Precision in Neuronavigation Systems: A Systematic Review and Meta-analysis

Precisão em sistemas de neuronavegação: Uma revisão sistemática e meta-análise

Evelen Rouse de Souza Santos[1] Fabiana Ramos Viana[1] Paulo Eduardo Gonçalves[2]
Maria Adriely Cunha Lima[1] Carlos Alberto Miranda Lyra[1] Bruno Fernandes de Oliveira Santos[1,2,3]

[1] Department of Medicine, Tiradentes University, Aracaju, SE, Brazil
[2] Department of Medicine, Federal University of Sergipe, Aracaju, SE, Brazil
[3] Health Sciences Graduate Program, Federal University of Sergipe, Aracaju, SE, Brazil

Address for correspondence Bruno Fernandes de Oliveira Santos, MD, MSc, PhD, Health Sciences Graduate Program, Federal University of Sergipe, Aracaju, SE, Brazil (e-mail: brunofernandes.se@gmail.com).

Arq Bras Neurocir 2024;43(4):e325–e336.

Abstract

Introduction To evaluate the accuracy of different neuronavigation systems and establish factors that influence their accuracy and their indications for use.

Methods This is a systematic review of the literature with meta-analysis based on the guiding question of the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA): What is the accuracy of neuronavigation systems and the factors that influence it? For that, a search was performed in PubMed, LILACS, SciELO, Embase, Web of Science, and SCOPUS databases using descriptors combined with two Boolean operators. The articles found were submitted to eligibility criteria, and the reading was partial and complete. A total of 51 studies were selected, and 11 were included in the meta-analysis.

Results In total, 5,316 procedures were evaluated using neuronavigation systems and different types of procedures performed on the skull and spine. After meta-analysis, it was possible to establish the accuracy of the optical ($N = 297$) and AR ($N = 195$), with SBT of 2.34 mm and 2.09 mm, respectively. However, studies were evaluated regarding the influence of different recording methods, the use of associated technologies, and their indications for use.

Conclusions The accuracy of the systems was established through the TRE of 2.34 mm for the optical and 2.09 mm for the augmented reality, while it was not possible to establish the electromagnetic one. Thus, the ARN is the system with the best accuracy value, in addition to presenting advantages during the surgical period when compared with the others.

Keywords
- neuronavigation
- accuracy
- reliability
- neurosurgery
- neurosurgical procedures
- image-guided surgery

received
December 13, 2023
accepted
October 18, 2024

DOI https://doi.org/10.1055/s-0044-1795095.
ISSN 0103-5355.

Thieme Revinter Publicações Ltda., Rua do Matoso 170, Rio de Janeiro, RJ, CEP 20270-135, Brazil

Resumo

Introdução Avaliar a precisão de diferentes sistemas de neuronavegação e estabelecer fatores que influenciam sua precisão e suas indicações de uso.

Métodos Trata-se de uma revisão sistemática da literatura com meta-análise baseada na questão norteadora do *Preferred Reporting Items for Systematic* Review *and Meta-Analyses* (PRISMA): Qual a precisão dos sistemas de neuronavegação e os fatores que a influenciam? Para tanto foi realizada uma busca nas bases de dados PubMed, LILACS, SciELO, Embase, Web of Science e SCOPUS utilizando descritores combinados com dois operadores booleanos. Os artigos encontrados foram submetidos aos critérios de elegibilidade e a leitura foi parcial e completa. Foram selecionados 51 estudos e 11 foram incluídos na meta-análise.

Resultados No total foram avaliados 5.316 procedimentos utilizando sistemas de neuronavegação e diferentes tipos de procedimentos realizados no crânio e na coluna vertebral. Após a meta-análise foi possível estabelecer a precisão da óptica (N = 297) e da RA (N = 195) com SBT de 2 34 mm e 2.09 mm, respectivamente. No entanto foram avaliados estudos quanto à influência de diferentes métodos de registro ao uso de tecnologias associadas e suas indicações de uso.

Conclusões A precisão dos sistemas foi estabelecida por meio do TRE de 2.34 mm para a óptica e 2.09 mm para a realidade aumentada enquanto não foi possível estabelecer o eletromagnético. Dessa forma a ARN é o sistema com melhor valor de precisão além de apresentar vantagens durante o período cirúrgico quando comparado aos demais.

Palavras-chave
- neuronavegação
- precisão
- confiabilidade
- neurocirurgia
- procedimentos neurocirúrgicos
- cirurgia guiada por imagem

Introduction

Neurosurgery encompasses various image-guided surgical approaches, among which neuronavigation emerges as a principal tool. These devices exhibit millimetric precision and accuracy, significantly enhancing procedural safety and facilitating less invasive surgeries. Neuronavigation employs a Cartesian framework, enabling the monitoring of calibrated instruments within three-dimensional space while considering their orientation and position relative to cranial structures.[1] Consequently, these systems find utility in a wide array of applications, including intracranial biopsies, spinal pedicle screw placement, precise localization of minimally invasive craniotomies, planning and execution of microsurgery for intracranial tumors and arteriovenous malformations, among other procedures.

Currently, the market offers diverse navigation technologies, predominantly featuring two tracking systems: optical and electromagnetic. These systems are responsible for perceiving the intraoperative environment in three dimensions, thereby enhancing surgical accuracy and yielding improved clinical outcomes. Moreover, augmented reality systems are available, providing an enhanced user experience.

Therefore, the purpose of this study is to conduct a systematic review focusing on the accuracy of neuronavigation. It aims to explore different navigation systems and investigate the impact of application errors (AE) and associated imaging techniques on the overall accuracy of neurosurgical procedures.

Methodology

This study comprises a systematic literature review with a meta-analysis, adhering to the criteria and guidelines outlined in the Cochrane Manual[2] (The Cochrane Collaboration) for investigating current neuronavigation technologies. The primary objective is to determine the accuracy of neuronavigation systems. The research question is formulated based on the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA)[3] guidelines.

Search Strategy

Comprehensive searches were conducted in multiple online databases, including PubMed, Latin American and Caribbean Literature in Health Sciences (LILACS), Online Scientific Electronic Library (SciELO), Embase, Web of Science, and SCOPUS. The descriptors "neuronavigation," "accuracy," "reliability," "neurosurgery," "neurosurgical procedures," and "image-guided surgery" were combined using Boolean operators. The search criteria employed were ("neurosurgery" OR "neurosurgical procedures") AND ("image-guided surgery" OR "neuronavigation") AND ("reliability" OR "accuracy"). The search spanned from 1993 to January 1, 2023.

Study Selection

Upon completing the initial search, two authors (E.R.S.S.; M. A.C.L.) independently assessed the identified articles. Discrepancies were resolved through discussion with a third author (B.F.O.S.) to achieve a consensus. The following inclusion criteria were applied: articles published in English; experimental, observational studies (including cross-sectional, cohort, and case-control) or clinical trials that reported the accuracy of the neuronavigation system; articles published within the past 30 years; and availability of the full text. Articles that did not address the topic or lacked sufficient data to fulfill the objectives of this review were excluded (see ►**Fig. 1**).

Data Extraction

A single author conducted the data extraction using a standardized form, and the collected data were organized in a Microsoft Office Excel®[4] table. Subsequently, a second author reviewed the extracted data from the studies. The extracted information included the number of participants, registration method, mean errors or precision, and the imaging method utilized.

