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RESEARCH ARTICLE

The development of three-dimensional printing in neurosurgical departments across Europe: A five-year perspective

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Abstract

Three-dimensional (3D) printing has evolved into a valuable adjunct in neurosurgery, enabling patient-specific surgical planning, simulation, education, and implant fabrication. Although its technical feasibility and clinical utility are well documented, institutional integration and further development across European neurosurgical departments remain insufficiently defined. Two cross-sectional online surveys were conducted among European neurosurgeons in 2020 and 2025. The initial survey was distributed via the European Association of Neurosurgical Societies (EANS), while the follow-up survey was disseminated through national neurosurgical societies and direct re-contact of prior participants. A total of 172 completed questionnaires from 44 countries were included. Descriptive and comparative statistical analyses were performed using chi-square or Fisher's exact tests with false discovery rate correction. Between 2020 and 2025, a significant maturation of 3D printing practices was observed. Routine or regular departmental use increased, whereas single-case-only applications declined significantly (20.0% vs. 0%; $p = 0.01$). Responsibility for printing shifted markedly toward in-house production: neurosurgeon-led printing increased from 0% to 20.68% ($p < 0.001$), while reliance on external providers decreased from 21.81% to 0% ($p < 0.01$). Implant fabrication emerged as a novel clinical application (0% vs. 27.58%; $p < 0.001$). Diversification of printing technologies and improved cost efficiency were reported; however, formal quality management procedures remained limited. Major barriers included restricted time resources, insufficient institutional support, and high costs. Over five years, 3D printing in European neurosurgery has transitioned from sporadic, externally dependent use toward structured, institutionally integrated workflows with expanding clinical applications. Standardized quality assurance, regulatory clarity, and high-quality prospective outcome studies are essential to further establish 3D printing as a routine clinical technology.

Keywords: Neurosurgery; Three-dimensional printing; Surgical planning; Additive manufacturing; Medical education

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1. Introduction

Neurosurgical practice relies fundamentally on accurate spatial perception of complex three-dimensional (3D) anatomy. Although computed tomography and magnetic resonance imaging provide detailed anatomical insights, these modalities produce planar, two-dimensional images that may constrain understanding of intricate surgical anatomy and spatial relationships critical to operative planning.[1] To overcome these limitations, 3D imaging and printing have emerged as potential techniques enabling surgeons to better appreciate the 3D orientation of objects within the surgical site prior to surgery.

Three-dimensional printing, an additive manufacturing technique involving layer-by-layer material deposition, has become a transformative asset within neurosurgery.[2] Since its initial utilization in the late 1990s for creating patient-specific neurovascular models, 3D printing has broadened its scope across several domains.[1,3,4] Its contemporary applications encompass patient-specific anatomical models for surgical planning, education for residents and patients, fabrication of tailored surgical instruments and implants, and simulation of complex pathologies.[3,5-8] Substantial evidence has emerged supporting its clinical utility. Patient-specific 3D models consistently outperform conventional imaging methods in surgical planning, especially regarding craniotomy design and selection of surgical approaches, with notable benefits for less experienced surgeons.[5,8,9] Systematic reviews validate the anatomical accuracy of printed models and their effectiveness across neurovascular, skull base, and tumor surgery.[10-14] Within neurosurgical education, 3D printing provides significant advantages for resident training, yielding nearly universally positive subjective outcomes across vascular, spine, and skull base subspecialties.[3,15-17] Furthermore, patient-specific implants and guidance tools also represent an expanding clinical application of 3D printing, for which reliable feasibility has been demonstrated.[6,18-22] Despite robust evidence and growing recognition of its potential, 3D printing adoption among neurosurgical institutions remains variable.[1]

Regardless of these documented advantages, the widespread integration of 3D printing into routine neurosurgical practice faces substantial barriers that have limited its transition from research innovation to a standard clinical tool. Organizational challenges, including high initial investment costs, lack of institutional adoption strategies, and unclear reimbursement pathways, represent primary obstacles to implementation.[1,14,23-25] Regulatory uncertainty surrounding medical device classification, quality assurance protocols, and compliance with evolving standards creates additional complexity for hospital-based programs.[23-25] Workflow integration remains challenging, requiring coordination between radiology, engineering, and surgical teams, the establishment of quality management systems, and the development of standardized processes from image acquisition to final model production.[26-28] Furthermore, the absence of standardized protocols for 3D printing in neurosurgery, combined with variability in available technologies and materials, contributes to heterogeneous implementation across institutions.[1,25,29] While low-cost entry-level solutions have emerged to address resource limitations, questions regarding cost-effectiveness, optimal clinical indications, and long-term sustainability of in-house versus outsourced production models remain incompletely resolved.[14,25,30] These diverse barriers underscore the need for a systematic evaluation of how 3D printing is currently being implemented in clinical practice and what factors facilitate or impede its broader adoption.

