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Original paper

Patient-specific three-dimensional printing of cerebral vasculature from digital subtraction angiography for aneurysm surgery: A practical workflow and preliminary clinical experience

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ABSTRACT

Introduction: Patient-specific three-dimensional (3D) printing has become an increasingly useful adjunct in neurosurgery, particularly in situations where precise understanding of spatial vascular anatomy is important for treatment planning. In intracranial aneurysm surgery, physical models may complement standard imaging by providing a tangible representation of the aneurysm and its relationship to the parent vessel and adjacent branches.

Material and methods: Source imaging data were obtained from routine digital subtraction angiography with rotational acquisition and 3D reconstruction. Selected datasets were processed in 3D Slicer, where vascular segmentation, removal of nonessential distal branches, island removal, surface smoothing, and STL export were performed. The final models were prepared for printing in Bambu Studio and printed on a Bambu Lab A1 mini printer using PLA filament and tree supports optimized for thin vascular structures.

Results: The described workflow enabled generation of patient-specific physical vascular models reproducing the aneurysm and the selected parent vessel anatomy relevant to surgical planning. The models were found to be useful as a supplementary aid in preoperative anatomical assessment, improving spatial understanding of aneurysm configuration and branch relationships within the selected vascular region of interest.

Conclusions: Patient-specific 3D printing of cerebral vasculature from digital subtraction angiography is feasible and can be implemented in routine practice using accessible software and desktop printing tools. Such models may serve as a useful adjunct in preoperative assessment, team discussion, and surgical education. Further evaluation in larger clinical series is warranted.

KEYWORDS

intracranial aneurysm, patient-specific model, neurosurgery, digital subtraction angiography, surgical planning, 3D printing of cerebral vessels

INTRODUCTION

Three-dimensional (3D) printing has gained increasing attention in neurosurgery over recent years. What began mainly as a technological curiosity is now being used in a more practical way: for surgical planning, simulation, education, and better visualization of complex anatomy. In cerebrovascular neurosurgery, this may be particularly useful, because the success of treatment often depends on a precise understanding of spatial relationships that are sometimes difficult to fully appreciate on a screen alone [1,2].

This is especially true in intracranial aneurysm surgery. Preoperative assessment is not limited to identifying the aneurysm itself, but also includes careful evaluation of its neck, its orientation, the geometry of the parent vessel, and the relationship to adjacent branches. Even when high-quality angiographic reconstructions are available, translating a 3D vascular configuration into an intuitive mental image remains challenging in some cases, particularly in anatomically complex lesions [2].

Digital subtraction angiography (DSA) remains one of the most important imaging methods in the evaluation of cerebral aneurysms and is still widely regarded as the reference technique for detailed visualization of intracranial vasculature [3,4,5]. At the same time, DSA data can serve not only diagnostic purposes, but also as a basis for patient-specific physical models. Previous studies have shown that aneurysm models derived from angiographic datasets can reproduce vascular anatomy with good geometric fidelity and may be useful in planning, simulation, and training [6,7,8,9,10].

The potential value of such models is not limited to the operating room. They may also support resident education, improve communication within the surgical team, and help patients better understand the anatomy of their disease and the rationale for treatment [2,11,12]. Despite this growing interest, the literature still shows considerable variation in imaging sources, segmentation strategies, printing methods, and intended applications. As a result, simple and reproducible workflow descriptions that could be realistically implemented in everyday practice remain relatively limited, particularly for models based specifically on DSA data [2].

For that reason, the present study aimed to describe a practical workflow for generating patient-specific 3D printed models of cerebral vasculature from DSA in the setting of aneurysm surgery. Such an approach may be useful not only for experienced vascular neurosurgeons, but also for residents and multidisciplinary teams involved in preoperative planning and anatomical education.

For that reason, the present study aimed to describe a practical workflow for generating patient-specific 3D printed models of cerebral vasculature from DSA in the setting of aneurysm surgery and to present preliminary clinical experience with this approach.