Critical Evaluation of Studies

Tools were employed to assess the articles based on their study design. For randomized studies, the revised Cochrane risk of bias tool for randomized trials (RoB2)[5] was utilized. Non-randomized clinical studies were evaluated using the Cochrane tool for assessing the risk of bias in non-randomized studies of interventions (ROBINS-I).[6] Cohort and case-control studies were evaluated using the Newcastle-Ottawa tool, while cross-sectional studies were assessed using the Joanna Briggs[7] tool. Diagnostic accuracy studies were evaluated using the revised tool for quality assessment in diagnostic accuracy studies (QUADAS-2).[8] One author critically evaluated all the studies using the appropriate tool for each study design, and discussions were held with a second author.

Statistical Analysis

To perform the meta-analysis means and standard deviations were extracted as effect measures. For studies that presented measures other than averages, such as medians with minimum and maximum intervals or quartile measures, the tool proposed by the Cochrane Manual (The Cochrane Collaboration)[2] was employed, as described and made available by Wang et al. In cases where necessary data were missing, attempts were made to contact the corresponding authors via email. If no response was received, the article was excluded from the synthesis. The measure of central tendency of the target's registration error distribution was considered as accuracy, while the measure of dispersion was considered as precision. The data were synthesized using weighted average grouping. All calculations were performed using R© (version 4.0.3, The R Foundation for Statistical Computing, 2020) and Python (version 3.9.10, NumPy version 1.22.4, Panda's version 1.4.4, and Matplotlib version 3.7.1).

Results

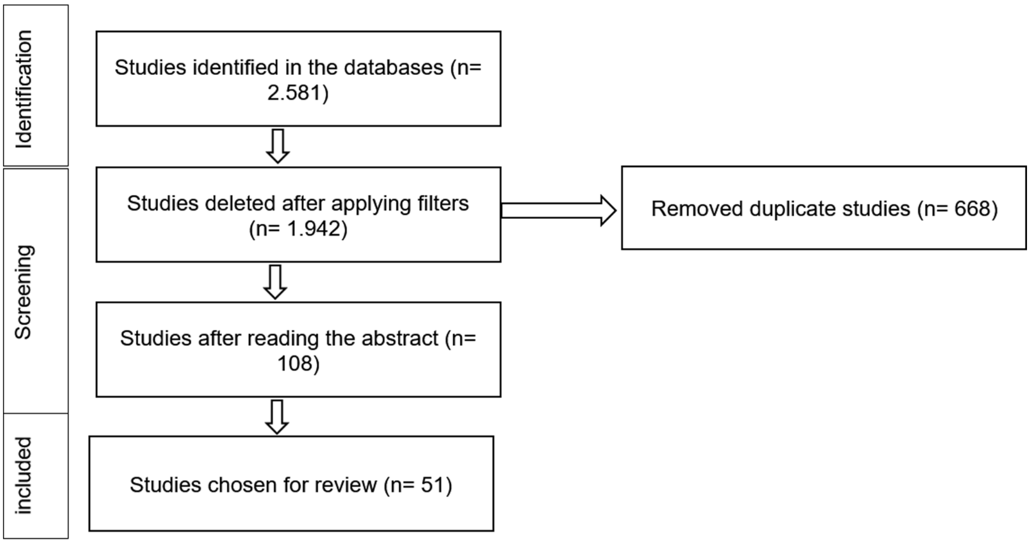
The tables below provide details regarding the analyzed articles, including the authors' descriptions, year of publication, titles, and summaries of each study. The selected articles that best address the research questions are highlighted for easier reference.

Study Selection

A total of 2,581 articles were identified from all databases. After applying the eligibility criteria, 1,942 articles were selected for title and abstract screening. Subsequently, 1,274 articles underwent full-text reading, and among them, 51 articles met the inclusion and exclusion criteria, thus forming the database for this study. Among the selected articles, 12 were included in the meta-analysis.

Quality Evaluation of Studies

The studies were assessed using the tools. The majority (93.2%) of the studies were classified as cross-sectional/accuracy studies and evaluated using the Joanna Briggs (Moola



Source: study data, 2023.

Fig. 1 Flowchart of the process performed to select articles.

et al., 2020) and QUADAS-2 tools. Both tools indicated a low risk of bias for the included studies. Randomized clinical trials, evaluated using the RoB2 tool, represented 5.8% of the included studies. The figure below illustrates the risk of bias for each study (►**Figure 2**):

Characteristics of the Studies

The total sample size included in this review comprised 5,316 procedures. In terms of location, many procedures (80%, *n* = 4,250) were performed on the cranium, while 20% (*n* = 1,066) were conducted on the spinal column. Among spinal procedures, the thoracolumbar region was the most frequently targeted, accounting for 36.9% (*n* = 393) of the total, followed by the lumbar spine with 34.7% (*n* = 370).

Out of the total procedures, 5,210 had their method of neuronavigation reported. Among these, the optical system (OP) was the most prevalent, comprising 2,673 cases (51.3%), followed by augmented reality (AR) with 1,835 cases (35.2%), and electromagnetic (EM) with 702 cases (13.5%). The method used for registration was mentioned in 40 studies (78.4%), with the fiducial method being the most employed, reported in 22 studies, followed by the anatomical marker method mentioned in 15 articles. It is noteworthy that the studies covered both cranial and spinal procedures (see ►**Chart 1**).

Different studies approached the application error results in various ways. Three studies reported the mean recording error, except for Van Doormaal et al.,[55] who obtained values of 7.20 ± 1.80 mm and 4.40 ± 2.50 mm. The remaining studies reported results ranging from 0.08 to 1.80 mm. Serej et al.[50] evaluated the fiducial registration error (FRE) using different methods. The anatomical landmark method yielded an FRE of 1.20 ± 0.40 mm, the surface method resulted in 1.00 ± 0.30 mm, and the projected method had the lowest value of 0.60 ± 0.10 mm (►**Chart 1**).

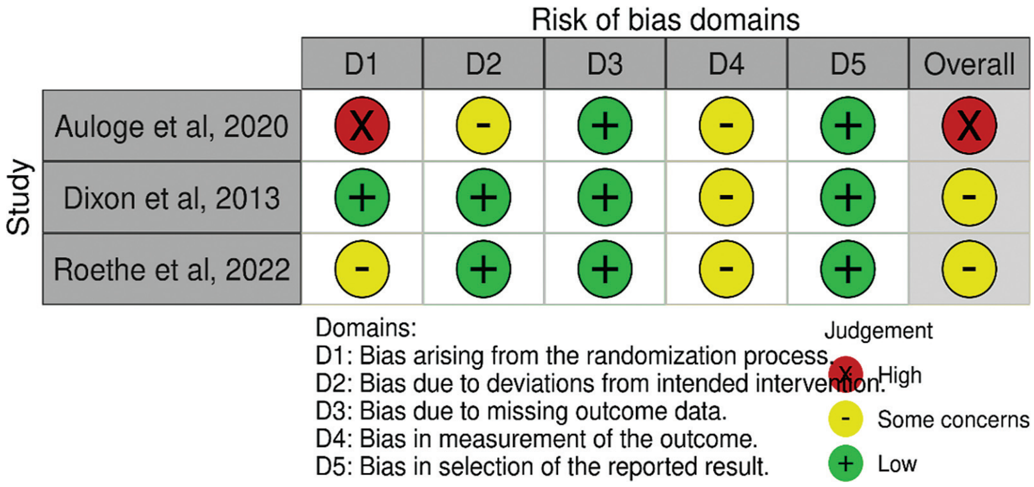
The target registration error (TRE) varied between 0.54 and 5.90 mm, with only 5 studies falling outside the commercially expected values. Salma et al.[48] assessed the TRE for different methods used and found that the scalping method had the highest average TRE of 3.24 mm, followed by the registration mask with 3.19 mm, while the bone fiducial method had a TRE within the target range of 1.95 mm. Other methods employed to assess the application error included general and average precision, location, and displacement precision, as well as average deviation (►**Chart 1**).

