Utility and Feasibility of a Low-Cost System to Simulate Clipping Strategy for Cerebral Aneurysms Using Three-Dimensional Computed Tomography Angiography with Virtual Craniotomy

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■ OBJECTIVE: **To assess utility and feasibility of a low-cost system to simulate clipping strategy for cerebral aneurysms using patient-specific surgically oriented three-dimensional (3D) computed tomography angiography with virtual craniotomy.**

■ METHODS: **From 2017 to 2021, 53 consecutive patients scheduled for aneurysm clipping underwent preoperative planning using 3D computed tomography angiography with virtual craniotomy. The model was oriented in the surgical position to observe the anatomy through surgical corridors. Clipping was planned considering 3 parameters: shape of the clip, clip type (standard vs. fenestrated), and clipping strategy (simple vs. multiple). We used a scoring system (0—3) to assess the concordance of virtual planning with real surgery by assigning 1 point for each correctly predicted parameter. Qualitative assessment of 3D models was a secondary end point.**

■ RESULTS: **In 51 patients, 3D images perfectly matched the real anatomy shown in surgical videos. Concordance scores of 0, 1, 2, and 3 occurred with a frequency of 5%, 14%, 38%, and 43%, respectively. Concerning the shape of the clip, clip type, and clipping strategy, the concordance occurred in 73%, 80%, and 59%, respectively. Compared with simple clipping, strategies with multiple clippings were more difficult to predict correctly. Concordance scores of 0, 1, 2, and 3 occurred with a frequency of 5.7%, 5.7%, 31.4%, and 57.1%, respectively, in simple clipping and 4.8%, 28.6%, 47.6%, and 19%, respectively, in multiple clipping.**

■ CONCLUSIONS: **In our experience, use of 3D computed tomography angiography with virtual craniotomy is an easy and useful solution to plan clipping strategy. The surgeon's awareness of the surgical anatomy is improved. Although this method has some technical limitations, it represents a low-cost alternative if complex and expensive simulation systems are not available.**

INTRODUCTION

Cerebral aneurysm surgery is well known for being a technically demanding procedure. It is particularly challenging for young or inexperienced surgeons. Adequate knowledge and awareness of three-dimensional (3D) anatomy according to the surgical view is essential. The learning curve for arachnoid dissection and clipping techniques is slow. In the last 10 years, some centers have introduced the use of surgical simulation systems to optimize the training process. These were initially based on physical models[1-3] and later virtual reality (VR) systems in which the surgeon can interact.[4-13] The simulation

Key words
- Cerebral aneurysms
- Microsurgical clipping
- Surgical planning
- Surgical simulation
- Virtual craniotomy

Abbreviations and Acronyms
2D: Two-dimensional
3D: Three-dimensional
CT: Computed tomography
CTA: Computed tomography angiography
VR: Virtual reality

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systems are used to acquire awareness of 3D space with the limitations created by surgical corridors. The cost of simulation systems is high, however, and not affordable for many centers with limited budgets. Yet adequate training to treat this pathology must be ensured in neurosurgery departments.[14]

To optimize preoperative planning for cerebral aneurysm clipping, in our department, low-cost software was used to provide 3D reconstruction of computed tomography angiography (CTA) imaging. We performed a virtual craniotomy on the 3D model, identical to the craniotomy that would be used during surgery. The virtual model was oriented in the surgical position, and the vascular anatomy was explored with the same surgical viewing angles and through the same anatomical corridors. This way the position and spatial orientation of the structures were identical to the surgical field, although interaction with the structures was not possible. The aim of the present study was to assess the feasibility and utility of the 3D CTA reconstructions and virtual craniotomy for preoperative planning in aneurysm surgery. This was determined by evaluating the precision in predicting surgical features such as shape and type of the clip and clipping strategy.

MATERIALS AND METHODS

This prospective study was performed at the Department of Neurosurgery of Azienda Ospedaliero Universitaria di Sassari. The study was approved by the institutional review board. From November 2017 to October 2021, all patients undergoing surgical treatment for cerebral aneurysms (craniotomy and clipping) were considered eligible. The data were collected anonymously, and the patients (or a family member) gave their consent to anonymous use of images at the same time as the consent was acquired for the intervention.

