgical departments. The literature lacks a systematic review on automated stereotactic planning for neurosurgical applications. We present a systematic review of the literature assessing all automated stereotactic planning procedures utilized to date in neurosurgery. Particular attention was paid to the comparison between manual and automated trajectories, in order to envision potential future clinical applications.

Methods

Search strategy and data sources

Seven electronic bibliographic databases—EMBASE, PubMed/MEDLINE, Web of Science, Cochrane Register of Controlled Trials, LiSSa, CINAHL, and PsycINFO—were searched from inception to 1 September 2019. Google Scholar was searched from 1 January 2010 to 1 September 2019. The search strategy included a combination of medical subject headings (MeSH terms) and key terms: "trajectory planning" and "neurosurgery". This combination allowed a comprehensive review of the literature with minimal risk of missing relevant studies. Concerning Google Scholar, the option "sort by relevance" was selected in order to limit the number of references. Electronic search strategy on PubMed/MEDLINE was performed by two senior investigators (MZ and JP) with the terms "trajectory planning" and "neurosurgery" while blinded from one another. Titles were screened and if they seemed relevant, corresponding abstracts were retained. The results of the searches carried out by the two investigators were compared: two discrepancies were found and the corresponding studies were included in the retrieved articles. All full-text publications were reviewed for each potentially eligible study. The references of the articles were reviewed to supplement the initial search. The same strategy applied for the other electronic databases. The gray literature was searched thanks to the help of Bibliotheque Inter Universitaire de Santé library assistants by one senior investigator (MZ).

Selection criteria

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statements to strengthen the methodology [35].

Studies that met the following criteria were deemed eligible for inclusion in the systematic review: all studies detailing neurosurgical stereotactic planning thanks to a dedicated software published in English or in French (authors' native language). Clinical studies, i.e., studies reporting effectiveness in a real-world setting, received the greatest emphasis. The conference papers were also included. Stereotactic planning had to deal with neurosurgical conditions and planning had to be, at least, semi-automated. The studies focusing on manual planning made with a dedicated software but without any

automated trajectory planning calculation were excluded. The studies reporting curved trajectories were excluded.

Data extraction

The data extraction from reports was executed in duplicate by two investigators (MZ and AR). A data extraction sheet was developed to collect all relevant information from the articles included. The variables of interest were the following: date of study publication (year), journal name, specification of the journal (clinical journal/fundamental journal), type of surgical procedure(s) studied, indications for the stereotactic procedure, brain target(s) of interest, imaging modalities used for stereotactic planning, constraints used for the stereotactic planning automation, proposition of an automated entry point, proposition of an automated target point, comparison with manual planning, actual clinical use of the automated stereotactic planning tool proposed, and subsequent publication(s) of developments of the automated stereotactic planning tool. The quantitative data were amalgamated from the different studies using each study's results. This process did not take into account a number of cases due to inconsistent reporting (number of patients vs number of trajectories vs number of simulated planning sessions).

Assessment of the risk of bias

The risk of bias for each included study was individually assessed by two investigators (MZ and AR) using a simple judgment of low-, high-, or unclear risk on different axes: description of the automated stereotactic calculation, number of calculated trajectories, status of the evaluator (blind or not).

Results

Literature search

A flow chart is presented in Fig. 1 according to PRISMA statements.

The initial database search yielded a total of 2843 studies. After ruling out duplicate studies, 1543 studies remained. After careful reading of abstracts and titles, 68 studies were deemed eligible for the review and 42 studies selected for the final analysis. Table 1 provides the main characteristics of the included studies.

These articles were published between 1997 and 2019. There was an increase in published studies over time: three studies (7.1%) were published between 1997 and 2008 and the remaining 39 studies (92.9%) were published between 2009 and 2019. The vast majority of studies were published in journals dealing with computer-assisted imaging (90.5%) and only four studies (9.5%) were published in clinical journals, all since 2016. Eighteen studies (42.9%) were conference papers. This research topic is led by three main groups across Europe, publishing more than 42.9% of the relevant literature. All studies presented a high risk of bias due to uncontrolled and retrospective design.

Type of stereotactic procedure

Figure 2 illustrates the trends in the relative numbers of published studies describing stereotactic procedure automation for neurosurgical applications since 1997 and the types of eligible neurosurgical procedures.

Regarding the type of stereotactic procedures, 14 studies (33.3%) investigated deep brain stimulation (n = 121 patients, mean 8.7 ± 9.9 planning sessions per study, median 6, range 0–30), 12 studies (28.6%) stereoelectroencephalography (n = 224 patients, mean 18.7 ± 18.8 planning sessions per study, median 16.5, range 3–75), 3 studies (7.1%) biopsy for brain neoplasm (n = 15 patients, mean 5 ± 8.7 planning sessions per study, median 1, range 0–15), two studies (4.8%) laser interstitial thermal therapy for pharmacoresistant epilepsy (n = 35, mean 17.5 ± 10.6 planning sessions per study, median 17.5, range 10–25), one single study (2.4%) external ventricular drainage placement (n = 43 patients), and the remaining 10 studies (23.8%) analyzed the surgical trajectory without any direct reference to a dedicated neurosurgical procedure, aiming at merely improving the surgical path to reach a given target (n = 17 patients, mean 1.7 ± 2.5 planning sessions per study, median 1, range 0–8). Table 1 demonstrates the specific targets investigated in each study.

The main type of stereotactic procedure referred to in the studies changed with time. Indeed, deep brain stimulation was the main surgical procedure of interest before 2012 and stereoelectroencephalography planning is the main surgical procedure of interest since 2012. Studies focusing on deep brain stimulation planning automation mainly concerned Parkinson's disease (13/14 studies, 92.9%), with only one study for dystonia and essential tremor. When getting more into details for the 14 studies on deep brain stimulation planning automation, the target was the subthalamus nucleus in eight studies (57.2%), three studies (21.5%) investigated different targets (subthalamic nucleus/internal globus pallidus; subthalamic nucleus/internal globus pallidus/ventral intermediate nucleus of the thalamus; subthalamic nucleus/ventral intermediate nucleus of the thalamus), one study (7.1%) targeted the ventral posterolateral nucleus of the thalamus, one study (7.1%) the internal globus pallidus, and one study (7.1%) did not describe any specific target.