In ►**Chart 1**, it is evident that most spinal procedures utilized the augmented reality method, with only one study employing the optical method. It is worth noting that the studies with the largest sample size for spinal procedures in this review were Fan et al.,[23] who achieved a location accuracy of 97.8% in a sample of 370, and Elmi et al.,[20] who reported an overall accuracy of 94.1% for procedures performed on 253 spinal columns.

Considering the variation in application error across studies, a meta-analysis was conducted specifically for articles that utilized the fiducial registration error (FRE) as an evaluation method. Six articles assessing the optical system were included in the analysis, with a total sample size of 297 tests, resulting in an average FRE of 2.34 mm and a standard deviation of 1.86 mm.

►**Fig. 3** illustrates that Shamir et al.[51] and Reinges et al.[46] reported the highest values for target registration error (TRE) compared with the overall results, with values of 5.90 ± 4.30 mm and 6.10 ± 3.40 mm, respectively. Conversely, McLaughlin et al.[36] achieved the lowest error with a TRE of 0.90 ± 0.70 mm. Notably, Castilla et al.[15] had an estimated registration error closest to that obtained in the meta-analysis. It is important to highlight that the study conducted by Mert et al.[37] contributed the largest sample size, thus having the highest number of cases among all included studies.

Additionally, six articles utilizing the augmented reality system were evaluated, comprising a total sample size of 195 cases. The average estimated registration error (ERT) for these studies was 2.09 mm, with a standard deviation of 1.42 mm. Consequently, ►**Fig. 4** demonstrates that Maruyama et al.[35] achieved the highest value within the meta-analysis, reporting a skull-based TRE of 3.10 ± 1.90 mm. In Carl et al.'s[12] study, the TRE for the skull was close to the overall value at 2.33 ± 1.30 mm. When comparing it to the spinal column TRE, which was 0.72 ± 0.24 mm, the skull TRE



Risk of bias domains

Study	D1	D2	D3	D4	D5	Overall
Auloge et al, 2020	X	-	+	-	+	X
Dixon et al, 2013	+	+	+	-	+	-
Roethe et al, 2022	-	+	+	-	+	-

Domains:
D1: Bias arising from the randomization process.
D2: Bias due to deviations from intended intervention.
D3: Bias due to missing outcome data.
D4: Bias in measurement of the outcome.
D5: Bias in selection of the reported result.

Judgement
X High
- Some concerns
+ Low

Fig. 2 RoB2 tool signal graph.

Chart 1 Characteristics of the selected studies

Author, year	Kind of study	Country	Study number (Place)	ST	Method	Result
Asano et al, 2017[9]	Accuracy/Transversal	Japão	184 (cranial)	OP	AL	Overall accuracy (average) 72.1%
Auloge et al, 2020[10]	Ensaio randomizado	França	10 (cranial)	AR	Fiducial	Mean precision of the sagittal entry point 1.65 ± 0.23 mm and coronal 1.88 ± 0.28 mm
Bilhar et al, 2018[11]	Accuracy/Transversal	Brasil	40 (thoracic)	AR	___	Failure 2.5% (pedicle violation)
Carl et al, 2019[12]	Accuracy/Transversal	Alemanha	47 (cranial) e 10 (cervical/thoracic)	AR	Fiducial	TRE skull 2.33 ± 1.30 mm PL 0.83 ± 0.44 mm TRE spine 0.72 ± 0.24 mm
Caversaccio et al, 2007[13]	Accuracy/Transversal	Rússia	406 (cranial)	AR	___	Precision range 1.00 - 1.80 mm ($N = 5$)
Carvi et al, 2007[14]	Accuracy/Transversal	Alemanha	36 (cranial)	OP	AL	Technical precision 0.50 mm Clinical Precision 1.20 mm
Castilla et al, 2003[15]	Accuracy/Transversal	Espanha	69 (64 cranial and 5 spinal)	OP	___	TRE 1.60 mm (0.50 - 3.80 mm)
Condino et al, 2021[16]	Accuracy/Transversal	Italia	60 (cranial)	AR	Fiducial	Accuracy level 97% at 1.50mm and 92% at 1.00mm
Deng et al, 2014[17]	Accuracy/Transversal	China	3 (cranial)	AR	AL	Alignment error 1.60 mm - 2.10 mm
Dixon et al, 2013[18]	Ensaio randomizado	Canadá	15 (cranial)	AR	Fiducial	Median distance from target point 2.10 mm, 1.29–2.37 mm
Eboli et al, 2011[19]	Accuracy/Transversal	EUA	208 (cranial)	EM	Fiducial	PL 1.00 - 2.00 mm
Elmi et al, 2018[20]	Accuracy/Transversal		253 (thoracic/lumbar)	AR	___	Overall accuracy 94.1%
Elmi et al, 2019[21]	Accuracy/Transversal	EUA	84 (thoracic/lumbar)	AR	Optical marker on the skin	Accuracy 2.20 ± 1.30 mm (89%)
Enchev et al, 2011[22]	Accuracy/Transversal	Bulgaria	7 (cranial)	OP	Laser	Precision range 1.00–1.70 mm Average 1.30 mm
Fan et al, 2020[23]	Accuracy/Transversal	China	370 (lumbar)	AR	___	PL 97.80%
Finger et al, 2017[24]	Accuracy/Transversal	Alemanha	43 (cranial)	AR	AL	Deviation from the midpoint of the target 1.20 ± 0.40 mm
Grayeli et al, 2009[25]	Accuracy/Transversal	França	1 → $n = 8$ 2 → $n = 25$ (cranial)	EM	AL[1] Invasive[2]	Position accuracy 4.90 ± 0.64 mm[1] 0.00 - 2.30 mm[2]
Gerard et al, 2018[26]	Accuracy/Transversal	Itália	8 (cranial)	AR	___	TRE 0.54–6.36 mm
Guedes et al, 2015[27]	Accuracy/Transversal	Brasil	40 (thoracic/lumbar)	AR	___	PP 77.50%
Hejazi et al, 2005[28]	Accuracy/Transversal	Austria	11 (cranial)	OP	Fiducial	

(*Continued*)

Chart 1 (*Continued*)