MATERIAL AND METHODS

Study design and clinical context

This study describes a practical workflow for generating patient-specific 3D printed models of cerebral vasculature from digital subtraction angiography data in patients with intracranial aneurysms. The work was based on preliminary clinical experience from a small proof-of-concept series in which these models were used for preoperative anatomical assessment and surgical planning.

This was not designed as a formal outcome study. The purpose of this work was to present a feasible and reproducible method that could be implemented in routine neurosurgical practice using standard angiographic data, widely available postprocessing tools, and desktop 3D printing.

Image acquisition

Source imaging data for model generation were obtained from routine digital subtraction angiography performed in patients with intracranial aneurysms. The examinations were acquired using a GE Innova angiography system and included rotational acquisition with 3D reconstruction. Only datasets with sufficient visualization of the aneurysm, the parent vessel, and the adjacent arterial branches relevant to surgical planning were selected for further processing.

Segmentation and 3D reconstruction

The selected angiographic datasets were imported into 3D Slicer for further processing. Segmentation was performed to isolate the aneurysm and the parent vascular anatomy relevant to surgical planning.

The reconstruction was deliberately simplified to preserve the most important anatomical relationships while keeping the model suitable for 3D printing. Typically, the proximal segments of the anterior and middle cerebral arteries were preserved, whereas more distal and smaller branches were removed to avoid excessive model complexity and reduce the risk of printing failure.

The final segmentation was then converted into a 3D surface model for subsequent postprocessing.

Model postprocessing

After initial segmentation in 3D Slicer, the vascular model was further refined to improve both anatomical clarity and printability. Small disconnected components (“islands”) and residual vascular fragments outside the selected region of interest were removed, and the final segmentation was converted into a closed surface representation.

Surface smoothing was applied in 3D Slicer with a smoothing factor of 0.5 to reduce segmentation-related irregularities and obtain a cleaner vascular contour. No mesh decimation was used. This postprocessing stage was performed iteratively, with repeated visual inspection of the model, in order to preserve the aneurysm and the key proximal arterial anatomy while removing distal or nonessential elements that would unnecessarily complicate printing. After final cleaning and smoothing, the model was exported from 3D Slicer in STL format for print preparation.

The preparation time for each model ranged from approximately 60 to 120 minutes, excluding printing time, which depended on model size and typically required several additional hours.

Print preparation and 3D printing

The final STL model was imported into Bambu Studio for print preparation. Model orientation was adjusted individually in order to improve stability during printing and to reduce the number of unsupported critical segments.

The models were printed on a Bambu Lab A1 mini printer equipped with a 0.4 mm stainless steel hotend, using PLA filament on a Textured PEI Plate. Printing was performed with a layer height of 0.20 mm, two wall loops, and 100% infill. The nozzle temperature was set at 220°C and the bed temperature at 60°C. The selected print profile used a first-layer speed of 50 mm/s, first-layer infill speed of 105 mm/s, external wall speed of 200 mm/s, inner wall speed of 300 mm/s, infill speed of 270 mm/s, internal infill speed of 250 mm/s, top surface speed of 200 mm/s, bridge speed of 50 mm/s, support speed of 150 mm/s, and travel speed of 700 mm/s.

Table I. Basic print settings used for fabrication of cerebral vascular models

Parameter	Setting
Printer	Bambu Lab A1 mini
Nozzle	0.4 mm stainless steel hotend
Build plate	Textured PEI Plate
Material	PLA
Layer height	0.20 mm
Wall loops	2
Infill	100%
Nozzle temperature	220°C
Bed temperature	60°C

Table II. Speed settings used for printing cerebral vascular models

Parameter	Setting
First layer speed	50 mm/s
First layer infill speed	105 mm/s
External wall speed	200 mm/s
Inner wall speed	300 mm/s
Infill speed	270 mm/s
Internal infill speed	250 mm/s
Top surface speed	200 mm/s
Bridge speed	50 mm/s
Support speed	150 mm/s
Travel speed	700 mm/s

Because of the thin and elongated geometry of cerebral vessels, tree supports were used. Rather than relying on default support settings, a dedicated support profile was applied to improve stabilization of delicate vascular branches while facilitating support removal after printing. The selected settings included a threshold angle of 90°, XY distance of 0.5 mm, Z distance of 0.3 mm, two top interface layers, no bottom interface layers, branch diameter of 2 mm, branch spacing of 8 mm, branch angle of 60°, and support density of 10%. The options “Remove small overhangs” and “Supports for critical regions only” were enabled.