Only three studies (7.1%) were multicentric: a nationwide study including two French tertiary referral centers investigating deep brain stimulation for Parkinson's disease, a nationwide study including three American tertiary referral centers investigating deep brain stimulation for Parkinson's disease,

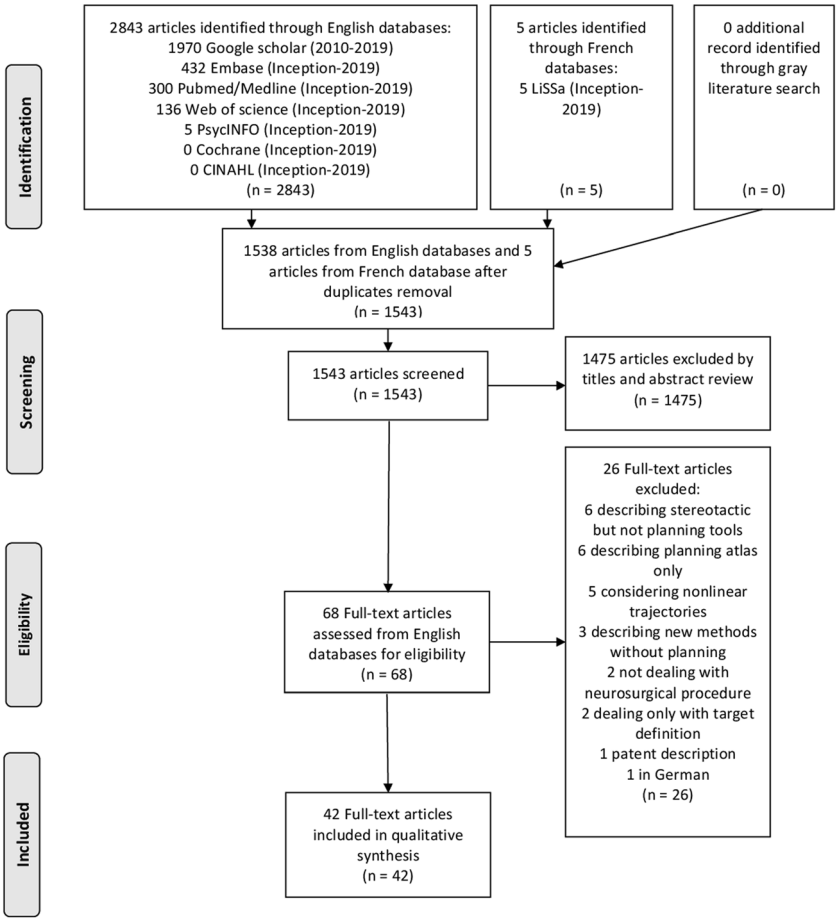

Fig. 1 PRISMA diagram

and an international study including two British tertiary referral centers, one Swedish tertiary referral center, one American tertiary referral center, and one Austrian tertiary referral center investigating stereoelectroencephalography.

None of the developed automated software was made commercially or freely available by the referring team. No study reported prospective clinical use of the developed software by a neurosurgical team different from the referring team.

Imaging modalities used, constraints applied, and automation procedures

Table 2 provides details as to the main technical characteristics used for stereotactic procedure automation.

All but one study (97.6%) were based on MRI imaging. Four studies (9.5%) proposed implementation of functional MRI data in the planning dataset (three not mentioning any specific procedure and one for stereoelectroencephalography) and one study proposed implementation of PET scan for stereoelectroencephalography. Twenty-seven studies (61.3%) required the use of vascular imaging in order to segment brain vessels: 12 studies used gadolinium enhanced T1-weighted MRI (two for biopsy, four for deep brain stimulation, four for stereoelectroencephalography procedures, and two unspecified), seven studies used CT-angiography (all for stereoelectroencephalography), and nine studies used MR angiography (six for unspecified procedures, three for deep brain stimulation). Three studies used both gadolinium-enhanced T1-weighted MRI and CT-angiography (all for stereoelectroencephalography).

The surgical and anatomical constraints most frequently incorporated in the trajectory planning automation were blood vessels (32 studies, 76.2%), cerebral sulci (27 studies, 64.3%), and ventricles (23 studies, 54.8%). Fifteen studies (35.7%) proposed avoiding those critical regions of interest. The 15 studies that did not take blood vessels into account in the planning automation were eight deep brain stimulation studies (five of them assuming that avoiding cerebral sulci equaled avoiding brain vessels), one laser interstitial thermal therapy study assuming that avoiding sulci equaled avoiding brain vessels, and one external ventricular drain study. The remaining five studies mentioned avoiding brain vessels but did not specify the type of vascular imaging used. Overall, 41 out of 42 studies directly or indirectly incorporated blood vessels in the planning automation.

Regarding stereotactic planning automation, 33 studies (78.6%) proposed an automated entry point, while only 12 studies (28.6%) proposed an automated target point. Of these

Table 1 General characteristics of studies reviewed

N	Authors and Year	Study title	Journal	Conference	Neurosurgical procedure
1	Vaillant, M., et al,1997[63]	A path-planning algorithm for image-guided neurosurgery	Conference paper	First Joint Conference Computer Vision, Virtual Reality and Robotics in Medicine and Medical Robotics and Computer-Assisted Surgery	Deep brain stimulation
2	Brunenberg, E.J.L. et al, 2007[10]	Automatic trajectory planning for deep brain stimulation: a feasibility study	Conference paper	Medical Image Computing and Computer-Assisted Intervention	Deep brain stimulation
3	Guo, T. et al, 2007[29]	Automatic target and trajectory identification for deep brain stimulation (DBS) procedures.	Conference paper	Medical Image Computing and Computer-Assisted Intervention	Deep brain stimulation
4	Ahmadi, S.A. et al, 2009[1]	Advanced Planning and Intra-operative Validation for Robot-Assisted Keyhole Neurosurgery In ROBOCAST	Conference paper	International Conference on Advanced Robotics	No detail
5	Shamir R. R., et al, 2010[55]	Trajectory planning method for reduced patient risk in image-guided neurosurgery: concept and preliminary results	Conference paper	Medical Imaging 2010: Visualization, Image-Guided Procedures, and Modeling	No detail
6	Navkar, N. V., et al, 2010[46]	Visualization and planning of neurosurgical interventions with straight access	Conference paper	Information Processing in Computer-Assisted Interventions	No detail
7	De Momi, E., et al, 2010[16]	Robotic and artificial intelligence for keyhole neurosurgery: the ROBOCAST project, a multi-modal autonomous path planner	Journal of Engineering in Medicine		No detail
8	Shamir, R. R., et al, 2010[57]	A Method for Planning Safe Trajectories in Image-Guided Keyhole Neurosurgery	Conference paper	Medical Image Computing and Computer-Assisted Intervention	No detail
9	Essert, C., et al, 2010[21]	Automatic Computation of Electrodes Trajectory for Deep Brain Stimulation	Conference paper	Medical Imaging and Augmented Reality	Deep brain stimulation
10	Bériault, S., et al, 2011[7]	Automatic trajectory planning of DBS neurosurgery from multi-modal MRI datasets	Conference paper	Medical Image Computing and Computer-Assisted Intervention	Deep brain stimulation
11	Herghelegiu, P. C., et al, 2012[35]	Biopsy Planner - Visual Analysis for Needle Pathway Planning in Deep Seated Brain Tumor Biopsy	Conference paper	Computer Graphics Forum	Biopsy
12	Beriault, S., et al, 2012[6]	A multi-modal approach to computer-assisted deep brain stimulation trajectory planning	Int J Comput Assist Radiol Surg		Deep brain stimulation
13	Liu, Y., et al, 2012[40]	A surgeon specific automatic path planning algorithm for deep brain stimulation	Conference paper	Medical Imaging: Image-Guided Procedures	Deep brain stimulation
14	Shamir, R. R. et al, 2012[56]	Reduced risk trajectory planning in image-guided keyhole neurosurgery	Med Phys		No detail
15	Caborni, C., et al, 2012[11]	Automatic trajectory planning in Stereo-electroencephalography image guided neurosurgery	Int J Comput Assist Radiol Surg		SEEG
16	Essert, C., et al, 2012[22]	Automatic computation of electrode trajectories for Deep Brain Stimulation: a hybrid symbolic and numerical approach	Int J Comput Assist Radiol Surg		Deep brain stimulation
17	Essert, C., et al, 2012[23]	Automatic parameters optimization for deep brain stimulation trajectory planning	Conference paper	Medical Image Computing and Computer-Assisted Intervention	Deep brain stimulation
18	Bériault, S., et al, 2013[8]	A Prospective Evaluation of Computer-Assisted Deep Brain Stimulation Trajectory Planning	Conference paper	Clinical Image-Based Procedures. From Planning to Intervention	Deep brain stimulation
19	De Momi, E., et al, 2013[14]	Automatic trajectory planner for StereoElectroEncephaloGraphy procedures: a retrospective study	IEEE Trans Biomed Eng		SEEG
20	De Momi, E., et al, 2014[13]	Multi-trajectories automatic planner for StereoElectroEncephaloGraphy (SEEG)	Int J Comput Assist Radiol Surg		SEEG