Author, year	Kind of study	Country	Study number (Place)	ST	Method	Result
						PL 1.80 - 2.20 mm Average 1.90 mm
Hermann et al, 2015[29]	Accuracy/Transversal	Alemanha	284 (cranial)	EM	Fiducial	Deviation from the surface of the target lesion 2.50 - 5.80 mm (mean 3.90 ± 1.10 mm)
Hermann et al, 2015[30]	Accuracy/Transversal	Alemanha	17 (cranial)	EM	AL	PL 2.00 e 9.00 mm
Inoue et al, 2013[31]	Accuracy/Transversal	Japão	3 (cranial)	AR	Fiducial	FRE 1.79, 1.67 e 1.65 mm
Jung et al, 2006[32]	Accuracy/Transversal	Coreia	420 (cranial)	OP	Fiducial	PL 1.15 mm
Mascitelli et al, 2018[33]	Accuracy/Transversal	EUA	84 (cranial)	AR	___	Accuracy excellent 71.4%; good 20.2%; bad 8.30%
Mascott et al, 2006[34]	Accuracy/Transversal	França	30 (cranial)	OP	Fiducial e AL	Accuracy 4.80 ± 2.00 mm
Maruyama et al, 2018[35]	Accuracy/Transversal	Japão	75 (cranial)	AR	Fiducial	TRE 0.20 to 8.10 mm (mean 3.10 ± 1.90 mm, median 2.70 mm)
McLaughlin et al, 2012[36]	Accuracy/Transversal	EUA	12 (cranial)	OP	Registration mask	TRE 0.90 ± 0.70 mm
Mert et al, 2013[37]	Accuracy/Transversal	Canada	136 (cranial)	OP	SF	TRE 0.70 (0.30 - 1.20 mm)
Muacevic et al, 2000[38]	Accuracy/Transversal	Alemanha	40 (cranial)	OP	Sticky markers	VME 1.45 ± 0.99 and 4.05 ± 3.62 mm
Nimsky et al, 2005[39]	Accuracy/Transversal	Alemanha	16 (cranial)	OP	Fiducial	TRE 1.20 ± 0.460 mm
Novák et al, 2021[40]	Accuracy/Transversal	República Checa	6 (cranial)	OP	Automatic registration	TRE 0.00 - 2.65 mm
Paraskevopoulos et al, 2011[41]	Accuracy/Transversal	Alemanha	10 (cranial)	OP	Fiducial[1] SF[2]	DM 1.45 ± 0.63 mm[1] 1.27 ± 0.53 mm[2]
Pinggera et al, 2018[42]	Accuracy/Transversal	Alemanha	1600 (cranial)	OP	Laser	TRE MD 1.97 mm (1.90 - 2.03 mm)
Pojskic et al, 2022[43]	Accuracy/Transversal	Alemanha	39 (cranial)	AR	Fiducial	TRE 0.82 ± 0.37 mm
Pojskic et al, 2021[44]	Accuracy/Transversal	Alemanha	16 (thoracic/lumbar)	AR	Automatic registration	TRE 0.84 ± 0.10 mm
Raabe et al, 2022[45]	Accuracy/Transversal	Alemanha	34 (cranial)	OP	AL	PL 2.40 ± 1.70 mm
Reinges et al, 2004[46]	Accuracy/Transversal	Alemanha	61 (cranial)	OP	Fiducial	TRE 0.80 - 14.30 mm (average 6.10; SD 3.40)
Roethe et al, 2022[47]	Ensaio randomizado	Alemanha	16 (OP) e 39 (AR) (cranial)	OP AR	___	Median accuracy of depth information OP 5.00 mm and RA 3.00 mm
Salma et al, 2012[48]	Accuracy/Transversal	EUA	20 (cranial)	OP	Bone fiducials,[1] scalp[2] and registration mask[3]	TRE 1.95 mm,[1] 3.24 mm[2]; 3.19 mm[3]

Chart 1 (*Continued*)

Author, year	Kind of study	Country	Study number (Place)	ST	Method	Result
Scheufler et al, 2011[49]	Accuracy/Transversal	Austria	248 (cervical/thoracic)	AR	___	71.4% of cases with excellent/good results
Serej et al, 2015[50]	Accuracy/Transversal	Irã	10 (cranial)	OP	Anatomical landmarks,[1] SF[2] e projected[3]	FRE 1.22 ± 0.43 mm,[1] 0.99 ± 0.31 mm[2], 043 ± 08 mm[3]
Shamir et al, 2011[51]	Accuracy/Transversal	Israel	15 (cranial)	OP	Fiducial AL	TRE 5.90 ± 4.30 mm Navigation record error 1.40 ± 0.40 mm
Suess et al, 2001[52]	Accuracy/Transversal	Alemanha	24 (cranial)	EM	Fiducial	In register 1.30 - 1.50 mm and EM target 3.20 mm
Suess et al, 2007[53]	Accuracy/Transversal	Alemanha	13 (cranial)	OP EM	Fiducial	Precision range 0.83 - 1.85 mm FRE 1.53 ± 0.51 mm
Tabrizi et al, 2015[54]	Accuracy/Transversal	Alemanha	15 (cranial)	AR	Fiducial	Em of projection 0.80 ± 0.25 mm, 1.20 ± 0.54 mm
Van Doormaal et al, 2019[55]	Accuracy/Transversal	Holanda	13 (cranial)	AR	Fiducial	FRE 7.20 ± 1.80 mm FRE 4.40 ± 2.50 mm
Yavas et al, 2021[56]	Accuracy/Transversal	Turquia	8 (cranial)	AR	3D marker	Directing error 0.50 - 3.50 mm; In1.56 mm (SD 0.79 mm and median of 1.56 mm)
Yoshino et al, 2015[57]	Accuracy/Transversal	Japão	9 (cranial)	OP	___	TRE 2.90 ± 1.90 mm
Zhao et al, 2006[58]	Accuracy/Transversal	China	63 (cranial)	OP	MA	Accuracy 2.30 ± 1.10 mm
Zhuang et al, 2011[59]	Accuracy/Transversal	China	11 (cranial)	OP	Fiducial	Prediction error 1.29 - 1.91 mm (1.62 ± 0.22 mm)

Abbreviations: AL, Anatomical Landmarks; AR, Augmented Reality; EM, Electromagnetic; FRE, Mean record error; In, Average Error; MD, Mean Deviation; OP, Optical; PL, Location accuracy; PP, Positioning Accuracy; SD, Standard Deviation; SF, Surface Fusion; ST, System; TRE, Destination accuracy error; VME, mean error value.

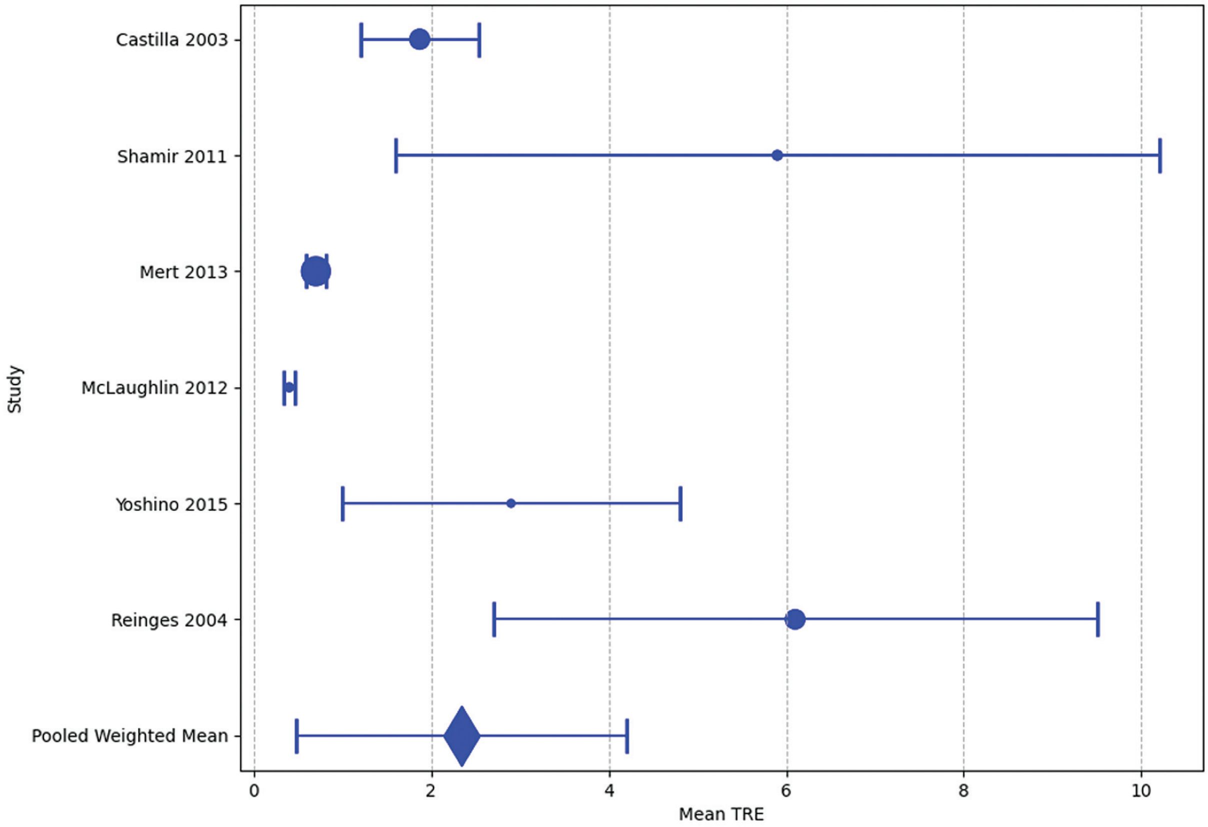


Fig. 3 ERT assessment in studies that used an optical system after the sensitivity of the heterogeneity index.