Table III. Support settings used for thin cerebral vascular models

Parameter	Setting
Support type	Tree
Threshold angle	90°
XY distance	0.5 mm
Z distance	0.3 mm
Top interface layers	2
Bottom interface layers	0
Branch diameter	2 mm
Branch spacing	8 mm
Branch angle	60°
Support density	10%
Remove small overhangs	Enabled
Supports for critical regions only	Enabled

After printing, the support structures were removed manually.

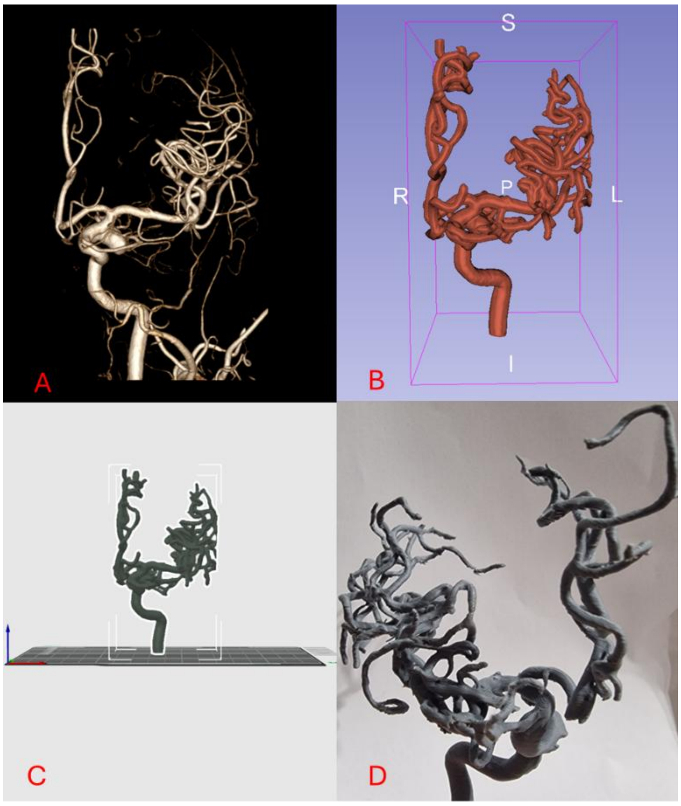

Fig. 1. Workflow of patient-specific model generation from DSA data. (A) 3D rotational DSA reconstruction of the aneurysm and parent vessel anatomy; (B) Vascular segmentation and digital model preparation in 3D Slicer; (C) Print preparation in Bambu Studio; (D) Final 3D-printed vascular model

RESULTS

Clinical application of the printed models

The printed vascular models were used as a supplementary tool during preoperative assessment in patients with intracranial aneurysms. Their main purpose was to provide a tangible 3D representation of the aneurysm and its relationship to the parent vessel and adjacent arterial branches, thereby improving spatial understanding of the vascular anatomy.

In everyday practice, the models supported preoperative anatomical orientation and facilitated inspection of the aneurysm configuration within the selected vascular region of interest. They were also useful for discussion of the planned procedure within the surgical team and had additional educational value in resident training.

Preliminary clinical experience

The described workflow was applied in a small proof-of-concept series of patients with intracranial aneurysms in whom patient-specific vascular models were generated from DSA data. In each case, the printing process resulted in a physical model that reproduced the selected vascular anatomy and the spatial relationship between the aneurysm, the parent vessel, and the adjacent proximal branches.