The progression of 3D printing integration and prevailing professional consensus regarding optimal clinical implementation remain inadequately characterized. Understanding temporal trends, institutional workflow integration, and perceived hindrances is crucial to guide future strategies. This study seeks to systematically evaluate the implementation and clinical integration of 3D printing technologies within European neurosurgical departments using a repeated cross-sectional survey approach. The cross-sectional investigation facilitates analysis of trends in technology adoption, shifts in institutional responsibility and workflow integration, diversification of printing technologies, perceived clinical impact, and persistent barriers inhibiting broader utilization. By documenting the development of 3D printing practices over this pivotal period, the study offers insights into the maturation of this technology in neurosurgery and identifies essential determinants influencing its transition from innovative promise to standard clinical tool.

2. Materials and methods

2.1. Study design and data collection

The study used a repeated cross-sectional survey design. The initial survey was distributed to neurosurgeons across Europe via the official European Association of Neurosurgical Societies (EANS) mailing list in February 2020. For a temporal trend analysis, a revised version of this survey was distributed again in October 2025 through the mailing lists of the national neurosurgical societies in Europe. Participants from the first survey were also contacted again using the email addresses they provided. Incomplete or double submissions from both surveys were excluded from the study.

2.2. Survey design

The survey was created and administered using Google Forms. Single- and multiple-choice questions, as well as free-text responses, were included. Participation was exclusively online-based.

2.3. Statistical analysis

Descriptive analysis was used to display respondents' baseline characteristics. Differences in proportions were analyzed with chi-square or Fisher's exact test based on the sample size. False discovery rate was calculated using the Benjamini–Hochberg procedure. For statistical analysis and visualization, RStudio 2025.05.1+513 and GraphPad Prism 10 were used. A p-value of <0.05 was considered statistically significant.

3. Results

3.1. Demographic characteristics and institutional background

A total of 172 completed questionnaires were included in the analysis, comprising 114 responses from 44 countries in 2020 and 58 responses from 19 countries in the 2025 follow-up survey. Sixteen participants completed both the 2020 and the 2025 surveys. As participation was voluntary and distributed via professional society mailing lists, the exact response rate relative to the total target population could not be determined. Regarding demographics and professional background, the age distribution of respondents was comparable between both survey periods, with the majority of participants aged between 31 and 50 years. A slight shift toward older age groups was observed in 2025, with an increased proportion of respondents above 40 years of age (Figure 1A). Participants represented a broad international distribution (Figure 1B). Regarding professional position, consultants and specialists constituted the largest respondent groups in both surveys (Figure 1C). Most respondents were affiliated with university hospitals, followed by municipal and medical practices, with only minor changes between the two survey years (Figure 1D). Regarding neurosurgical specialties and departmental involvement, respondents covered a wide range of neurosurgical subspecialties. Neuro-oncological surgery, skull base surgery, and spine surgery were most frequently represented in both cohorts (Figure 1E).

3.2. Utilization of three-dimensional printing in neurosurgery

Departments reported diverse applications of 3D printing. While surgical planning and resident training remained common use cases, implant fabrication and research-related applications increased in 2025. Conversely, single-case-only applications decreased over time (Figure 1F). Overall, 3D printing practice in departments increased, with a higher proportion of departments reporting routine or regular use in 2025 compared to 2020 (Figure 1G). In terms of personnel, software, and printing techniques, responsibility for 3D printing shifted significantly over time. In 2020, printing was predominantly performed by external companies and technicians, whereas in 2025, a marked increase in neurosurgeon-led and in-house printing was observed (Figure 1H). For image segmentation, rendering, and post-processing, various software solutions were reported; however, the majority of respondents in both 2020 and 2025 were unaware of the specific software used (Figure 1I and 1J). Fused deposition modeling remained the most applied printing technique in both surveys, although the use of selective laser sintering, selective laser melting, and multi-jet modeling increased in 2025 (Figure 1K). However, consistent with findings on software usage, most respondents were also unaware of the specific 3D printing technology used. The implementation of formal quality assessment procedures remained limited (Figure 1L). Respondents consistently reported high perceived potential for 3D printing in neuro-oncological surgery, skull base surgery, spine surgery, and vascular neurosurgery in 2025 (Figure 1M). Potential applications were most frequently identified in surgical planning and resident training, followed by research purposes and patient education (Figure 1N).