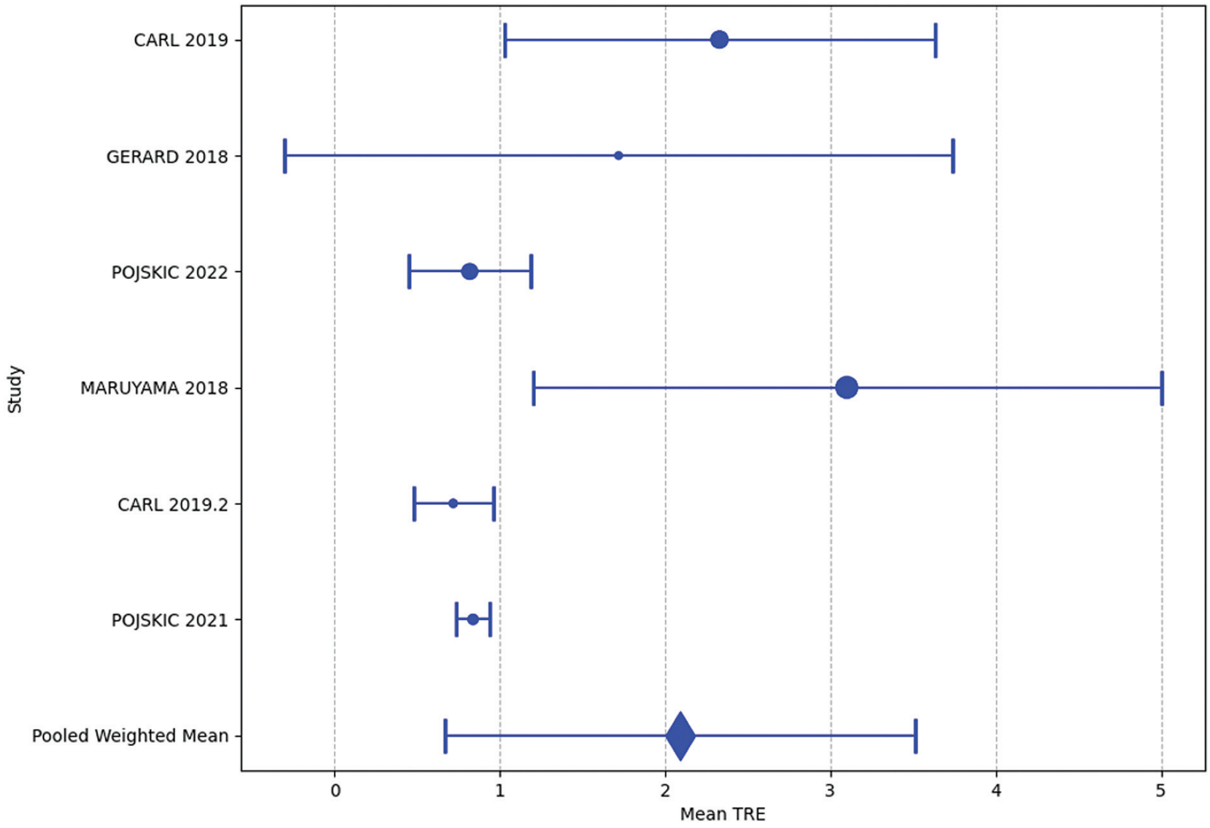


Fig. 4 ERT assessment in studies that used the augmented reality system after the sensitivity of the heterogeneity index.

exhibited higher values, indicating a smaller error than the studies included in the meta-analysis.

Discussion

Neuronavigation is utilized in various cranial and spinal procedures to provide enhanced visualization of spatial relationships between different structures. This is achieved by superimposing data from diverse preoperative imaging methods, allowing for intraoperative correction of displacement known as "Brain-Shift." The acquired information is processed by a computer system that guides the surgeon throughout the procedure.

The application of neuronavigation involves four steps. First, volumetric images are obtained in a modality determined by the surgeon. These images are then imported into the system, initiating the surgical planning. The third step involves patient registration, typically performed on the face using two methods: point cloud or point-to-point mapping with a probe and a fixed reference on the patient's head. The precise acquisition of these registration points and their correlation with pre-defined points in the system enables intraoperative navigation.[60]

Application Errors (AE) arise from failures at any stage of the neuronavigation process and directly impact the accuracy and final clinical outcome. The accuracy of these systems depends on variables inherent to their types, including application and mechanical execution errors during surgery. These errors can be categorized into two subgroups: those related to anatomical differences between the obtained image and the patient, and those associated with failure to transfer the point of interest between the image and the patient. Examples include mean registration error (FRE), target registration error (TRE), and surface registration error (SRE).[60,61]

Errors in the registration phase, which involves transforming the patient's space into image space using fiducials (paired points, skin or bone markers, or surface), are crucial predictors of overall accuracy. Recording errors, combined with errors during mechanical execution in surgery, significantly affect accuracy. Subsequently, errors occurring after the registration phase, such as the root mean squared error of registration (RMSE) and TRE, serve as primary predictors of neuronavigation accuracy.[62] RMSE measures the distance between a fiducial point obtained with the tracker in real space and its corresponding point in the image, while TRE measures the distance between a point in real space and its corresponding point in the image space, representing the clinically more relevant error. The estimated vector of the TRE allows surgeons to correct the path based on visualization.

Accuracy depends on variables specific to the system types, comprising a combination of application errors (AE) and mechanical execution during surgery. Previous studies have defined an upper limit error value of 3.00 to 4.00 mm.[63] However, in the clinical setting, navigation systems typically operate within an accuracy range of 0.50 to 2.70 mm, aiming for a TRE value of 1.00 to 2.00 mm to ensure greater safety.[64]

Multiple factors influence the accuracy of the procedure, including the specific procedure itself, the utilized system, and the mechanical execution. Analysis of the studies revealed that the various techniques for patient registration did not significantly impact accuracy and yielded similar distances when correlated with the surgical point of interest.

Registration based on anatomical landmarks offers advantages such as low cost and improved efficiency in terms of performance time.[65] However, fiducial registration is considered the preferred method among non-invasive approaches, as it demonstrates greater accuracy compared with the combination of anatomical points and surface registration.[41]

Among the different methods, anatomical landmarks exhibit the most discrepant results, whereas the others show comparable levels of precision, leading to satisfactory clinical outcomes. In a comparative study ($N = 30$), a substantial difference in accuracy was observed, with fiducials achieving a precision of 1.70 ± 0.70 mm, while anatomical landmarks yielded 4.80 ± 1.90 mm, placing them outside the security range.[34]

For skull base procedures, the automatic registration mask provided by the system demonstrated favorable results with a target registration error (TRE) of 0.90 ± 0.70 mm. This method proves to be a practical, reliable, and non-invasive alternative for this specific type of surgery.[36]

The use of fiducials was observed in 22 out of 51 evaluated studies, across various procedure types and in conjunction with the three types of systems examined in the research. Although a few results fell outside the acceptable range, most exhibited safe values, justifying the position of fiducial registration as the gold standard among non-invasive methods. Furthermore, the accuracy of fiducial application remains unaffected even when adjusting the patient's head position as necessary.