Table 1 (continued)

21	Zombori, G., et al, 2014[72]	A Computer Assisted Planning System for the Placement of SEEG Electrodes in the Treatment of Epilepsy	Conference paper	Information Processing in Computer-Assisted Interventions	SEEG
22	Zelmann, R., et al, 2014[71]	Automatic Optimization of Depth Electrode Trajectory Planning	Conference paper	Clinical Image-Based Procedures. Translational Research in Medical Imaging	SEEG
23	Rincón-Nigro, M., et al, 2014[52]	GPU-Accelerated Interactive Visualization and Planning of Neurosurgical Interventions	IEEE Computer Graphics and Applications		Biopsy
24	Liu, Y., et al, 2014[42]	Multi-Surgeon, Multi-Site Validation of a Trajectory Planning Algorithm for Deep Brain Stimulation Procedures	IEEE Trans Biomed Eng		Deep brain stimulation
25	De León Cuevas, A., et al, 2015[15]	Trajectory planning for keyhole neurosurgery using fuzzy logic for risk evaluation	Conference paper	International Conference on Electrical Engineering, Computing Science and Automatic Control	No detail
26	Essert, C., et al, 2015[20]	Statistical study of parameters for deep brain stimulation automatic preoperative planning of electrodes trajectories	Int J Comput Assist Radiol Surg		Deep brain stimulation
27	Zelmann, R., et al, 2015[70]	Improving recorded volume in mesial temporal lobe by optimizing stereotactic intracranial electrode implantation planning	Int J Comput Assist Radiol Surg		SEEG
28	Trope, M., et al, 2015[62]	The role of automatic computer-aided surgical trajectory planning in improving the expected safety of stereotactic neurosurgery	Int J Comput Assist Radiol Surg		No detail
29	Sparks, R., et al, 2016[60]	Efficient anatomy driven automated multiple trajectory planning for intracranial electrode implantation	Conference paper	Medical Image Computing and Computer-Assisted Intervention	SEEG
30	Nowell, M., et al, 2016[47]	Comparison of computer-assisted planning and manual planning for depth electrode implantations in epilepsy	J Neurosurg		SEEG
31	Hamze, N., et al, 2016[34]	Pareto Front vs. Weighted Sum for Automatic Trajectory Planning of Deep Brain Stimulation	Conference paper	Medical Image Computing and Computer-Assisted Intervention	Deep brain stimulation
32	De Leon-Cuevas, A., et al, 2017[12]	Risk map generation for keyhole neurosurgery using fuzzy logic for trajectory evaluation	Neurocomputing		No detail
33	Scorza, D., et al, 2017[53]	Retrospective evaluation and SEEG trajectory analysis for interactive multi-trajectory planner assistant	Int J Comput Assist Radiol Surg		SEEG
34	Sparks, R. et al, 2017[59]	Anatomy-driven multiple trajectory planning (ADMTP) of intracranial electrodes for epilepsy surgery	Int J Comput Assist Radiol Surg		SEEG
35	Vakharia, VN., et al, 2018[65]	Computer-assisted planning for the insertion of stereoelectro-encephalography electrodes for the investigation of drug-resistant focal epilepsy: an external validation study.	J Neurosurg		SEEG
36	Beckett, JS., et al, 2018[4]	Autonomous Trajectory Planning for External Ventricular Drain Placement	Oper Neurosurg (Hagerstown)		External ventricular drain
37	Vakharia, VN., et al, 2018[64]	Automated trajectory planning for laser interstitial thermal therapy in mesial temporal lobe epilepsy	Epilepsia		Laser interstitial thermal therapy
38	Dergachyova, O., et al, 2018[18]	Automatic preoperative planning of DBS electrode placement using anatomo-clinical atlases and volume of tissue activated	Int J Comput Assist Radiol Surg		Deep brain stimulation
39	Villanueva-Naquid, I., et al, 2018[66]	Novel Risk Assessment Methodology for Keyhole Neurosurgery with Genetic Algorithm for Trajectory Planning	Preprints		No detail
40					SEEG

Table 1 (continued)

	Scorza, D., et al, 2018[51]	Experience-based SEEG planning: from retrospective data to automated electrode trajectories suggestions	Healthc Technol Lett		
41	Li, K., et al, 2019[38]	Optimizing Trajectories for Cranial Laser Interstitial Thermal Therapy Using Computer-Assisted Planning: A Machine Learning Approach	Neurotherapeutics		Laser interstitial thermal therapy
42	Marcus, HJ., et al, 2019[41]	Computer-Assisted Versus Manual Planning for Stereotactic Brain Biopsy: A Retrospective Comparative Pilot Study	Oper Neurosurg (Hagerstown)		Biospsy