3.3. Progression in responsibility and departmental use of three-dimensional printing

A comparative statistical analysis between the 2020 and 2025 survey cohorts revealed several statistically significant shifts in responsibility for 3D printing and its application within neurosurgical departments (Figure 2). After correction for multiple testing using the false discovery rate, six variables demonstrated significant differences between the two survey years. Most notably, responsibility for 3D printing shifted toward increased in-house involvement in 2025. The proportion of departments in which neurosurgeons directly performed 3D printing increased from 0% in 2020 to 20.68% in 2025 ($p < 0.001$), representing the largest positive change observed. Similarly, printing performed by engineers and research staff increased significantly over time (engineers: 1.18% vs. 18.96%; $p = 0.006$; research staff: 0% vs. 12.06%; $p = 0.009$). In contrast, reliance on external companies for 3D printing decreased markedly. While 21.81% of departments reported external providers as the primary printing resource in 2020, this proportion declined to 0% in 2025 ($p = 0.007$). A similar reduction

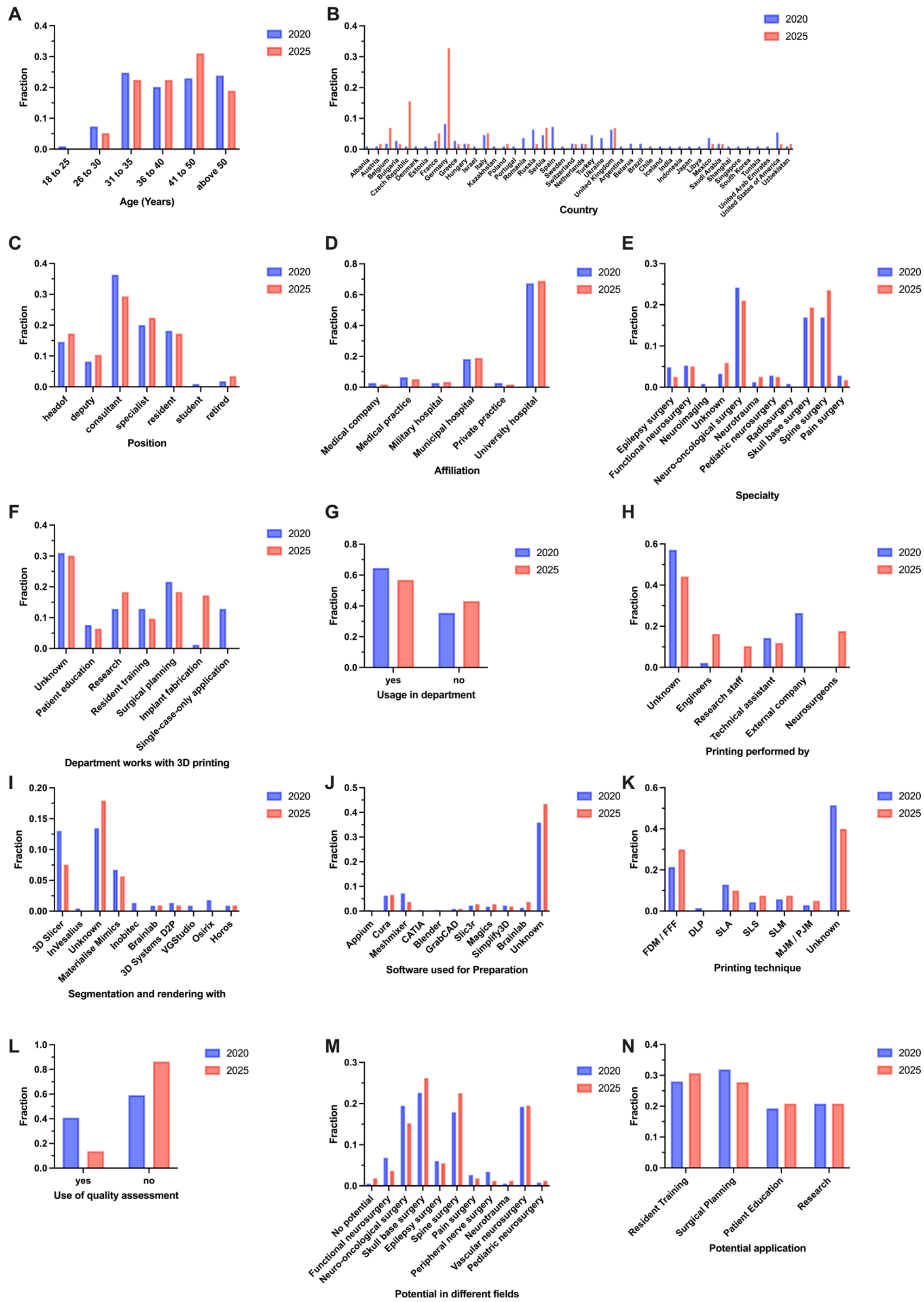

Figure 1. Demographic characteristics, institutional background, and current use of three-dimensional (3D) printing in neurosurgery. (A) Age distribution, (B) country of respondents, (C) professional position, (D) institutional affiliation, (E) neurosurgical specialty, (F) departmental application of 3D printing, (G) routine usage within the department, (H) personnel responsible for printing, (I) software used for segmentation and rendering, (J) software used for print preparation, (K) printing techniques, (L) use of quality assessment procedures, (M) perceived potential of 3D printing across neurosurgical subspecialties, and (N) potential clinical and educational applications. Blue and red bars indicate survey data from 2020 and 2025, respectively. Values are presented as relative frequencies (%).

Abbreviations: DLP: Digital light processing; FDM: Fused deposition modeling; MJM: Multi-jet modeling; SLA: Stereolithography; SLM: Selective laser melting; SLS: Selective laser sintering.