From a practical perspective, the models were found to be useful as a supplementary tool in preoperative anatomical assessment. Their main value was related to improved spatial understanding of the vascular configuration within the selected region of interest. Brief illustrative cases are presented below to demonstrate the clinical applicability of this workflow.

Case 1

A 66-year-old woman with intermittent headaches was diagnosed with an aneurysm of the left internal carotid artery at the origin of the posterior communicating artery. Digital subtraction angiography with rotational acquisition and 3D reconstruction demonstrated a left C7 ICA aneurysm measuring 11 × 6.5 × 8.4 mm, with a neck width of 4.9 mm. The patient was qualified for surgical treatment, and left pterional craniotomy with aneurysm clipping was performed. A patient-specific 3D printed vascular model was used as a supplementary aid in preoperative anatomical assessment.

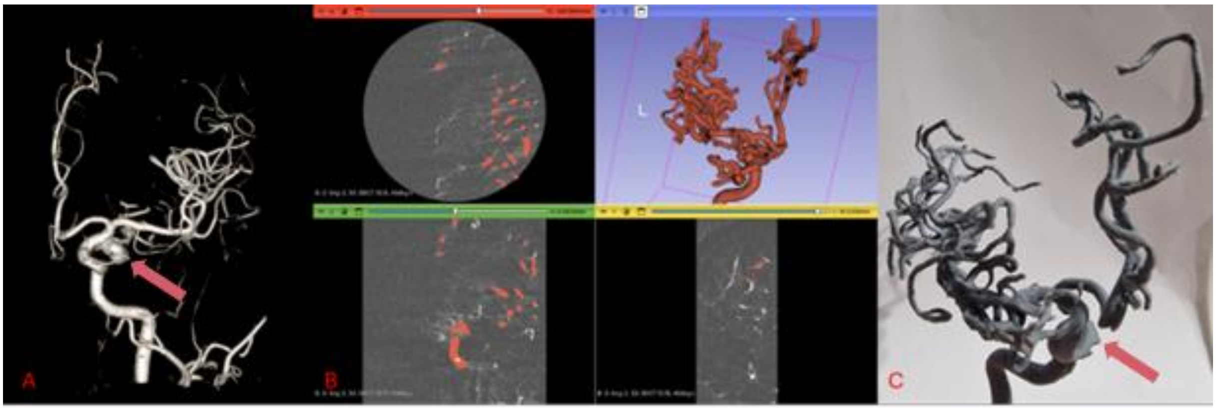

Fig. 2. Case 1. (A) 3D rotational DSA reconstruction; (B) Patient-specific digital model generated in 3D Slicer; (C) Final 3D-printed vascular model. Red arrow indicates the aneurysm sac