Regarding the accuracy of different system types, the meta-analysis included 6 values for each system, optical ($N = 297$) and augmented reality (AR) ($N = 195$), resulting in target registration errors (TRE) of 2.34 mm and 2.09 mm, respectively. Both systems exhibit close values and fall within the safety range expected for commercial systems. As for the electromagnetic system, due to a lack of studies establishing the TRE value, an average value could not be determined.

Studies comparing precision values between optical and augmented reality systems did not reveal significant differences in accuracy. However, in a clinical study directly comparing these systems, the augmented reality system demonstrated greater application security by exhibiting better depth accuracy with a median of 3.00 mm, compared with 5.00 mm in the conventional system.[47]

Moreover, the visual coordination between the surgical field and the monitor can be distracting for the surgeon when using the conventional system.[66,67] Therefore, viable and advantageous augmented reality neuronavigation (ARN) techniques have gained traction, as they provide fewer distractions compared with conventional image navigation (CIN) and do not restrict surgical positions.[66] This makes it possible to use ARN in patients who cannot be stabilized with a head clamp, such as pediatric patients and those with bone fractures.[56]

Regarding the optical and electromagnetic systems, although few clinical studies evaluating the accuracy of the latter were found, studies indicate that although the electromagnetic system enables continuous navigation through tracked instruments and better integration during the intraoperative period, the TRE values were similar to those obtained with the optical system.[37]

While these systems are more commonly used in cranial surgeries, they also offer good accuracy for spinal procedures. In most studies, the augmented reality (ARN) system was employed and consistently demonstrated accurate positioning in pedicle screw insertion, ranging from 77.5% to 97.8%.

However, like conventional methods, current systems are still unable to precisely detect anatomical changes during the surgical period.[56] Despite achieving good clinical results in most analyzed procedures, there is still room for improvement to further minimize application errors within an even narrower safety range, as proposed in more recent studies.

In this context, methods such as intraoperative ultrasonography and augmented reality techniques emerge as valuable tools, allowing for the updating of images during surgery and aiming to further reduce application errors. Influence of different imaging methods.

Various imaging methods serve as additional techniques for different systems. For preoperative image acquisition, computed tomography (CT) and magnetic resonance imaging (MRI) are commonly used and exhibit comparable accuracy and reliability of information.

A more recent method that has gained popularity is the O-Arm Cone Beam Tomography, particularly when combined with the optical system, demonstrating improved accuracy with an average error of 0 mm in two clinical studies.[40] One of the main advantages of this method is the ability to acquire intraoperative images without the need to correlate them with the patient's anatomy. Furthermore, it offers the flexibility to acquire new images if necessary, such as when the patient moves.[40]

Hence, in addition to selecting the optimal system, surgeons need to have access to other techniques that contribute to precision by compensating for brain shifts. Therefore, it is crucial to have imaging tools available that allow the system to be recalibrated using post-craniectomy images, including auxiliary techniques for three-dimensional reconstruction.[68,69]

Neuronavigation is employed in neurosurgery with well-defined objectives, aiming to make procedures less invasive, increase mechanical precision in target localization, and reduce surgical time. The technique provides enhanced safety for both surgeons and patients, making its indications nearly limitless. It proves particularly useful in approaching small, deep brain lesions and operating in eloquent areas, earning its place in brain tumor resection surgeries.[68]

Apart from tumor surgeries, two other well-established indications for neuronavigation are epilepsy and spine surgery. In epilepsy surgery, the technique assists in precisely locating epileptogenic zones for subsequent ablation. While its application in vascular surgery is somewhat limited due to insufficient studies and increased intraoperative time, the few available reviews acknowledge positive aspects of neuronavigation, such as improved anatomical orientation for arteriovenous malformations (AVM) and aneurysms through three-dimensional reconstruction, reducing the risk of damage to adjacent structures.[67]

In the realm of spine surgeries, the use of neuronavigation has been extensively studied for the insertion of pedicle screws in recent years, especially in comparison to the widely used fluoroscopy guidance. In a study conducted on fresh cadavers to evaluate the accuracy of both methods, similar precision was observed, yet neuronavigation provided greater safety for the surgical team by eliminating radiation exposure.[11] Additionally, a retrospective study with the same objective revealed not only superior precision with neuronavigation but also improved clinical outcomes and fewer subsequent surgical interventions.[27]

Conclusion

Augmented reality systems combined with a target registration error of 2.09 mm within the safety range provide the best accurate results. Optical systems also exhibit similar accuracy with a target registration error of 2.34 mm. Various factors influence system accuracy throughout the surgical procedure, and strategies are employed to minimize errors. However, there is a need for standardized predictors to assess accuracy consistently across studies.

Funding
There is no funding source for this article.

Conflict of Interest
All authors declare no conflict of interest.

References

1 Figueras-Benitez G, Urbano L, Acero A, Huerta M, Castro M. Surgical Navigation Systems: *A Technological Overview*. 2014https://doi.org/10.13140/RG.2.1.2449.1043
2 Clarke M, Horton R. Bringing it all together: Lancet-Cochrane collaborate on systematic reviews. Lancet 2001;357(9270):1728
3 Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372(71):n71. Doi: 10.1136/bmj.n71
4 Microsoft Corporation. Microsoft Office Excel. Microsoft, 2018
5 Sterne JAC, Savović J, Page MJ, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ 2019;366:l4898. Doi: 10.1136/bmj.l4898
6 Wells GA, Shea B, O'Connell D, et al. The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. Ottawa Hospital,; 2021
7 Munn Z, Moola S, Lisy K, Riitano D, Tufanaru C. Methodological guidance for systematic reviews of observational epidemiological studies reporting prevalence and cumulative incidence data. Int J Evid-Based Healthc 2015;13(03):147–153. Doi: 10.1097/XEB.0000000000000054

8 Whiting PF, Rutjes AW, Westwood ME, et al; QUADAS-2 Group. QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. Ann Intern Med 2011;155(08):529–536. Doi: 10.7326/0003-4819-155-8-201110180-00009

9 Asano K, Katayama K, Kakuta K, Oyama K, Ohkuma H. Assessment of the Accuracy and Errors of Head-Up Display by an Optical Neuronavigation System in Brain Tumor Surgery. Oper Neurosurg (Hagerstown) 2017;13(01):23–35. Doi: 10.1093/ons/opw001

10 Auloge P, Cazzato RL, Ramamurthy N, et al. Augmented reality and artificial intelligence-based navigation during percutaneous vertebroplasty: a pilot randomised clinical trial. Eur Spine J 2020;29 (07):1580–1589. Doi: 10.1007/s00586-019-06054-6

11 Bilhar RPO, de Lima DA, Leite JAD, Porto MA. Accuracy of pedicle screw insertion: A comparison between fluoroscopic guidance and navigation techniques. Acta Ortop Bras 2018;26(06): 397–400. Doi: 10.1590/1413-785220182606180635

12 Carl B, Bopp M, Saß B, et al. Reliable navigation registration in cranial and spine surgery based on intraoperative computed tomography. Neurosurg Focus 2019;47(06):E11. Doi: 10.3171/ 2019.8

13 Caversaccio M, Langlotz F, Nolte LP, Häusler R. Impact of a self-developed planning and self-constructed navigation system on skull base surgery: 10 years experience. Acta Otolaryngol 2007; 127(04):403–407. Doi: 10.1080/00016480601002104