N	Disease	Target	Number of Studied cases	Study design	Multicentric (City, Country of 1st author)
1	No detail	Ventral posterolateral nucleus of the thalamus	0	Retrospective	No (Boston, USA)
2	Parkinson disease	Subthalamic nucleus	0	Retrospective	No (Eindhoven, The Netherlands)
3	Parkinson disease	Subthalamic nucleus	5 patients 10 targets (5 right/5 left)	Retrospective	No (London, Canada)
4	No detail	No detail	0	Retrospective	No (Munich, Germany)
5	No detail	No detail	1 patient	Retrospective	No (Jerusalem, Israel)
6	No detail	No detail	2 patients	Retrospective	No (Houston, Texas)
7	No detail	No detail	1 patient	Retrospective	No (Milan, Italy)
8	No detail	No detail	4 patients	Retrospective	No (Jerusalem, Israel)
9	Parkinson disease	Subthalamic nucleus	4 patients 8 targets (4 right/4 left)	Retrospective	No (Strasbourg, France)
10	Parkinson disease	Subthalamic nucleus/Internal globus pallidus	3 patients 12 targets (STN & GPi/both sides)	Retrospective	No (Montreal, Canada)
11	Tumor	No detail	0	Retrospective	No (Iasi, Romania)
12	Parkinson disease	Subthalamic nucleus	8 patients 14 targets (8 right/6 left)	Retrospective	No (Montreal, Canada)
13	Parkinson disease	Subthalamic nucleus	0	Retrospective	No (Nashville, USA)
14	No detail	No detail	1 patient 8 targets	Retrospective	No (Jerusalem, Israel)
15	Drug resistant epilepsy	No detail	8 patients (9–14 electrodes)	Retrospective	No (Milan, Italy)
16	Parkinson disease/dystonia/non-Parkinsonian essential tremor	Subthalamic nucleus/internal globus pallidus/ventral intermediate nucleus of the thalamus	18 patients 29 targets (14 internal globus pallidus, 11subthalamic nuclei, 5 ventral intermediate nuclei of the thalamus)	Retrospective	No (Strasbourg, France)
17	Parkinson disease	Subthalamic nucleus	1 patient	Retrospective	No (Strasbourg, France)
18	Parkinson disease	Subthalamic nucleus/ventral intermediate nucleus of the thalamus	8 patients 14 targets	Prospective	No (Montreal, Canada)
19	Drug-resistant epilepsy	No detail	15 patients 199 targets	Retrospective	No (Milan, Italy)
20	Drug-resistant epilepsy	No detail	3 patients	Retrospective	No (Milan, Italy)

Table 1 (continued)

			26 targets		
21	Drug-resistant epilepsy	No detail	6 patients 30 targets	Retrospective	No (London, UK)
22	Drug-resistant epilepsy	No detail	6 patients 27 targets	Retrospective	No (Montreal, Canada)
23	Tumor	No detail	0	Retrospective	No (Houston, USA)
24	Parkinson disease	Subthalamic nucleus	30 patients 60 targets	Retrospective	Yes nationwide (Nashville-Louisville-Winston-Salem, USA)
25	No detail	No detail	0	Retrospective	No (Querétaro City, Mexico)
26	Parkinson disease	No detail	28 patients 56 targets	Retrospective	Yes nationwide (Strasbourg-Rennes-Paris, France)
27	Drug-resistant epilepsy	No detail	20 patients 65 targets	Retrospective	No (Montreal, Canada)
28	No detail	No detail	8 patients 120 targets	Retrospective	No (Jerusalem, Israel)
29	Drug-resistant epilepsy	No detail	20 patients 186 targets	Retrospective	No (London, UK)
30	Drug-resistant epilepsy	No detail	18 patients 166 targets	Retrospective	No (London, UK)
31	Parkinson disease	Subthalamic nucleus	7 patients 14 targets	Retrospective	No (Strasbourg, France)
32	No detail	No detail	0	Retrospective	No (Querétaro City, Mexico)
33	Drug resistant epilepsy	No detail	20 patients 53 targets	Retrospective	No (Milan, Italy)
34	Drug-resistant epilepsy	No detail	20 patients 190 targets	Retrospective	No (London, UK)
35	Drug-resistant epilepsy	No detail	13 patients 104 targets	Retrospective	Yes International (London, UK - Vienna, Austria - Cleveland, USA - Göteborg, Sweden)
36	No detail	Monro foramen	43 patients	Retrospective	No (Los Angeles, USA)
37	Drug-resistant epilepsy	Hippocampal sclerosis	25 patients	Retrospective	No (London, UK)
38	Parkinson disease	Internal globus pallidus	9 patients 18 targets	Retrospective	No (Strasbourg, France)
39	No detail	No detail	0	Retrospective	No (San Luis Potosi,Mexico)
40	Drug-resistant epilepsy	No detail	75 patients 1100 targets	Retrospective	No (Milan, Italy)
41	Drug-resistant epilepsy	No detail	10 patients	Retrospective	No (London, UK)
42	Tumor	No detail	15 patients	Retrospective	No (London, UK)

SEEG, stereoelectroencephalography

12 studies proposing an automated target point, six were stereoelectroencephalography studies (50%), and only one was published before 2014. Twelve studies (28.6%) proposed a risk map generated after imaging data processing, 24 studies (57.1%) proposed a set of automated trajectories, and six studies (14.3%) proposed only one single automated trajectory.

The duration of imaging data processing required for planning automation (mainly segmentation) was detailed in only seven studies (16.7%). The mean duration of imaging data pre-processing was 71.7 ± 42.6 min (median 60, range 30–140). The duration of automated trajectory production was detailed in 23 studies (54.8%). The mean duration of automated trajectory production was 5.2 ± 11.3 min (median 2, > 0.1–51.8).

Clinical validation of the automated stereotactic procedure

Table 3 detailed the clinical validation of the reviewed studies.

Regarding the clinical validation of the stereotactic planning automation, at least one neurosurgeon was involved in 36 studies (85.7%). The number of neurosurgeons involved in each study varied from 0 to 5 (mean 1.9 ± 1.5, median 1.5). In five studies, neurosurgery residents were included in the clinical validation team. All the implicated neurosurgeons expressed interest in the automated stereotactic planning. Nine studies (21.4%) offered the choice between automatic and manual trajectories. The automated stereotactic trajectory was preferred in 75.4% of the studied cases (range 30–92.9).

Twenty-two studies (52.4 %) provided a comparison between automated and manual stereotactic trajectories using the constraints defined for stereotactic planning automation and figures were available in 18 studies. In all cases, the automated trajectories were superior to the manual trajectories regarding at least one of these constraints. The superiority was demonstrated by greater distance between trajectories and critical structures that were measured on the set of images used to produce automated trajectories between the two nearest voxels. The distance from blood vessels ranged from 1.96 to 4.78 mm for manual trajectories and from 2.47 to 7.0 mm for automated trajectories. The distance from sulci ranged from 1.27 to 2.827 mm for manual trajectories and from 2.11 to 8.952 mm for automated trajectories.

Discussion

Key points

The present systematic review screened 2843 studies and included 42 studies in the final analysis emphasizing the interest of the neuroscientific and neurosurgical communities in the development of automated neurosurgical stereotactic planning in human brains. Several key points need to be underlined: (1) the search for stereotactic planning automation has been a long-standing mantra for more than 20 years; (2) about two-thirds of reviewed studies focused on deep brain stimulation and/or stereoelectroencephalography, i.e., quite rare and highly complex stereotactic procedures in a seemingly normal brain with no noticeable shift, though epileptic lesions can induce subtle changes in gross brain anatomy notable on imaging; (3) only four reviewed studies investigated biopsy for brain tumors and implantation of a ventricular drain, i.e., the most common neurosurgical procedures requiring stereotactic approach in an often distorted brain with noticeable shift; (4) robust clinical validation of any proposed automated stereotactic tool is lacking and no prospective multicentric studies on clinical validation have been published before September 1, 2019 (date of the end of the literature review); and (5) none of the published studies leads to an open-source and user-friendly software suited for clinical practice to the best of our knowledge.