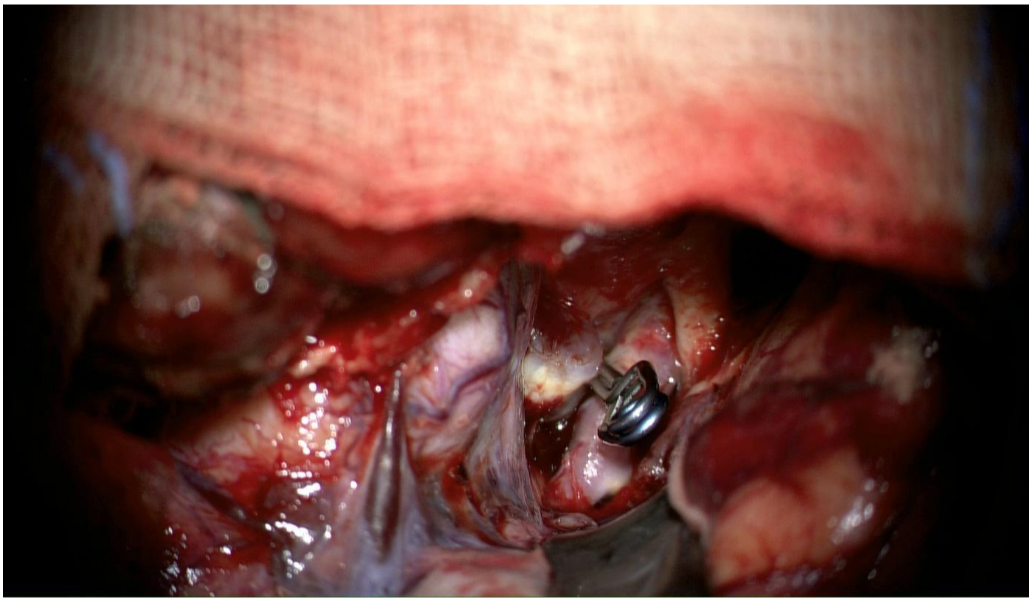

Fig. 3. Intraoperative view after aneurysm clipping in Case 1. Microsurgical view showing the clipped aneurysm after final clip placement

Case 2

A 70-year-old man underwent diagnostic digital subtraction angiography after progression of an intracranial aneurysm detected on follow-up computed tomography angiography. DSA demonstrated a right middle cerebral artery aneurysm measuring approximately 5 × 3 mm and an additional basilar artery aneurysm measuring approximately 3.5 × 2.5 mm. Because of the size and morphology of the right middle cerebral artery aneurysm, the patient was qualified for surgical treatment, and right pterional craniotomy with clipping of the aneurysm was performed. A patient-specific 3D printed vascular model was used as a supplementary aid in preoperative anatomical assessment.

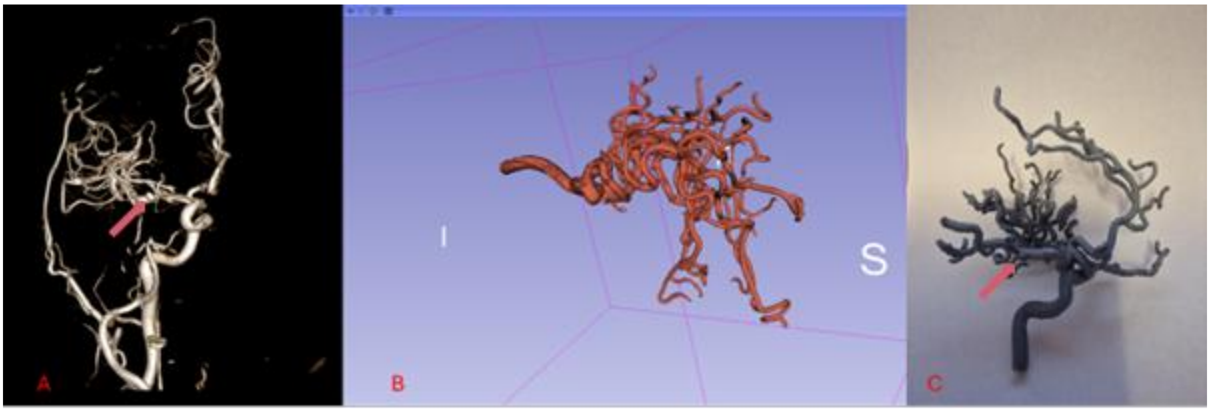

Fig. 4. Case 2. (A) 3D rotational DSA reconstruction; (B) Patient-specific digital model generated in 3D Slicer; (C) Final 3D-printed vascular model. Red arrow indicates the aneurysm sac

Case 3

A 42-year-old man was referred for planned neurosurgical treatment of a right middle cerebral artery aneurysm. The aneurysm was detected during diagnostic work-up after an episode of collapse. Computed tomography demonstrated hemorrhagic changes within the deep structures of the left cerebral hemisphere, and computed tomography angiography revealed focal dilatation in the RMCA territory. Diagnostic digital subtraction angiography with rotational acquisition and 3D reconstruction confirmed an aneurysm arising from the first branch of the right middle cerebral artery, measuring 4.1 × 4.0 × 3.7 mm, with a neck width of 3.1 mm. A patient-specific 3D printed vascular model was generated as a supplementary aid in anatomical assessment and preoperative planning.