14 Carvi Y Nievas MN, Höllerhage HG. Reliability of neuronavigation-assisted trans-sphenoidal tumor resections. Neurol Res 2007;29 (06):557–562. Doi: 10.1179/016164107 × 164184

15 Castilla JM, Martín V, Fernández-Arconada O, Delgado P, Rodríguez-Salazar A. [First steps in neuronavigation]. Neurocirugia (Astur) 2003;14(05):398–408. Doi: 10.1016/s1130-1473(03) 70519-3

16 Condino S, Montemurro N, Cattari N, et al. Evaluation of a Wearable AR Platform for Guiding Complex Craniotomies in Neurosurgery. Ann Biomed Eng 2021;49(09):2590–2605. Doi: 10.1007/s10439-021-02834-8

17 Deng W, Li F, Wang M, Song Z. Easy-to-use augmented reality neuronavigation using a wireless tablet PC. Stereotact Funct Neurosurg 2014;92(01):17–24. Doi: 10.1159/000354816

18 Dixon BJ, Daly MJ, Chan H, Vescan AD, Witterick IJ, Irish JC. Surgeons blinded by enhanced navigation: the effect of augmented reality on attention. Surg Endosc 2013;27(02):454–461. Doi: 10.1007/s00464-012-2457-3

19 Eboli P, Shafa B, Mayberg M. Intraoperative computed tomography registration and electromagnetic neuronavigation for transsphenoidal pituitary surgery: accuracy and time effectiveness. J Neurosurg 2011;114(02):329–335. Doi: 10.3171/2010.5. JNS091821

20 Elmi-Terander A, Nachabe R, Skulason H, et al. Feasibility and Accuracy of Thoracolumbar Minimally Invasive Pedicle Screw Placement With Augmented Reality Navigation Technology. Spine 2018;43(14):1018–1023. Doi: 10.1097/BRS.0000000000002502

21 Elmi-Terander A, Burström G, Nachabe R, et al. Pedicle Screw Placement Using Augmented Reality Surgical Navigation With Intraoperative 3D Imaging: A First In-Human Prospective Cohort Study. Spine 2019;44(07):517–525. Doi: 10.1097/ BRS.0000000000002876

22 Enchev Y, Tzekov C, Ferdinandov D, Cekov A, Spiriev T. Neuronavigation in cranioorbital neurosurgery - do we really need it? Turk Neurosurg 2011;21(02):119–126

23 Fan Y, Yao X, Xu X. A robust automated surface-matching registration method for neuronavigation. Med Phys 2020;47(07): 2755–2767. Doi: 10.1002/mp.14145

24 Finger T, Schaumann A, Schulz M, Thomale UW. Augmented reality in intraventricular neuroendoscopy. Acta Neurochir (Wien) 2017;159(06):1033–1041. Doi: 10.1007/s00701-017-3152-x

25 Grayeli AB, Esquia-Medina G, Nguyen Y, et al. Use of anatomic or invasive markers in association with skin surface registration in image-guided surgery of the temporal bone. Acta Otolaryngol 2009;129(04):405–410. Doi: 10.1080/00016480802579025

26 Gerard IJ, Kersten-Oertel M, Drouin S, et al. Combining intraoperative ultrasound brain shift correction and augmented reality visualizations: a pilot study of eight cases. J Med Imaging (Bellingham) 2018;5(02):021210. Doi: 10.1117/1. JMI.5.2.021210

27 Guedes VP, Manffra EF, Aguiar LR. Image-guided surgery in the spine: Neuronavigation vs. fluoroscopy. Coluna/Columna 2015;14 (03):181–185

28 Hejazi N. Frameless image-guided neuronavigation in orbital surgery: practical applications. Neurosurg Rev 2006;29(02): 118–122. Doi: 10.1007/s10143-005-0007-3

29 Hermann EJ, Petrakakis I, Polemikos M, et al. Electromagnetic navigation-guided surgery in the semi-sitting position for posterior fossa tumours: a safety and feasibility study. Acta Neurochir (Wien) 2015;157(07):1229–1237. Doi: 10.1007/s00701-015-2452-2

30 Hermann EJ, Esmaeilzadeh M, Ertl P, Polemikos M, Raab P, Krauss JK. Endoscopic intracranial surgery enhanced by electromagnetic-guided neuronavigation in children. Childs Nerv Syst 2015;31 (08):1327–1333. Doi: 10.1007/s00381-015-2734-2

31 Inoue D, Cho B, Mori M, et al. Preliminary study on the clinical application of augmented reality neuronavigation. J Neurol Surg A Cent Eur Neurosurg 2013;74(02):71–76. Doi: 10.1055/s-0032-1333415

32 Jung TY, Jung S, Kim IY, et al. Application of neuronavigation system to brain tumor surgery with clinical experience of 420 cases. Minim Invasive Neurosurg 2006;49(04):210–215. Doi: 10.1055/s-2006-948305

33 Mascitelli JR, Schlachter L, Chartrain AG, et al. Navigation-Linked Heads-Up Display in Intracranial Surgery: Early Experience. Oper Neurosurg (Hagerstown) 2018;15(02):184–193. Doi: 10.1093/ons/opx205

34 Mascott CR, Sol JC, Bousquet P, Lagarrigue J, Lazorthes Y, Lauwers-Cances V. Quantification of true in vivo (application) accuracy in cranial image-guided surgery: influence of mode of patient registration. Neurosurgery 2006;59(1, Suppl 1)ONS146–ONS156, discussion ONS146–ONS156 . Doi: 10.1227/01.NEU.0000220089.39533.4E

35 Maruyama K, Watanabe E, Kin T, et al. Smart Glasses for Neurosurgical Navigation by Augmented Reality. Oper Neurosurg (Hagerstown) 2018;15(05):551–556. Doi: 10.1093/ons/opx279

36 McLaughlin N, Carrau RL, Kassam AB, Kelly DF. Neuronavigation in endonasal pituitary and skull base surgery using an autoregistration mask without head fixation: an assessment of accuracy and practicality. J Neurol Surg A Cent Eur Neurosurg 2012;73(06): 351–357. Doi: 10.1055/s-0032-1326943

37 Mert A, Gan LS, Knosp E, Sutherland GR, Wolfsberger S. Advanced cranial navigation. Neurosurgery 2013;72(Suppl 1):43–53. Doi: 10.1227/NEU.0b013e3182750c03

38 Muacevic A, Uhl E, Steiger HJ, Reulen HJ. Accuracy and clinical applicability of a passive marker based frameless neuronavigation system. J Clin Neurosci 2000;7(05):414–418. Doi: 10.1054/ jocn.1999.0226

39 Nimsky C, Grummich P, Sorensen AG, Fahlbusch R, Ganslandt O. Visualization of the pyramidal tract in glioma surgery by integrating diffusion tensor imaging in functional neuronavigation. Zentralbl Neurochir 2005;66(03):133–141. Doi: 10.1055/s-2005-836606

40 Novák V, Hrabálek L, Valošek J, et al. The use of an O-arm in endonasal endoscopic operations of the skull base. BMC Surg 2021;21(01):58. Doi: 10.1186/s12893-021-01066-w

41 Paraskevopoulos D, Unterberg A, Metzner R, Dreyhaupt J, Eggers G, Wirtz CR. Comparative study of application accuracy of two frameless neuronavigation systems: experimental error assessment quantifying registration methods and clinically influencing factors. Neurosurg Rev 2010;34(02):217–228. Doi: 10.1007/ s10143-010-0302-5

42 Pinggera D, Kerschbaumer J, Bauer M, et al. Accuracy Validation of Neuronavigation Comparing Headholder-Based System with Head-Mounted Array-A Cadaveric Study. World Neurosurg 2018;120:e313–e317. Doi: 10.1016/j.wneu.2018.08.059