History of stereotactic planning automation for neurosurgical purposes

The first study on this topic dates back to 1997. Overall, the relevant literature is scarce with less than 50 studies over the last 20 years and with 90% of studies published since 2010. In addition, this research topic is led by three main groups across Europe, publishing more than 40% of the relevant literature: a French group based in Strasbourg led by Caroline Essert, an Italian team based in Milan led by Elena De Momi, and a British group based in London led by Sebastien Ourselin [1, 6–8, 10, 12–15, 26, 30, 37, 41, 42, 46, 48, 49, 54].

Type of automated stereotactic planning

Interestingly, we observed an inverse correlation between the frequency of stereotactic procedures in actual neurosurgical practice (mostly tumor biopsies and ventricular drain placements) and those studied for stereotactic planning automation. Indeed, studies focused mainly on deep brain stimulation and stereoelectroencephalography that often require planning of multiple trajectories, making the case for automated stereotactic planning worthwhile. These procedures share a common methodological advantage of being performed on a grossly normal brain from an anatomical point of view. Such a brain is easier to normalize according to reference atlases and to incorporate in the pipeline of stereotactic planning, as compared with a distorted brain by an intracranial lesion causing mass effect, hence losing its usual surrounding anatomical landmarks. If these factors simplify the planning methodology, it precludes the methodological developments that are required to extend the stereotactic planning automation to the most frequent clinical situations (i.e., stereotactic brain

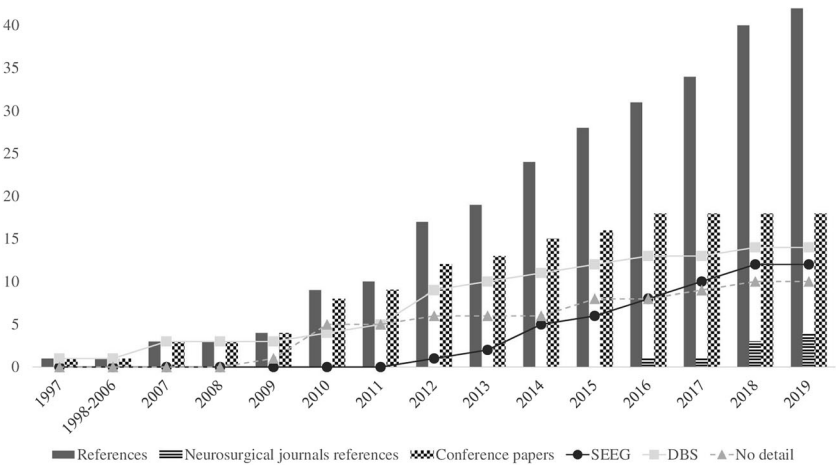

Fig. 2 Trends in the relative numbers of studies in the literature since 1997 examining stereotactic procedure automation in neurosurgery with details regarding conference and neurosurgical journal references (histogram) and studies looking at the three most frequent automated neurosurgical procedures (DBS, deep brain stimulation; SEEG, stereoelectroencephalography; no detail, surgical approach of non-specified brain target)

biopsy) and in frequent other clinical situations for which a stereotactic methodology would improve the accuracy and safety of the surgery (i.e., ventricular catheter placement and ventriculocisternostomy). Of note, several studies report misdiagnosis and morbidity following biopsies for brain neoplasm and report suboptimal rates of correct placement of external ventricular drains and of shunt system ventricular catheters performed under free-hand procedure [2, 17, 19, 23, 34, 47, 51, 52]. As a consequence, all these neurosurgical procedures may benefit from improved accuracy and safety thanks to stereotactic planning, and the development of a widely applicable automation procedure suited for any pathological condition is warranted. Artificial intelligence could be used to propose an optimal target (i.e., those associated with least shunt failures or maximum yield for diagnostic biopsies). Furthermore, the automated stereotactic planning could be applied for other conditions, beyond neurosurgical practice, including liver or lung biopsies [4, 43]. The broad scope of potential clinical applications may favor transversal collaborations with multicentric and transdisciplinary prospective validations of automated planning softwares.

Software availability for the neurosurgical community

The widespread use of the developed softwares is difficult to assess. To the best of our knowledge, the developed softwares remain exclusively used by the clinical team involved in their development. No use of a software for clinical purposes or for external validation has been reported by an external team. The multicentric and external validation of a stereotactic planning automation software was first reported in 2014 but no clinical use on a daily basis has been reported to date [31]. Indeed, only three studies were multicentric and the clinical comparisons were always retrospective [15, 31, 49]. Of note, soon after the search end, the London group reported in October 2019 the first prospective study assessing the use of a computer-assisted automated trajectory planning to improve trajectory safety of current manual planning for SEEG electrodes [50].

Several reasons may explain the difficulties in spreading on a larger scale these stereotactic planning automation softwares: (1) the lack of a user-friendly easy-to-use interface developed by research teams; (2) the lack of sufficient financial support to develop a reliable, validated, and clinically applicable software; (3) the narrow focus on deep brain stimulation and stereoelectroencephalography, procedures that remain highly specialized and performed in tertiary care centers with solid stereotactic skills and experience, thus lessening the need for such an automated planning tool; (4) the quest for very high and unrealistic levels of accuracy (submillimetric) by research teams that exceed what is truly applicable to most stereotactic procedures in real-world conditions, such as the integration of brain shift during deep brain stimulation procedures for example [24], the precision of the deep brain stimulation procedures being millimetric in current clinical practice [5, 29, 45]; (5) the processing time associated with the automation process—median processing duration up to 60 min—is not negligible in the context of common and basic stereotactic procedures such as tumor biopsy or external ventricle drain placement, lasting less than 45 min in real-word setting. Interestingly, the London group recently demonstrated that a computer-assisted automated planning with human review and adjustments (mean 62 ± 17 min) was significantly quicker than manual planning (221 ± 39 min) [50].

Characteristics of the automation process

Imaging data used to plan automated stereotactic trajectories varied widely between studies, from single MRA sequence to multiple imaging datasets (including functional magnetic resonance imaging, diffusion tensor imaging, and susceptibility weighted imaging). This heterogeneity calls for a rule regarding the clinical constraints. Of note, more than 20% of the studies did not consider blood vessels. The standardization