All phases of patient management (diagnosis, medical therapy, surgical therapy, follow-up) were carried out in accordance with the guidelines for subarachnoid hemorrhage from ruptured cerebral aneurysm.[14] All procedures were performed by a main surgeon (a highly experienced surgeon [R.B.] or a medium-experienced surgeon [D.P.]) with 1 or 2 assistant surgeons. A highly experienced surgeon was defined as having performed >500 clipping procedures as first surgeon during the last 20 years; a medium-experienced surgeon was defined as having performed 50–500 clipping procedures as first surgeon during the last 20 years.

We included only ruptured aneurysms because during the reference period unruptured aneurysms were managed in another department. Occurrence of ruptured cerebral aneurysm was investigated in all patients presenting to our center with subarachnoid hemorrhage on computed tomography (CT) scan. According to international guidelines, during the referral period, every patient with subarachnoid hemorrhage underwent CTA on a 16-channel multidetector CT scanner (Philips Healthcare, Best, The Netherlands) with volumetric acquisition consisting of a contiguous axial series with a thickness of 0.6 mm and 0.3-mm interval (scanning time, 0.4–0.5 seconds; acquisition time, 14–15 seconds). All demographic and clinical data were collected for each patient. All cases of ruptured aneurysms were discussed with the whole treatment team. The clinical and radiological data (Hunt and Hess classification, Glasgow Coma Scale score, Fisher grade, general conditions and/or comorbidities) were considered, and the therapeutic strategy was chosen (surgery vs. endovascular treatment). In surgical patients, the timing (ultra-early, 0–12 hours; early, 12–72 hours; delayed, >72 hours) was decided, and the approach was selected: decompressive hemicraniectomy, standard pterional craniotomy, or minipterional craniotomy for anterior circulation aneurysms; suboccipital median, posterolateral, or far lateral craniotomy for posterior circulation aneurysms; interhemispheric for anterior cerebral artery aneurysms.

After the meeting with the whole team, the surgical team (main surgeon and assistant) performed a simulation of the procedure using software provided in all the personal computers of the hospital (Suitestensa RIS PACS; Esaote, Genoa, Italy). CT/CTA data were automatically uploaded in Digital Imaging and Communications in Medicine format to the hospital's digital network immediately after scan acquisition and were available for postprocessing, which took an average of 5–10 minutes. The data in Digital Imaging and Communications in Medicine format were then transferred to the neuronavigator system.

The first step of the simulation was the study of two-dimensional (2D) CTA with multiplanar reconstructions (axial, coronal, and sagittal). A patient-specific 3D model of the entire skull was later created, and a virtual craniotomy (established during the preoperative briefing) was performed. Software functions were used to modify the orientation of the model, reproducing the viewing angles allowed by the craniotomy while simulating the movements of the operating microscope. This enabled a depiction of the surgical anatomy (orientation of the aneurysm; neck/dome ratios; position, size, and course of afferent and efferent vessels) and a formulation of a clipping plan (Figures 1 and 2 show 2 planning examples). A table was then completed for each case evaluating 3 parameters: 1) type of clip—simple or fenestrated; 2) shape of the clip—straight, angled, curved, or bayonet; 3) clipping strategy—simple or multiple (tandem, staged, intersected, etc.). The plan was downloaded and later compared with intraoperative videos (see examples in Figures 1 and 2) to assess concordance.

All procedures were performed under general anesthesia. The intraoperative setting included a neuronavigation system (StealthStation S8; Medtronic, Minneapolis, Minnesota, USA)[6] on which the base CT/CTA imaging data were uploaded. An intraoperative 3D ultrasound system (SonoWand Invite; Sonowand AS, Trondheim, Norway)[15,16] was used for difficult external ventricular drain positioning or minimally invasive intracerebral hematoma evacuation. A micro-Doppler probe and intraoperative indocyanine green videoangiography (Flow 800; Carl Zeiss Meditec AG, Jena, Germany)[17] were used to check clipping sufficiency. All surgical procedures were video-recorded.

After each procedure, a debriefing was carried out during which the surgical videos were compared with the preoperative planning elaborated at the workstation. The concordance or discrepancy between the preoperative planning and the clipping was verified. Level of agreement was evaluated with a score from 0 to 3: score 3 (total) in case of agreement of all 3 considered parameters; score 2 or 1 (partial) for agreement of 2 parameters or 1 parameter, respectively; score 0 (absent) in case of no concordance at all. Results were analyzed using the standard 2-tailed t test to assess differences between considered parameters.