was observed for departments reporting single-case use only, which decreased from 20.0% in 2020 to 0% in 2025 ($p = 0.01$). Concurrently, the use of 3D printing for implant fabrication emerged as a significant new application. No departments reported implant fabrication in 2020, whereas 27.58% indicated this use in 2025 ($p < 0.001$).

3.4. Institutional implementation and impact of three-dimensional printing in 2025

The 2025 survey included additional questions addressing institutional development, utilization patterns, and the perceived impact of 3D printing in neurosurgery. The results are summarized in Figure 3. Regarding institutional implementation, 3D printing was already established in a subset of departments before 2020, while additional institutions reported implementation after 2020. Nevertheless, a considerable proportion of respondents still reported no formal institutional implementation of 3D printing at the time of the 2025 survey (Figure 3A). Despite this, more than half of respondents indicated improved access to 3D printing capacity since 2020 (Figure 3B). With respect to utilization, most departments reported occasional or regular use of 3D printing, whereas routine use remained limited (Figure 3C). A smaller proportion of respondents indicated that 3D printing was never used in their department. Technical developments since 2020 were frequently reported, most notably improvements in printing quality, while increases in material diversity and printing speed were reported less consistently (Figure 3D). The establishment of dedicated 3D printing centers after 2020 was reported by the majority of respondents, indicating a trend toward institutional consolidation of 3D printing workflows (Figure 3E). Collaboration models varied considerably, with centralized in-house laboratories being the most common approach. However, a considerable number of respondents reported either no cooperation or only small working groups (Figure 3F). A substantial proportion of participants reported evidence of clinical and educational impact based on respondents' own research, although the majority indicated that such evidence was