Table 2 Studies included in review, details of automation procedure

N	Imaging data modalities	Vascular imaging	Constraints used to plan stereotactic trajectories	Automated software output	Proposed automated entry	Proposed automated target	Number of neurosurgeons involved (n of residents)	Numbered comparison with manual planning (results between AT and MT)	Time to process imaging data (min)	Time to generate trajectories (s)
1	MRI	No detail	Optic radiations Brodman areas 1–4 and 17–19 Thalamus VPL nucleus Path Length	Risk map	No	No	0	No	N/A	210
2	MRI: T1-weighted and T2-weighted sequence, CT	Contrast-enhanced T1-weighted sequence	Blood Vessels Ventricles Cerebral sulci Hairline In front of the motor cortex Safe up to a small distance below the target Entry points only into the frontal lobe gyri	Set of trajecto-ries	Yes, point	No	3 (2)	No	60	N/A
3	MRI: 3D T1-weighted sequence	No detail	Ventricles Cerebral sulci	Risk Map	Yes, point	Yes, point	0	No	N/A	N/A
4	MRI: T1-weighted sequence and MRA *Optional: DWI, fMRI, CT, CTA*	MRA	No-go area Blood Vessels	Set of trajecto-ries	No	No	0	No	N/A	N/A
5	MRI	MRA	No-go area Blood Vessels	Set of trajecto-ries	No	No	1	Yes (AT>MT)	N/A	N/A
6	MRI: 3D T2-weighted sequence and MRA	MRA (TOF)	Blood Vessels Path length	Set of trajecto-ries	Yes, point	No	3	No	N/A	N/A
7	MRI: T1-weighted, , fMRI and DTI sequence	MRA	Anatomy Blood Vessels Functional area White matter tracts	Set of trajecto-ries	No	No	1	No	N/A	N/A
8	MRI	No detail	Blood Vessels Ventricles Path Lenght	Set of trajecto-ries	No	No	1	Yes (AT>MT)	N/A	198
9	MRI: 3D T1-weighted sequence CT	No detail	*Strict constraints:* Placing the Electrode in the Target Position of the insertion point Path lenght Ventricles Blood Vessels Cerebral Sulci	Risk map	Yes, zone	No	2	Yes (AT>MT)	N/A	N/A

Table 2 (continued)

N	Imaging data modalities	Vascular imaging	Constraints used to plan stereotactic trajectories	Automated software output	Proposed automated entry	Proposed automated target	Number of neurosurgeons involved (n of residents)	Numbered comparison with manual planning (results between AT and MT)	Time to process imaging data (min)	Time to generate trajectories (s)
			Soft constraints: Minimizing the length of the path Maximizing the Distance Between Electrode and Risky Structures Optimizing the Orientation of the Electrode According to Target Shape							
10	MRI: T1-weighted sequence, SWI	MRA (TOF)	Surgeon-chosen region-of-interest Blood Vessels Ventricles Cerebral Sulci Midline	Set of trajecto-ries	Yes, point	No	2 (1)	Yes (AT>MT)	N/A	240
11	MRI: Post Gadolinium T1-weighted sequence	Contrast-enhanced T1-weigthed sequence	Surgeon-chosen region-of-interest Blood Vessels	Risk map	No	No	5 (2)	No	N/A	150
12	MRI: T1-weighted sequence and T2-weighted sequence and SWI and MRA	MRA (TOF)	*Hard constraints:* Entry point within the frontal lobe Midline Ventricles (Hard/Soft) Cerebral sulci (Hard/Soft) *Soft constraints*: Blood Vessels Minimize overlap with caudate Minimize overlap with CGM	Risk map	Yes, point	No	2 (1)	Yes (AT>MT)	120	21
13	MRI: Post Gado … , T1-weighted sequence	Contrast-enhanced T1-weigthed sequence	Surgeon-chosen region-of-interest (Hairline) Blood Vessels Ventricles Cerebral Sulci Near of coronal suture Intersect the thalamus	Risk map	Yes, point	No	2	No	N/A	N/A
14	MRI: MRA	MRA	Blood Vessels Critical structures	Risk map	Yes, point	No	1	Yes (AT>MT)	N/A	354
15	MRI		Blood Vessels		Yes, point	No	1	Yes (AT>MT)	N/A	10

Table 2 (continued)

N	Imaging data modalities	Vascular imaging	Constraints used to plan stereotactic trajectories	Automated software output	Proposed automated entry	Proposed automated target	Number of neurosurgeons involved (n of residents)	Numbered comparison with manual planning (results between AT and MT)	Time to process imaging data (min)	Time to generate trajectories (s)
	CTA	CTA (3D rotational angiographies)	Cerebral sulci Entry angle	Set of trajecto-ries						
16	MRI: T1-weighted sequence CT	No detail	*Strict constraints:* Placing the Electrode in the Target Position of the insertion point Path lenght Ventricles Cerebral sulci *Soft constraints*: Minimizing the length of the path Maximizing the Distance Between Electrode and Risky Structures Optimizing the Orientation of the Electrode According to Target Shape Placing the tip as close as possible to the center of the target	Set of trajecto-ries	Yes, point	No	2	Yes (AT>MT)	N/A	138.36
17	MRI: T1-weighted sequence	No detail	Ventricles Cerebral Sulci Position of the insertion point	Set of trajecto-ries	Yes, point	No	2	No	N/A	3106.2
18	MRI: T1-weighted sequence and T2-weighted sequence and SWI	MRA (TOF)	*Hard constraints:* Entry point within the frontal lobe Midline Ventricles (Hard/Soft) Cerebral sulci (Hard/Soft) *Soft constraints*: Blood Vessels Minimize overlap with caudate Minimize overlap with CGM	Risk map	Yes, point	No	1	No	N/A	40
19	MRI: 3D T1-weighted sequence CTA	CTA (3-D rotational angiographies)	Blood Vessels Cerebral Sulci		Yes, point	No	3	Yes (AT>MT)	N/A	60

Table 2 (continued)

N	Imaging data modalities	Vascular imaging	Constraints used to plan stereotactic trajectories	Automated software output	Proposed automated entry	Proposed automated target	Number of neurosurgeons involved (n of residents)	Numbered comparison with manual planning (results between AT and MT)	Time to process imaging data (min)	Time to generate trajectories (s)
			Entry angle Distance between electrodes	Set of trajecto-ries						
20	MRI: 3D T1-weighted sequence CTA	CAT (3-D rotational angiographies)	Blood Vessels Cerebral Sulci Entry angle Distance between electrodes Predefined entry and target points	Set of trajecto-ries	Yes, point	No	4	Yes (AT>MT)	N/A	N/A
21	MRI, DTI, fMRI SPECT PET image EEG/MEG sources	CTA, 3D Phase Contrast MR imaging and MRA (TOF)	White matter tracts Lesions Eloquent cortex Blood Vessels Areas of ictal hyperperfusion derived from SPECT Areas of hypometabo-lism derived from PET image Ictal or interictal EEG/MEG sources Path length Entry angle	Risk map	Yes, point	No	1	Yes (AT>MT)	N/A	150
22	MRI: T1-weighted sequence and Contrast-enhanced T1-weighted sequence	Contrast-enhanced T1-weighted sequence	Blood Vessels Cerebral Sulci Ventricles Electrode distance Target volume Gray Matter	Set of trajecto-ries	Yes, point	Yes	1	Yes (AT>MT)	N/A	120
23	N/A	No detail	Blood Vessels Path length	Risk map	No	No	2	Yes (AT>MT)	N/A	0.13
24	MRI: T1-weighted sequence and Contrast-enhanced T1-weighted sequence	Contrast-enhanced T1-weighted sequence	Hairline Blood Vessels Primary motor cortex Cerebral Sulci Ventricles Coronal suture Thalamus	Risk map	Yes point	No	4	Yes (AT>MT)	140	N/A
25	MRI	No detail	*Strict constraints* Midline of the brain Blood Vessels Ventricles Path length	Risk map	Yes, point	No	0	No	N/A	N/A