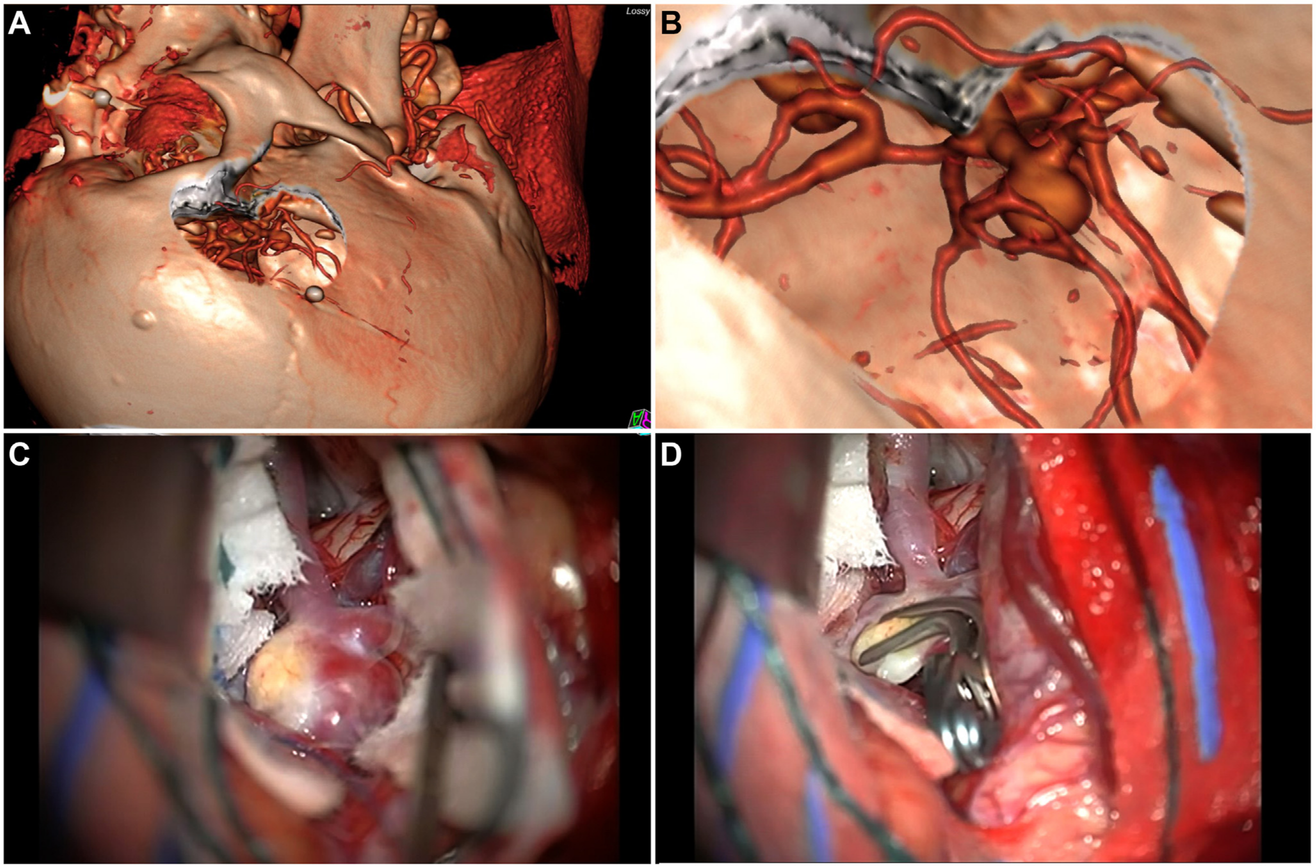


Figure 1. Example of middle cerebral artery aneurysm. (**A**) Three-dimensional reconstruction with right pterional craniotomy. (**B**) Magnification to simulate vision of the operating microscope; M1 segment and the 2 M2 segments of the middle cerebral artery and the aneurysm are well reconstructed. (**C**) Intraoperative view of the aneurysm before clipping. (**D**) Surgical vision after clip placement. In this case, we planned simple clipping with a standard angled clip; due to the presence of a calcification, we performed multiple clipping using 2 parallel stacked standard angled clips. Concordance score was 2.