43 Pojskić M, Bopp MHA, Saβ B, Carl B, Nimsky C. Microscope-Based Augmented Reality with Intraoperative Computed Tomography-Based Navigation for Resection of Skull Base Meningiomas in Consecutive Series of 39 Patients. Cancers (Basel) 2022;14(09): 2302. Doi: 10.3390/cancers14092302

44 Pojskić M, Bopp M, Saß B, Kirschbaum A, Nimsky C, Carl B. Intraoperative Computed Tomography-Based Navigation with Augmented Reality for Lateral Approaches to the Spine. Brain Sci 2021;11(05):646. Doi: 10.3390/brainsci11050646

45 Raabe A, Krishnan R, Wolff R, Hermann E, Zimmermann M, Seifert V. Laser surface scanning for patient registration in intracranial image-guided surgery. Neurosurgery 2002;50(04):797–801, discussion 802–803 . Doi: 10.1097/00006123-200204000-00021

46 Reinges MH, Nguyen HH, Krings T, Hütter BO, Rohde V, Gilsbach JM. Course of brain shift during microsurgical resection of supratentorial cerebral lesions: limits of conventional neuronavigation. Acta Neurochir (Wien) 2004;146(04):369–377, discussion 377 . Doi: 10.1007/s00701-003-0204-1

47 Roethe AL, Rösler J, Misch M, Vajkoczy P, Picht T. Augmented reality visualization in brain lesions: a prospective randomized controlled evaluation of its potential and current limitations in navigated microneurosurgery. Acta Neurochir (Wien) 2022;164 (01):3–14. Doi: 10.1007/s00701-021-05045-1

48 Salma A, Makiese O, Sammet S, Ammirati M. Effect of registration mode on neuronavigation precision: an exploration of the role of random error. Comput Aided Surg 2012;17(04):172–178. Doi: 10.3109/10929088.2012.691992

49 Scheufler KM, Franke J, Eckardt A, Dohmen H. Accuracy of image-guided pedicle screw placement using intraoperative computed tomography-based navigation with automated referencing, part I: cervicothoracic spine. Neurosurgery 2011;69(04):782–795, discussion 795. Doi: 10.1227/NEU.0b013e318222ae16

50 Serej ND, Ahmadian A, Mohagheghi S, Sadrehosseini SM. A projected landmark method for reduction of registration error in image-guided surgery systems. Int J Comput Assist Radiol Surg 2015;10(05):541–554. Doi: 10.1007/s11548-014-1075-z

51 Shamir RR, Joskowicz L, Spektor S, Shoshan Y. Target and trajectory clinical application accuracy in neuronavigation. Neurosurgery 2011;68(01, Suppl Operative)95–101, discussion 101–102. Doi: 10.1227/NEU.0b013e31820828d9

52 Suess O, Kombos T, Kurth R, et al. Intracranial image-guided neurosurgery: experience with a new electromagnetic navigation system. Acta Neurochir (Wien) 2001;143(09):927–934. Doi: 10.1007/s007010170023

53 Suess O, Picht T, Kuehn B, Mularski S, Brock M, Kombos T. Neuronavigation without rigid pin fixation of the head in left frontotemporal tumor surgery with intraoperative speech mapping. Neurosurgery 2007;60(4, Suppl 2)330–338, discussion 338. Doi: 10.1227/01.NEU.0000255378.80216.52

54 Besharati Tabrizi L, Mahvash M. Augmented reality-guided neurosurgery: accuracy and intraoperative application of an image projection technique. J Neurosurg 2015;123(01):206–211. Doi: 10.3171/2014.9.JNS141001

55 van Doormaal TPC, van Doormaal JAM, Mensink T. Clinical Accuracy of Holographic Navigation Using Point-Based Registration on Augmented-Reality Glasses. Oper Neurosurg (Hagerstown) 2019;17(06):588–593. Doi: 10.1093/ons/opz094

56 Yavas G, Caliskan KE, Cagli MS. Three-dimensional-printed marker-based augmented reality neuronavigation: a new neuronavigation technique. Neurosurg Focus 2021;51(02):E20. Doi: 10.3171/2021.5.FOCUS21206

57 Yoshino M, Saito T, Kin T, et al. A Microscopic Optically Tracking Navigation System That Uses High-resolution 3D Computer Graphics. Neurol Med Chir (Tokyo) 2015;55(08):674–‒679https://doi.org/10.2176/nmc.tn.2014-0278

58 Zhao Y, Yu S, Wang R, Zhao J. Clinical application of a neuronavigation system in transsphenoidal surgery of pituitary macroadenoma. Neurosurg Rev 2006;29(04):306–311, discussion 311–312 . Doi: 10.1007/s10143-006-0031-y

59 Zhuang DX, Liu YX, Wu JS, et al. A sparse intraoperative data-driven biomechanical model to compensate for brain shift during neuronavigation. AJNR Am J Neuroradiol 2011;32(02):395–402. Doi: 10.3174/ajnr.A2288

60 Wang M, Song Z. How does adding anatomical landmarks as fiducial points in the point-matching registration of neuronavigation influence registration accuracy? Comput Assist Surg (Abingdon) 2016;21(01):39–45. Doi: 10.1080/24699322.2016.1180429

61 Wang MN, Song ZJ. Classification and analysis of the errors in neuronavigation. Neurosurgery 2011;68(04):1131–1143, discussion 1143. Doi: 10.1227/NEU.0b013e318209cc45

62 FITZPATRICK. J. M.; WEST, J. B. The distribution of target registration error in rigid-body point-based registration. IEEE transactions on medical imaging, [s. l.], v. 20, n. 9, p. 917–927, 2001. Disponível em: https://pubmed.ncbi.nlm.nih.gov/11585208/. Acesso at: 4 Jun. 2022

63 Grauvogel TD, Engelskirchen P, Semper-Hogg W, Grauvogel J, Laszig R. Navigation accuracy after automatic- and hybrid-surface registration in sinus and skull base surgery. PLoS One 2017;12 (07):e0180975. Doi: 10.1371/journal.pone.0180975

64 Kuehn B, Mularski S, Schoenherr S, et al. Sensor-based neuronavigation: evaluation of a large continuous patient population. Clin Neurol Neurosurg 2008;110(10):1012–1019. Doi: 10.1016/j.clineuro.2008.06.017

65 Pfisterer WK, Papadopoulos S, Drumm DA, Smith K, Preul MC. Fiducial versus nonfiducial neuronavigation registration assessment and considerations of accuracy. Neurosurgery 2008;62(3, Suppl 1)201–207, discussion 207–208. Doi: 10.1227/01.neu.0000317394.14303.99

66 Meola A, Cutolo F, Carbone M, Cagnazzo F, Ferrari M, Ferrari V. Augmented reality in neurosurgery: a systematic review. Neurosurg Rev 2017;40(04):537–548. Doi: 10.1007/s10143-016-0732-9

67 Qi Z, Li Y, Xu X, et al. Holographic mixed-reality neuronavigation with a head-mounted device: technical feasibility and clinical application. Neurosurg Focus 2021;51(02):E22. Doi: 10.3171/2021.5.FOCUS21175

68 Pereira ELR, Rodrigues BE, Gomes DL, Lima LO, Viegas LCM. Neuronavegação em neurocirurgia / Neuronavigation in neurosurgery. Braz Neurosurg 2014;33(04):340–346

69 Drouin S, Kochanowska A, Kersten-Oertel M, et al. IBIS: an OR ready open-source platform for image-guided neurosurgery. Int J Comput Assist Radiol Surg 2017;12(03):363–378. Doi: 10.1007/s11548-016-1478-0