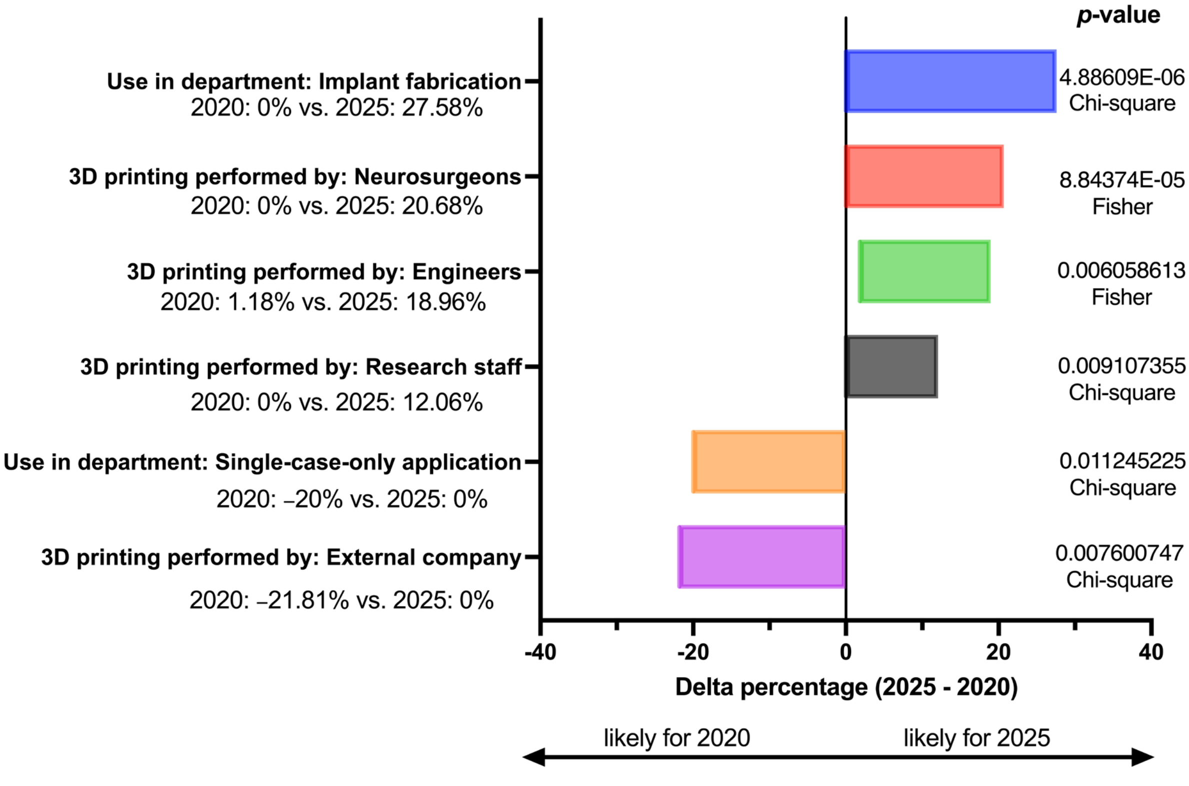

Figure 2. Differences in departmental use and responsibility. The x-axis shows the delta percentage (2025 minus 2020), with positive values indicating higher prevalence in 2025 and negative values indicating higher prevalence in 2020. Significant shifts include increased involvement of neurosurgeons, engineers, and research staff in performing three-dimensional (3D) printing, as well as changes in departmental usage patterns, including implant fabrication and single-case use only. The significance of external providers in the application of 3D printing within neurosurgical departments decreased significantly. Corresponding *p*-values derived from chi-square or Fisher's exact tests are reported.

not yet available (Figure 3G). Nevertheless, increased institutional application of 3D printing in neurosurgical education since 2020 was reported by more than half of respondents (Figure 3H). The perceived clinical value of 3D printing had improved over time, with most respondents rating the change as slightly or much more positive, while a smaller proportion reported no change (Figure 3I). Despite this positive perception, improvements in funding or institutional support since 2020 were reported less frequently (Figure 3J). In contrast, most respondents noted improved cost efficiency in 3D printing (Figure 3K). The main barriers to broader implementation of 3D printing were limited time resources, insufficient institutional support, and high costs, followed by a lack of expertise and regulatory issues (Figure 3L). Finally, approximately 38% of respondents reported ongoing research activities related to 3D printing (Figure 3M).