The primary end point was the percentage of agreement between the preoperative planning and the surgical clipping. Secondary end points were qualitative assessment of the 3D reconstruction (suitable or unsuitable) and variation in the concordance rate over the considered time period.

RESULTS

The study included 53 patients; 3 patients underwent clipping of 2 aneurysms during the same procedure for a total of 56 aneurysms. One case with double aneurysm was approached with a single craniotomy, while the other 2 cases were approached with separate craniotomies during the same procedure. The patients include 42 women and 11 men. The average age was 61 years (range, 38–79 years). Table 1 summarizes the demographic, clinical, and surgical data of all patients (age, sex, Hunt and Hess classification, Fisher grade, surgical timing, approach, aneurysm site, hydrocephalus, Glasgow Outcome Scale score).

The qualitative analysis of the 3D CTA reconstructions compared with intraoperative videos was suitable and adequate for the study of vascular anatomy in 51 patients. In 2 patients, the quality of the reconstruction was not sufficient, and it was not possible to complete adequate preoperative planning (concordance score 0). The concordance data between preoperative planning and the actual surgical procedure were evaluated in the 56 treated aneurysms. A score of 0 was assigned in 3 cases (5.3%), a score of 1 was assigned in 8 cases (14.28%), and a score of 2 was assigned in 21 cases (37.5%). Total concordance—a score of 3—was found in 24 cases (42.8%) (Figure 3). Considering scores of 2 and 3 together, we obtained a complete or nearly complete concordance in 45 cases (80.3%).

Taking into consideration the degree of concordance with respect to the clipping strategy (simple vs. multiple), we found that the degree of complete agreement and the average concordance were higher in cases of simple clipping. Simple clipping average concordance was 2.4; multiple clipping average