Table 2 (continued)

N	Imaging data modalities	Vascular imaging	Constraints used to plan stereotactic trajectories	Automated software output	Proposed automated entry	Proposed automated target	Number of neurosurgeons involved (n of residents)	Numbered comparison with manual planning (results between AT and MT)	Time to process imaging data (min)	Time to generate trajectories (s)
			Critical area of the cortex *Soft constraint* Length trajectory Voxel risk							
26	MRI: T1-weighted sequence	No detail	Soft constraints Standard Trajectory Cerebral sulci Ventricles	Set of trajecto-ries	Yes, point	No	2	No	30	7
27	MRI CT: CTA	CTA	Blood Vessels Gray Matter Ventricles Cerebral sulci Entry angle Temporal muscle crossing Ear canal and surrounding cartilages No trajectory conflict	Set of trajecto-ries	Yes, point	Yes	2	Yes (AT>MT)	N/A	N/A
28	MRI : Contrast-enhanced T1-weighted sequence and FLAIR sequence and DTI and fMRI	Contrast-enhanced T1-weighted sequence	Blood Vessels Ventricles White matter tracts: pyramidal tract, optic radiation, and superior longitudinal fasciculus Language regions Motor regions	Set of trajecto-ries	Yes, point	No	5 (3)	Yes (AT>MT)	N/A	N/A
29	MRI: T1-weighted sequence and Contrast-enhanced T1-weighted sequence CT:CTA	Contrast-enhanced T1-weighted sequence CTA	Blood Vessels Cerebral Sulci Path length Entry angle Superficial Region of Interest No trajectory conflict	Set of trajecto-ries	Yes, point	Yes	2	Yes (AT>MT)	N/A	61.14
30	MRI: Contrast-enhanced T1-weighted sequence and 3D phase-contrast sequence CT: CTA	Contrast-enhanced T1-weighted sequence CTA	Blood Vessels Sulci Gray Matter Hairline Entry Angle Conflict trajectory Redundant coverage Path length	Set of trajecto-ries	Yes, point	No	3	Yes (AT>MT)	30	480
31	MRI: T1-weighted sequence and T2-weighted sequence	No detail	Standard trajectory Blood Vessels		Yes, point	No	1	No	N/A	42

Table 2 (continued)

N	Imaging data modalities	Vascular imaging	Constraints used to plan stereotactic trajectories	Automated software output	Proposed automated entry	Proposed automated target	Number of neurosurgeons involved (n of residents)	Numbered comparison with manual planning (results between AT and MT)	Time to process imaging data (min)	Time to generate trajectories (s)
			Cerebral Sulci	Set of trajecto-ries						
32	MRI: T1-weighted sequence and Contrast-enhanced T1-weighted sequence	Contrast-enhanced T1-weighted sequence	Midline Blood Vessels Ventricles Path length Primary motor cortex Hairline	Set of trajecto-ries	Yes, point	No	0	No	N/A	N/A
33	MRI CT: CTA	CTA	Blood Vessels Cerebral sulci Entry angle No trajectory conflict	Set of trajecto-ries	Yes, point	Yes	1	Yes (AT>MT)	N/A	160.5
34	MRI: 3D T1-weighted sequence and Contrast-enhanced T1-weighted sequence and MRA and MRV CT	Contrast-enhanced T1-weighted sequence and MRA and MRV	Blood Vessels Cerebral sulci Path Length Entry Angle Superficial Region of Interest No trajectory conflict	Set of trajecto-ries	Yes, point	Yes	1	Yes (AT>MT)	N/A	54.5
35	MRI: 3D T1-weighted sequence and Contrast-enhanced T1-weighted sequence and MRA and MRV	Contrast-enhanced T1-weighted sequence and MRA and MRV	Blood Vessels Cerebral sulci Path Length Entry Angle Superficial Region of Interest No trajectory conflict	Set of trajecto-ries	Yes, point	Yes	5	Yes (AT>MT)	60	120
36	CT	No detail	Ventricles	Trajectory	No	Yes	0	No	N/A	N/A
37	MRI: T1-weighted sequence	No detail	Cerebral sulci Ventricles Deep Region of Interest Path length Entry angle	Trajectory	Yes, point	No	1	Yes (AT>MT)	N/A	N/A
38	MRI: T1-weighted sequence CT	No detail	Standard Trajectory Cerebral sulci Ventricles	Trajectory	Yes, point	Yes	1	Yes (AT>MT)	N/A	10
39	MRI: MRA	MRA	Ventricles Blood Vessels	Trajectory	No	No	5	No	N/A	1423.6
40	MRI: 3D T1-weighted sequence	No detail	Blood Vessels Cerebral sulci Entry angle No trajectory conflict	Set of trajecto-ries	Yes, point	Yes	1	Yes (AT>MT)	N/A	N/A

Table 2 (continued)

N	Imaging data modalities	Vascular imaging	Constraints used to plan stereotactic trajectories	Automated software output	Proposed automated entry	Proposed automated target	Number of neurosurgeons involved (n of residents)	Numbered comparison with manual planning (results between AT and MT)	Time to process imaging data (min)	Time to generate trajectories (s)
41	MRI: T1-weighted sequence	No detail	Ventricles Brainstem Cerebellum Path length Ventricles Blood Vessels Cerebral sulci Entry angle Distance to brainstem Ablation of the mesial hippocampal head and AHC	Trajectory	Yes, point	Yes	1	No	N/A	N/A
42	MRI: Contrast-enhanced T1-weighted sequence	Contrast-enhanced T1-weighted sequence	Cerebral Sulci Blood Vessels Entry angle Path length	Trajectory	Yes, point	Yes	3	Yes (AT>MT)	60	N/A

AT, automatic trajectory(ies); *CT*, computed tomography; *CTA*, computed tomography angiography; *DTI*, diffusion tensor imaging; *EEG*, electroencephalogram; *FLAIR*, fluid-attenuated inversion recovery; *fMRI*, functional magnetic resonance imaging; *MEG*, magnetoencephalography; *MRA*, magnetic resonance angiography; *MRI*, magnetic resonance imaging; *MRV*, magnetic resonance venography; *MT*, manual trajectory(ies); *PET*, positron emission tomography; *SPECT*, single photon emission computed tomography; *SWI*, susceptibility weighted imaging; *TOF*, time of flight