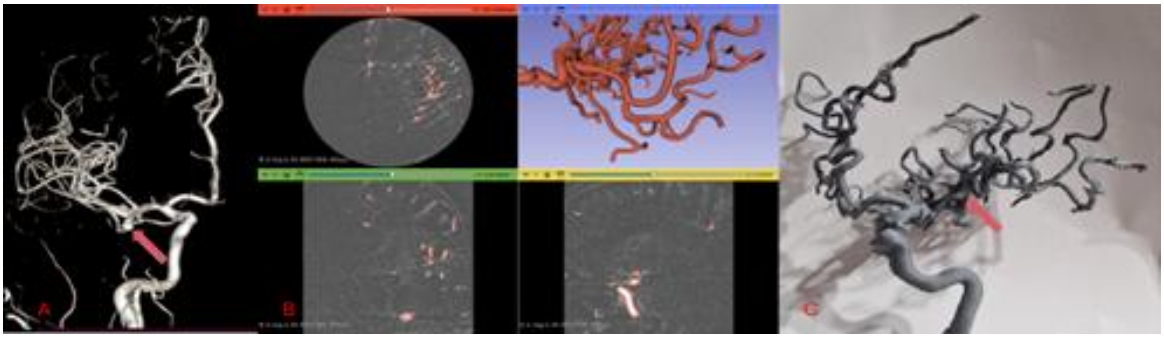

Fig. 5. Case 3. (A) 3D rotational DSA reconstruction; (B) Patient-specific digital model generated in 3D Slicer; (C) Final 3D-printed vascular model. Red arrow indicates the aneurysm sac

DISCUSSION

The use of 3D printing in neurosurgery has expanded noticeably in recent years. In the available literature, cerebrovascular pathology – and intracranial aneurysms in particular – appears among the most frequently described areas of application, alongside skull base surgery, tumor surgery, and resident training [1,2].

This study belongs to this group of reports, but its purpose is narrower and more practical. The intention was not to test a new imaging method or to demonstrate an effect on surgical outcomes. Instead, the aim was to show that DSA-based vascular models can be generated using tools that are already accessible in routine practice, including standard angiographic data, 3D Slicer, and desktop FDM printing. This general approach is consistent with previously published DSA-based studies, which have shown that angiographic datasets can be transformed into patient-specific aneurysm models with potential value for planning and training [7].

From a practical standpoint, the most important advantage of a printed model is simple: it allows the vascular anatomy to be held, rotated, and inspected physically. That may sound almost too obvious to mention, but it matters in aneurysm surgery, where understanding the spatial relationship between the sac, the parent vessel, and nearby branches is often central to preoperative thinking. Earlier reports have also emphasized that printed aneurysm models may improve appreciation of these anatomical relationships, particularly in cases where screen-based reconstructions are less intuitive [7].

In this workflow, the printed models were used only as a supplement to standard imaging, and that is probably where their role is best placed. They are not meant to replace DSA, 3D reconstructions, or conventional image review. Rather, they add one more layer of anatomical understanding. This is also how most of the literature frames them: as adjunctive tools that support orientation, planning, rehearsal, or teaching, rather than as independent decision-making instruments [2].

This educational aspect is worth emphasizing. Reviews focused on neurosurgical training have shown that vascular models are among the most commonly described 3D-printed tools in residency education, and in most reports trainee feedback has been favorable [13]. DSA-based aneurysm models have also been presented as useful in training settings, which makes sense given how difficult it can be for junior surgeons to mentally reconstruct vascular anatomy from imaging alone [7].

There is also a communication benefit. Beyond planning and teaching, patient-specific aneurysm models may help explain the disease itself. In a recent study, the use of 3D-printed aneurysm models during consultation improved patient understanding of the diagnosis, vascular relationships, and proposed treatment, suggesting that these models may also have value in informed consent and preoperative discussion [11,12].