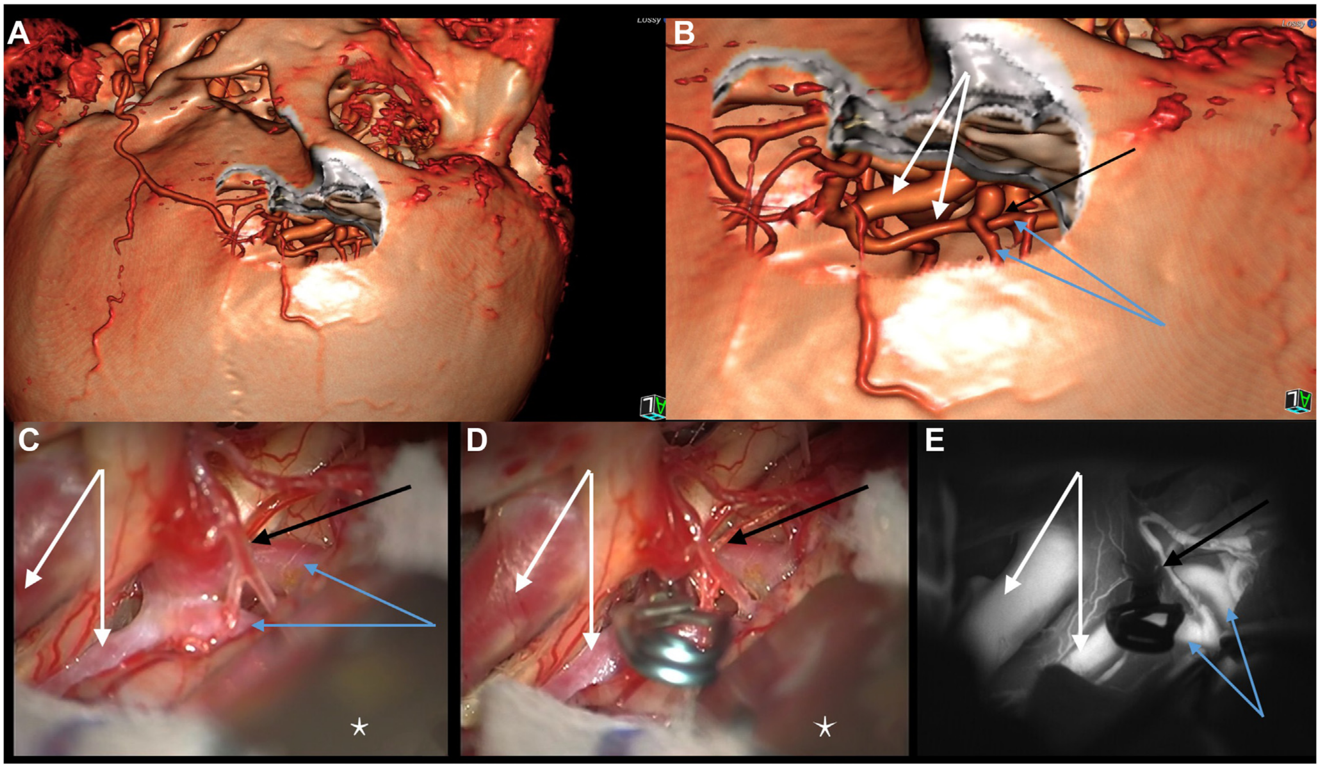


Figure 2. Example of anterior communicating artery aneurysm. (**A**) Reconstruction with left pterional craniotomy. (**B**) Magnification to simulate vision of the operating microscope. (**C**) Intraoperative view of the aneurysm before clipping. (**D**) Surgical vision after clip placement. (**E**) Indocyanine green videoangiography confirming complete exclusion of the aneurysm and patency of A1 and A2 segments of the anterior cerebral artery bilaterally. In the 3D model (**A** and **B**), the frontal sinus was opened by the virtual craniotomy; in the real surgery, we obtained the same opening of the frontal sinus to indicate that the 3D virtual model perfectly matched the real anatomy. In this case, we obtained complete concordance (score 3). *White arrows* indicate the internal carotid artery and left A1 segment; the left A1 segment is quite long with a course parallel to the internal carotid artery (the three-dimensional (3D) reconstruction is very faithful to the real image). The *black arrow* indicates the angle between the neck and the origin of the right A2 segment where the distal blade of the clip will be positioned (to exclude the aneurysm without obstructing the A2 segment). *Blue arrows* indicate A2 branches. The *white star* represents the spatula.

concordance was 1.8 (t test $P = 0.018$). Simple clipping concordance scores were 0 in 5.7%, 1 in 5.7%, 2 in 31.4%, and 3 in 57.1%. Multiple clipping concordance scores were 0 in 4.8%, 1 in 28.6%, 2 in 47.6%, and 3 in 19% (Figure 4). Overall, combined scores of 2 and 3 showed high concordance rates in 66.6% of multiple clipping cases and 88.5% of simple clipping cases.

Considering the 3 parameters separately (clip shape, clip type, and clipping strategy), we obtained the following data: clip shape concordance in 41 cases (73%), clip type concordance in 45 cases (80%), and clipping strategy concordance in 33 cases (59%). The clipping strategy was the most difficult parameter to predict correctly. Simple clipping was proposed in 44 cases and performed in 35 cases. Multiple clipping was planned in 12 cases and performed in 21 cases.

We observed an increase in the complete concordance rate (score 3) during the last year of the study. Figure 5 shows the variation in the concordance rate for each year taken into consideration: complete agreement (score 3) in the first, second, third, and fourth year was 39%, 36%, 33%, and 59%, respectively. Partial agreement (score 2) was 46%, 36%, 42%, and 29%, respectively.

By evaluating only the average concordance result over the 4 years, we obtained 2.23, 2, 2.08, and 2.35 respectively. Although during the fourth year the mean concordance was higher, the difference with the previous years was not significant (t test $P > 0.1$).

We assessed the differences in concordance between the 2 treating surgeons. R.B. performed 23 clipping procedures; average concordance was 2.16; concordance scores were 0 in 2 patients (9%), 1 in 3 patients (13%), 2 in 9 patients (39%), and 3 in 9 patients (39%). D.P. performed 33 clipping procedures; average concordance was 2.19; concordance scores were 0 in 1 patient (3%), 1 in 5 patients (16%), 2 in 12 patients (36%), and 3 in 15 patients (45%). D.P. obtained an average concordance higher than R.B. (2.19 vs. 2.16), but this did not reach the threshold of statistical significance (t test $P = 0.29$).