4. Discussion

In the present study, we conducted a survey to evaluate the maturation of the application of 3D imaging and printing among neurosurgical departments associated with the EANS. The present study is based on a repeated cross-sectional design and therefore reflects temporal trends rather than changes within institutions. Although respondents represented a broad international distribution, participation in 2025 was limited to fewer countries than in 2020, which may reflect variability in dissemination pathways and engagement rather than true differences in adoption. The predominance of older, more senior clinicians among respondents may be explained by the higher representation of fully qualified specialists within the EANS and national neurosurgical societies, which served as primary distribution channels for the survey. The high proportion of university hospital affiliations underscores the importance of institutional infrastructure and financial resources for implementing technology-intensive workflows, potentially contributing to disparities between academic and non-academic centers. Respondents represented a broad range of neurosurgical subspecialties and consistently reported a high perceived potential for 3D printing in vascular neurosurgery, skull base surgery, neuro-oncological surgery, and spine surgery. The literature supports the use of 3D-printed models for tumor resection planning, skull base approaches, and spinal instrumentation, with demonstrated benefits for surgical precision, operative time, and patient outcomes.[5,31-33] The most striking finding is the transition in responsibility for 3D printing operations. The proportion of departments in which neurosurgeons directly performed 3D printing increased from 0% in 2020 to 20.68% in 2025, while reliance on external companies decreased from 21.81% to 0%. This shift reflects a broader trend toward institutional ownership of 3D printing capabilities, consistent with the establishment of dedicated 3D printing centers reported by the majority of respondents in 2025. This evolution aligns with recommendations from the literature emphasizing the importance of standardized workflows for medical 3D printing.[24,27] The increased involvement of neurosurgeons, engineers, and research staff in 3D printing operations suggests successful interdisciplinary integration. This collaborative model is essential for optimizing the clinical utility of 3D-printed models, as it combines clinical expertise with technical proficiency in image segmentation, model design, and printing processes.[1,5,34] Overall, these findings suggest that the integration of 3D printing is not solely technology-driven but closely linked to institutional structures, interdisciplinary collaboration, and local resource availability. The diversification of printing techniques observed in 2025 further indicates technological maturation and institutional investment in advanced capabilities. The emergence of implant fabrication as a significant application (0% in 2020 vs. 27.58% in 2025) marks a critical shift from planning and educational uses to direct clinical intervention. This expansion reflects growing confidence in the accuracy, biocompatibility, and regulatory compliance of 3D-printed medical devices.[1,35] The concurrent decrease in single-use-only applications (20.0% to 0%) and increase in routine or regular departmental use demonstrates a transition from experimental applications to integrated clinical workflows. Interestingly, a substantial proportion of respondents reported limited knowledge of the specific software tools and printing technologies used in their departments. This observation indicates that the clinical application of 3D printing within institutions frequently depends on the initiative of individual users who manage the technical implementation, even when such technologies are available on-site. The sustained emphasis on surgical planning, resident training, and patient education across both survey periods confirms the established value of 3D printing in these domains. Multiple studies have demonstrated that patient-specific 3D-printed models significantly improve surgical planning, particularly for complex cases involving skull base pathology, vascular lesions, and brain tumors.[5,31] The benefit appears most pronounced for less experienced neurosurgeons, supporting the educational value reported by survey respondents.[1,3,5] More than half of respondents reported increased institutional application of 3D printing in neurosurgical education since 2020, consistent with systematic reviews demonstrating the effectiveness of 3D-printed models for resident training.[3,36] The literature supports the use of 3D-printed models across diverse neurosurgical