From a practical perspective, the time required to prepare a model is an important consideration. In the present workflow, model preparation typically required approximately 60 to 120 minutes, with additional time needed for printing depending on model size and support configuration. The most time-consuming steps were segmentation and manual post-processing, while slicing and print setup were relatively straightforward. In urgent clinical scenarios, such as ruptured aneurysms, this approach is unlikely to replace standard imaging-based decision-making. However, in selected cases with complex vascular anatomy, or when surgery is performed after initial stabilization, the preparation of a simplified model may still be feasible within a clinically relevant timeframe.

Another important practical aspect is the cost of the presented workflow. The approach is based on widely accessible tools, including a low-cost desktop fused deposition modeling (FDM) 3D printer (approximately 200–400 EUR) and inexpensive PLA filament. The material cost of a single vascular model is low, typically in the range of 2–10 EUR, depending on model size and printing parameters. Importantly, the software used in this workflow (e.g., 3D Slicer, Bambu Studio) is freely available, which further reduces the overall cost and makes the approach feasible even in smaller centers.

One important feature of the present workflow is that it was intentionally simplified. The printed models did not attempt to reproduce the entire vascular tree. Distal and very small branches were removed when they did not materially improve anatomical understanding but would make the model harder to print and more fragile after fabrication. That choice reflects a practical compromise rather than a technical shortcoming. Similar reports in the literature have also focused on the aneurysm-bearing vessel segment rather than a complete anatomical reconstruction, and reviews of aneurysm modeling repeatedly note that many printed models do not include surrounding bone, brain tissue, cranial nerves, or other structures that may also matter during surgery [7,14].

Although the presented workflow was developed and applied primarily from the perspective of microsurgical aneurysm clipping, it is important to note that endovascular treatment of cerebral aneurysms is routinely performed in the author’s institution. However, in the present study, the 3D-printed models were not utilized for planning endovascular procedures.

Nevertheless, patient-specific 3D vascular models may have potential value in endovascular treatment planning. They can enhance spatial understanding of aneurysm morphology, including neck configuration, parent vessel geometry, and branching patterns, which are crucial for selecting appropriate techniques such as coiling, stent-assisted embolization, or flow diversion. Therefore, such models may serve as a useful adjunct in multidisciplinary decision-making, particularly in complex aneurysms [1,2].

That, in turn, points to a broader limitation of 3D-printed aneurysm models. Even when the vascular geometry itself is reproduced well, the model still represents only part of the operative situation. Validation studies suggest that printed aneurysm models can achieve good geometric correspondence with source imaging, but they also underline the technical difficulty of reproducing very fine vascular details and handling delicate branches without damage during postprocessing or support removal [15].

Another limitation is the quality of the current evidence base. Reviews of neurosurgical and neurovascular 3D printing are generally encouraging, but they also describe substantial heterogeneity between studies with respect to source imaging, segmentation methods, printing materials, fabrication techniques, validation methods, and intended clinical use. Because of that variability, and because larger comparative studies remain limited, it is still difficult to draw strong conclusions about measurable clinical benefit [1,2].

For this reason, the present study should be read primarily as a technical and practice-oriented contribution. It does not show that printed models improve outcomes, reduce complications, or shorten procedures. What it does show is that a DSA-based workflow can be integrated into routine practice using accessible tools and that the resulting models have plausible value in anatomical understanding, team discussion, and education. In that respect, the present work is closer to previously published pilot and proof-of-concept studies, which have framed patient-specific aneurysm printing as a feasible and promising adjunct rather than a definitive solution [16].

CONCLUSIONS

Patient-specific 3D printing of cerebral vasculature from digital subtraction angiography is feasible and can be implemented in routine practice using accessible software and desktop printing tools. The presented workflow enables preparation of simplified vascular models that may improve spatial understanding of aneurysm anatomy during preoperative assessment.

These models should be regarded as a supplementary aid rather than a replacement for standard imaging. Their potential value appears to lie mainly in anatomical orientation, team discussion, and surgical education. Further evaluation in larger clinical series is warranted.

Use of AI tools statement

ChatGPT (OpenAI) was used as an auxiliary tool for language editing and stylistic improvement of the manuscript text. All scientific content, literature selection, interpretation of data, and final approval of the manuscript were performed by the author.

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