Table 1. Demographic, Clinical, and Surgical Data of Patients Enrolled in Study

Characteristic	Value
Number of patients	53
Number of aneurysms	56
Age, years, average (range)	61 (38—79)
Sex	
Female	42 (79%)
Male	11 (21%)
HH classification	
1	11 (20.8%)
2	16 (30.2%)
3	12 (22.6%)
4	14 (26.4%)
Fisher grade	
1	3 (5.7%)
2	12 (22.6%)
3	19 (35.8%)
4	19 (35.8%)
Timing	
Ultra-early	20 (37.7%)
Early	27 (50.9%)
Delayed	6 (11.3%)
Approach	
Minipterional	38 (69.1%)
Pterional	2 (3.6%)
DHC	9 (16.4%)
Interhemispheric	4 (7.3%)
Suboccipital	2 (3.6%)
Site	
MCA	17 (30.4%)
AComA	19 (33.9%)
PComA	13 (23.2%)
ICA ophthalmic segment	1 (1.8%)
ACA	4 (7.1%)
AICA	1 (1.8%)
PICA	1 (1.8%)
EVD	
Yes	32 (60.4%)
No	21 (39.6%)
VP shunt	
Yes	19 (35.8%)
No	34 (64.2%)
GOS score	
1	5 (9.4%)
2	3 (5.7%)
3	10 (18.9%)
4	12 (22.6%)
5	23 (43.4%)

Continues

Table 1. Continued

HH, Hunt and Hess; DHC, decompressive hemicraniectomy; MCA, middle cerebral artery; AComA, anterior communicating artery; PComA, posterior comunicanting artery; ICA, internal carotid artery; ACA, anterior cerebral artery; AICA, anterior inferior cerebellar artery; PICA, posterior inferior cerebellar artery; EVD, external ventricular drain; VP, ventriculoperitoneal; GOS, Glasgow Outcome Scale.

DISCUSSION

Cerebral aneurysm surgery requires technical skills and adequate experience. In recent years, endovascular techniques have evolved with a growing number of neurosurgical centers. This has resulted in a reduction of aneurysm cases per single neurosurgeon, thus slowing down and complicating the training process. Nevertheless, surgical clipping remains a valid therapeutic option, and this option must be ensured with high-quality standards in all neurosurgical centers treating brain pathologies.[18-20] The inevitable reduction of surgical experience therefore must be compensated with theoretical preparation to accelerate the training. A thorough preoperative knowledge of the case-specific 3D vascular anatomy (aneurysm and adjacent vessels and structures) is essential. However, mental elaboration of 3D information from 2D radiological imaging can be difficult. Even more complex is the depiction of surgical anatomy according to the operative view. To facilitate this process, we applied a virtual craniotomy on patient-specific CTA 3D reconstructions, exploring the anatomy through the viewing angles limited by the craniotomy and the surgical position (simulating the vision of the operating microscope through the surgical corridors).

Perfect patient-specific anatomical knowledge and adequate awareness of the 3D corridors are considered mandatory for aneurysm surgery.[8,13] Although neuronavigation systems and other intraoperative imaging techniques are widespread, it may not be sufficient for neurovascular surgery.[6,16] Many authors have suggested implementing the use of 3D diagnostics for clipping planning; preliminary reports[21,22] proposed different methods of study and postprocessing of neuroimaging with different goals (improve the rate of complete aneurysm exclusion, optimize diagnosis, choice of approach). The primary purpose of our study was not to know the clipping strategy to increase the complete exclusion rate of the aneurysm, but rather to increase the knowledge of the patient-specific anatomy to provide the surgeon with better awareness of the procedure. Therefore, we used 3D diagnostics as a simulation system for preoperative training to accelerate the learning curve of surgeons.