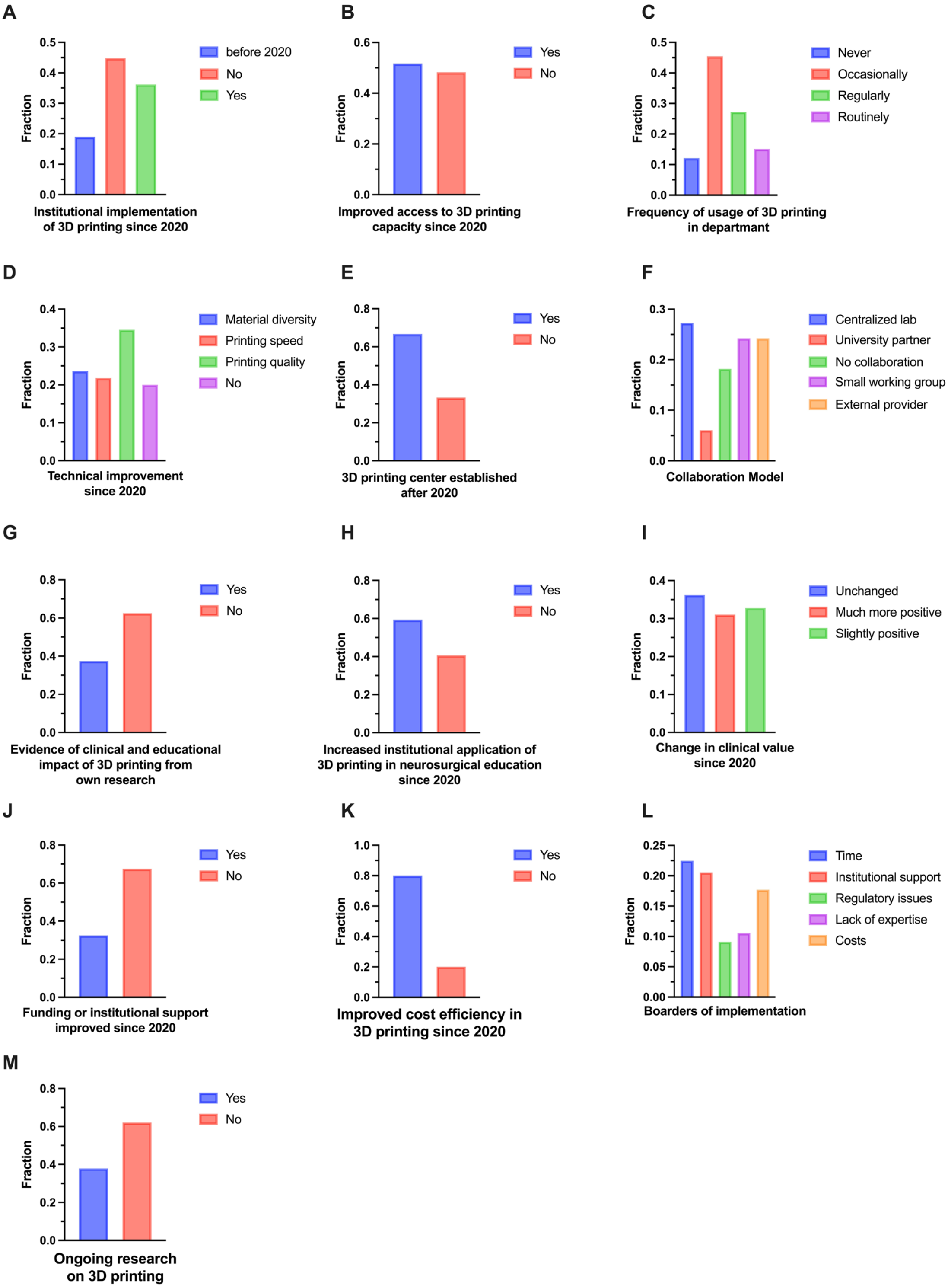

Figure 3. Institutional development, utilization patterns, and perceived impact of three-dimensional (3D) printing in neurosurgery. (A) Institutional implementation of 3D printing, (B) improved access to 3D printing capacity, (C) frequency of departmental use, (D) technical improvements, (E) establishment of a 3D printing center after 2020, (F) collaboration models, (G) evidence of clinical and educational impact based on respondents' own research, (H) increased institutional application of 3D printing in neurosurgical education, (I) change in perceived clinical value, (J) changes in funding or institutional support, (K) improved cost efficiency, (L) barriers to implementation, and (M) ongoing research activities related to 3D printing. Data are presented as relative frequencies (%).

subspecialties, including aneurysm clipping, spine surgery, craniosynostosis, transsphenoidal approaches, and tumor resection.[3,37] Subjective outcome measures from neurosurgical residents have been almost unanimously positive, and the technology provides realistic simulation opportunities in a field where direct operative exposure to complex cases is increasingly limited.[6,10] The integration of 3D printing with emerging technologies such as mixed reality further enhances training capabilities, allowing residents to practice the entire surgical workflow from planning through execution. This multimodal approach addresses the constraints imposed by reduced working hours and increased subspecialization in contemporary neurosurgical training.[6,38] Despite substantial progress, significant barriers to broader implementation remain. Limited time resources, insufficient institutional support, and high costs were identified as the primary obstacles, followed by regulatory issues and a lack of expertise. These findings are consistent with qualitative studies from other healthcare systems, which have identified organizational barriers, particularly high costs and lack of central decision-making, as the most prominent impediments to 3D printing adoption.[38] Notably, improvements in funding or institutional support since 2020 were reported less frequently than improvements in perceived clinical value, suggesting a disconnect between clinical enthusiasm and administrative commitment. This gap may reflect the challenges of demonstrating cost-effectiveness and return on investment for 3D printing programs, particularly in the absence of standardized reimbursement mechanisms. The learning curve associated with constructing 3D models poses additional difficulty, particularly for institutions without dedicated personnel.[39,40]