Table 3 Details of clinical validation

	First author	Percentage of preferred AT vs MT by experts	Dedicated form/type of scale	Form detail	Distance from brain vessels (mm) MT/AT/(*p*, if applicable)*	Distance from sulci (mm) MT/AT/(p, if applicable)*	Distance from ventricles (mm) MT/AT/(*p*, if applicable)*	Insertion angle (°) MT/AT/(*p*, if applicable)*	Path length (mm) MT/AT/(*p*, if applicable)*
2	Brunenberg, E.J.L. et al		Yes/numbered scale (1 "very poor" to 5 "excellent")	Path visualization (3 questions)/path approval (2 questions)/general (4 questions)/improvement compared with current system (1 question)/amount of time to be gained (min) (1 question)					
5	Shamir R. R., et al				3.2/7.0				38.9/57.4
6	Navkar, N. V., et al		Yes/numbered scale (1 "not very effective" to 5 "extremely effective")	Effectiveness of the access maps for: stereotactic biopsy, laser ablation of tumors, and deep brain stimulation/shunt and external ventricle drainage insertion, cyst drainage/endoscopy (3 questions)					
11	Herghelegiu, P. C., et al		Yes/five-point attitude Likert scale	Experience (2 questions)/usability (10 questions)/functionality (4 questions)/tasks (3 questions)/details (9 questions)/comments (3 questions)/impressions (2 questions)					
12	Beriault, S., et al	92.9				2.3/4.0	4.6/> 5.0		
13	Liu, Y., et al								
14	Shamir, R. R. et al				4.45/6.18		19.85/20.15		48.94/50.47
15	Caborni, C., et al				1.962/3.185			28.038/14.669	
16	Essert, C., et al					2.827/7.169			
18	Bériault, S., et al	87.5							
19	De Momi, E., et al	50			1.3/2.9/$p = 0.00$				
22	Zelmann, R., et al	92.6			1.59/4.03/$p < 0.01$				
23	Rincón-Nigro, M., et al								
24	Liu, Y., et al	76.67			3.67/4.50/$p = 0.0925$		4.30/3.80/$p = 0.2111$		
27	Zelmann, R., et al				2.21/2.47/$p = 0.038$ [distance to small vessels (mm): 0.79/1.6/$p < 0.001$]	1.27/2.11/$p < 0.001$	12/16/$p = 0.08$	0.42/12.1/$p < 0.001$	
28	Trope, M., et al	85					12.6/10.1		
29		78							

Table 3 (continued)

	First author	Percentage of preferred AT vs MT by experts	Dedicated form/type of scale	Form detail	Distance from brain vessels (mm) MT/AT/(*p*, if applicable)*	Distance from sulci (mm) MT/AT/(p, if applicable)*	Distance from ventricles (mm) MT/AT/(*p*, if applicable)*	Insertion angle (°) MT/AT/(*p*, if applicable)*	Path length (mm) MT/AT/(*p*, if applicable)*
	Sparks, R., et al								
30	Nowell, M., et al				4.48/4.52/$p < 0.05$			16.2/13.0/$p < 0.05$	57.9/53.9/$p < 0.05$
31	Hamze, N., et al	85.7							
33	Scorza, D., et al				4.78/5.54 [distance to small vessels (mm): 1.66/1.95]			20.65/14.53	
34	Sparks, R. et al								
35	Vakharia, VN., et al				2.8/5.4/$p < 0.001$			18.9/14.8/$p < 0.001$	54.0/39.8/$p < 0.001$
37	Vakharia, VN., et al							31.1/32.3/$p = 0.47$	90/82/$p = 0.007$
38	Dergachyova, O., et al					2.451/8.952	7.950/11.852		
40	Scorza, D., et al				3.5/4.0 [distance to small vessels (mm): 1.8/1.2]			17.0/16.7	
42	Marcus, HJ., et al							14.6/10.0/$p = 0.07$	43.5/38.5/$p = 0.01$

*If two automation processes were used, the one proposing the lowest values was favored/the studies proposing only figures without extractable numbers were not included.

AT, automatic trajectory(ies); *MT*, manual trajectory(ies)

of the imaging data and constraints would ease software comparison and discussion across teams, eventually leading to a global software composed of several modules, each developed by a dedicated team.

The clinical evaluation of the developed stereotactic planning automation was performed in 52.4% of studies. It showed, in all available cases, the superiority of automated stereotactic methods versus standard manual stereotactic planning and suggested that automation would improve the standard of care. When neurosurgeons were surveyed, they all recognized the potential of such tools and preferred the automated trajectories in more than 75% of cases. Regarding clinical validation, the London group recently developed a clinical decision support software (EpiNav, UCL, London, UK) generating 3D models of critical structures and regions of interest and allowing computer-assisted automated planning of electrode trajectories [50]. They prospectively demonstrated, in 13 SEEG patients and 125 electrode trajectories, that computer-assisted automated planning with human review and adjustments had lower mean risk score than manual planning and were preferred in 100% of cases.

Automation bias—the tendency to over-rely on automation—should be taken into account in validation studies of automated trajectory planning tools [20]. Two types of errors are possible: commission errors due to following incorrect advice and omission errors due to the absence of action because of the lack of incentive to do so [44]. These biases have been mostly studied in the aviation research field, but one has to be mindful that with increasing automation in surgery, the neurosurgeon will take on a more passive role with these pathologies and thus be more exposed to similar biases [32, 44].

Limitations

Although this review represents the first comprehensive assessment of stereotactic planning automation for neurosurgical purposes, the present results should be interpreted with caution. The review was limited to the English and French-language literature and limited to stereotactic procedures with a straight trajectory. The literature search was restricted in the Google Scholar database from 1 January 2010 to 1 September 2019, which allows for possible omission of earlier studies. Despite 42 studies reporting stereotactic planning automation for neurosurgical purposes, none met rudimentary standards for an ideal design. Therefore, further studies—possibly multicentric studies with international collaboration—of large, unbiased samples of patients undergoing stereotactic procedures, for different intracranial pathologies, are needed. Other studies proposing a new surgical viewer or facilitating targeting through dedicated atlases may be of great interest and deserve a specific review [22, 38, 53]. In addition, as no study reported and compared the complication rates (including postoperative hematoma) of computer-assisted automated planning compared with manual planning, the question as to whether stereotactic planning automation translates into increased safety remains to be established.

Conclusion

Stereotactic planning automation in neurosurgery, mainly involving deep brain stimulation and stereoelectroencephalography, is an emerging and scarcely studied area of research. The next step in developing automated stereotactic trajectory planning tools is proper assessment of the superiority of automated planning versus manual planning, in terms of clinical complication avoidance, including a reduction in hemorrhagic events. However, there is little doubt that extending stereotactic reasoning (more accurate targeting with minimal risks) to common neurosurgical procedures usually performed free hand in daily practice would be highly beneficial for patients. Larger studies involving neurosurgeons along with biomedical engineers are required to develop such tools. Future studies should follow adequate guidelines, such as the IDEAL framework, to produce scientific reliable proofs-of-concept before large-scale implementation [33]. Moreover, the development of a software enabling automatically generated, safe and accurate stereotactic trajectories is required as an initial step to achieve true robotic stereotactic neurosurgical procedures, i.e., surgical procedures performed exclusively by robots without any direct human intervention [7]. The development of such a software containing different specialized modules (external ventricle drainage insertion, brain tumor biopsy, deep brain stimulation…) and user friendly represents the next step in this research field.

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Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical approval For this type of study, formal consent is not required.

Informed consent This article does not contain any studies with human participants performed by any of the authors.

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