With the easy availability of image processing software, we added surgically oriented virtual craniotomy to overcome the mental process of reconstructing and rotating 2D images into 3D images oriented in surgical views. The usefulness of simulation systems for surgeons has been known for some time. Over the last 2 decades, various surgical simulation systems have been developed,[5] initially based on physical models[2,3,23] and now commonly based on advanced but expensive VR simulators.[8-13,24-26] Due to high costs, the modern VR simulators are not available at every center. However, over the years image acquisition techniques and post-processing software have evolved, and at this time there are many low-cost or free programs available on the market.[12,27] We used common software that is available in our hospital, Suitestensa RIS PACS, which we usually use to design cranial defect reconstruction.[28] This program allows one to obtain a 3D model in a few minutes; therefore it can be used for preoperative planning even in cases of emergency surgery. We did not use the software provided in the StealthStation S8 neuronavigation system for planning because we found Suitestensa RIS PACS to be easier to use; it is available on all personal computers in our hospital and allows us to obtain very satisfactory quality images. Qualitative evaluation of the virtual models was based on the comparison of the digital images with the surgical videos. It was carried out by the surgeons based on a subjective criterion similar to that used by other authors.[9,10] The obtained 3D reconstructions were compared with intraoperative videos and perfectly matched the real anatomy in 51 of 53 patients (a secondary end point of the present study).

To obtain a more objective assessment of the preoperative simulation, we used the ability to predict clipping as the primary end point. We considered 3 parameters: clip shape, clip type (standard vs. fenestrated), and clipping strategy (simple vs. multiple). This represents a simplification but appears sufficient to describe clipping with high accuracy; we obtained complete concordance on all parameters (score 3) in 42.8% and at least on 2 parameters in a further 37.5% of cases. This means that in 80.3% of cases at least 2 parameters were correctly predicted. In our opinion, these results indicate that the 3D reconstruction is faithful to real anatomy and sufficient to adequately represent the surgical field. In our simulation, the planning is based exclusively on the orientation of the aneurysm neck and the course of the adjacent vessels; it was not possible to predict the elastic deformation of the aneurysm after clip application and reproduce the positioning of the spatula on the brain or neurovascular structures. A case of an A3 segment anterior cerebral artery aneurysm is shown in **Figure 6**. Observing the 3D model through the virtual craniotomy, we noted that the callosomarginal artery projected over the pericallosal artery making it impossible to visualize the aneurysm neck in the surgical position. We therefore virtually rotated the head to observe the aneurysm from a different angle. However, during the real procedure (**Figure 6D—F**), the spatula was positioned on the cingulate gyrus, moving the parenchyma and the callosomarginal artery laterally, thus exposing the neck. This manipulation cannot be simulated or predicted with our system. The concordance score for this case was 1.

Our planning method cannot reach complete agreement in all cases because there are variables that cannot be analyzed. It has an insufficient resolution to visualize small perforators (whose location and course are appreciable with an operating microscope and indocyanine green videoangiography and may influence clip placement). It allows us to identify calcific plaques in the image processing stage; however, we do not have a standardized protocol

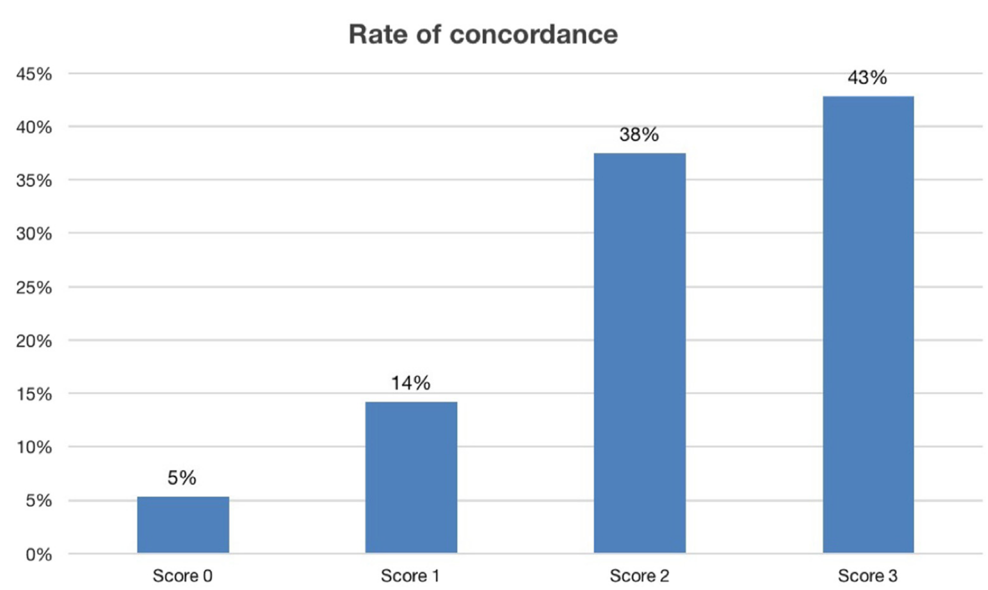


Figure 3. Concordance rate in the whole group.