The limited implementation of formal quality assessment procedures represents a critical area for development. Quality management systems are essential for ensuring the accuracy, safety, and clinical utility of 3D-printed models, particularly as applications expand to include implantable devices.[24,27] The lack of standardized quality control protocols may contribute to regulatory uncertainty and hinder broader institutional adoption. The complex regulatory landscape for medical 3D printing remains a significant barrier. The United States Food and Drug Administration oversees 3D-printed medical devices through the Center for Devices and Radiological Health, publishing technical guidance including Technical Considerations for Additive Manufactured Devices that addresses data manipulation, hardware validation, and cleaning and sterilization protocols.[35,41] Regulatory requirements vary depending on intended use, extent of data modification, and whether the model enters the surgical field. The Radiological Society of North America emphasizes the need for infrastructure, staff training, digital workflow design, and ongoing quality assurance, including in-house quality control programs and supervision by medical imaging experts.[23,24]

Respondents reported notable technical improvements since 2020, particularly in printing quality. The diversification of printing techniques observed in 2025 reflects the availability of more sophisticated technologies capable of producing high-fidelity, multi-material models. Improved cost efficiency was reported by the majority of respondents, consistent with decreasing manufacturing costs documented in the literature.[10] The reported shift toward in-house production may also contribute to cost savings by eliminating external vendor fees and enabling more efficient workflows.

A substantial proportion of respondents reported evidence of clinical and educational impact based on their own research, although the majority indicated that such evidence was not yet available. This finding highlights the need for rigorous, prospective studies evaluating the impact of 3D printing on surgical outcomes, complication rates, operative time, and cost-effectiveness.[42] While existing studies have demonstrated the anatomic accuracy of 3D-printed models and positive subjective feedback from surgeons and trainees, high-quality evidence linking 3D printing to improved patient outcomes remains limited.[3,5,43] The heterogeneity of research activities across institutions suggests opportunities for collaborative, multi-center studies that could provide more robust evidence for the clinical value of 3D printing. Standardization of outcome measures, quality metrics, and reporting standards would facilitate comparison across studies and support evidence-based decision-making regarding 3D printing implementation.

Based on our findings, a successful implementation of 3D printing in neurosurgical departments appears to rely on several key factors, including structured workflow integration, interdisciplinary collaboration between clinicians and technical experts, and the establishment of basic quality assurance processes. A potential implementation pathway may involve initial collaboration with external providers, followed by gradual development of in-house capabilities and dedicated 3D printing units. Standardization of segmentation protocols, validation procedures, and clinical indications may further facilitate broader adoption. Such frameworks may also serve as a foundation for the future integration of more advanced biofabrication technologies. In this context, 3D bioprinting has emerged as a promising extension of conventional 3D printing, enabling the fabrication of complex biological constructs through the spatial organization of cells and biomaterials.[44] In neurosurgical applications, bioprinting has shown potential, particularly in spinal research, with recent proof-of-concept studies successfully replicating intervertebral disc anatomy.[45]

This study is limited by its survey-based design, reliance on self-reported data, and reduced sample size in 2025. However, it provides valuable insights into the temporal trends of 3D printing adoption in neurosurgery across Europe.

5. Conclusion

Our study demonstrates a substantial maturation of 3D printing practices in neurosurgery between 2020 and 2025, characterized by increased institutional integration, enhanced in-house expertise, and expanded clinical applications. The findings reveal a significant shift from sporadic, externally dependent use toward structured, institutionalized implementation of 3D printing workflows within neurosurgical departments.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

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Ethics approval and consent to participate

The study was conducted as an anonymous online survey. Participation was entirely voluntary and did not involve any clinical interventions or the collection of sensitive personal data. Hence, formal ethical approval is not required for this type of non-interventional, anonymous survey study.

Consent for publication

While all respondents consented to the publication of the data, the study design ensured complete anonymity. No personal data that could lead to the identification of any individual was recorded.

Availability of data

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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