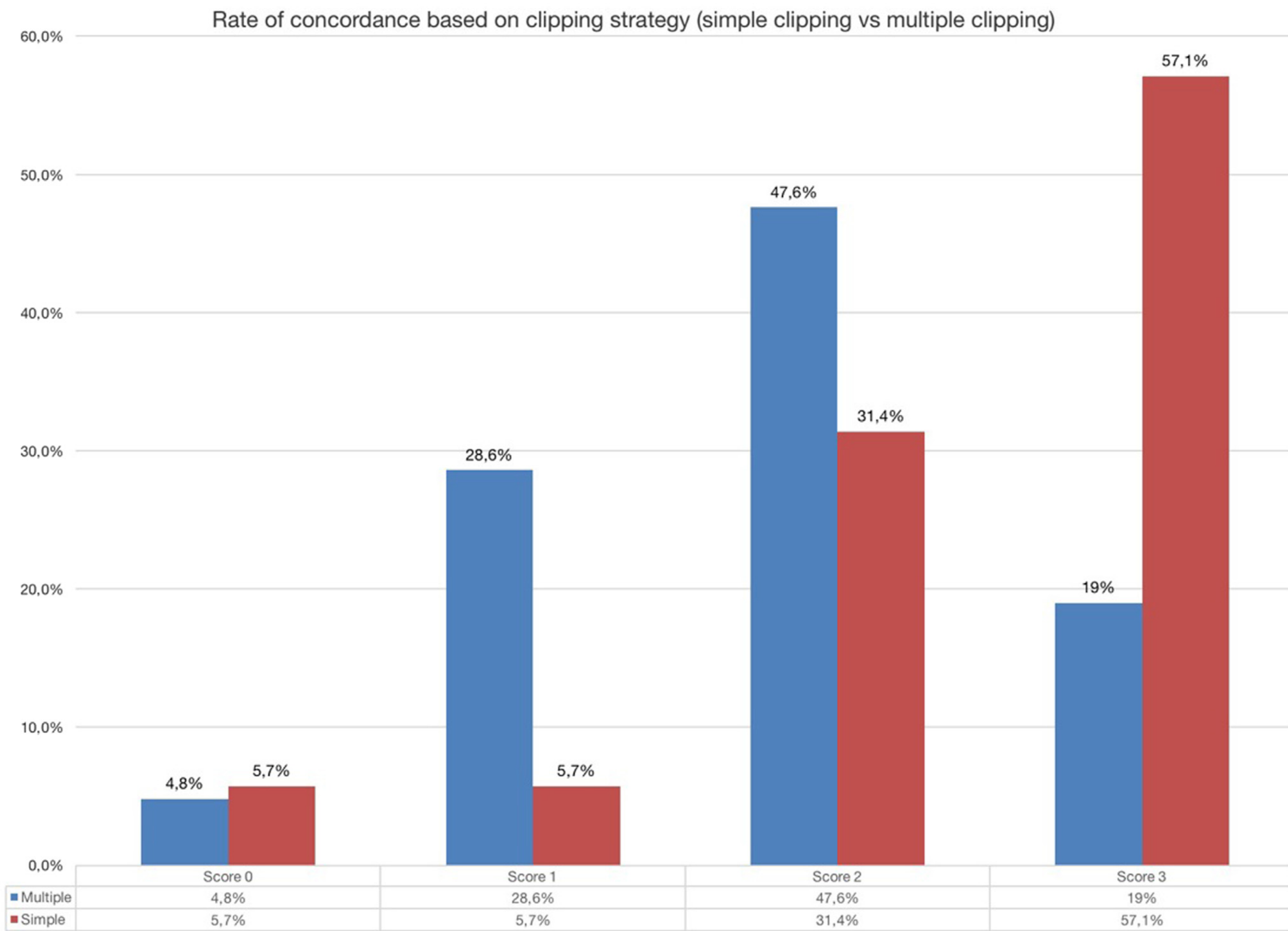


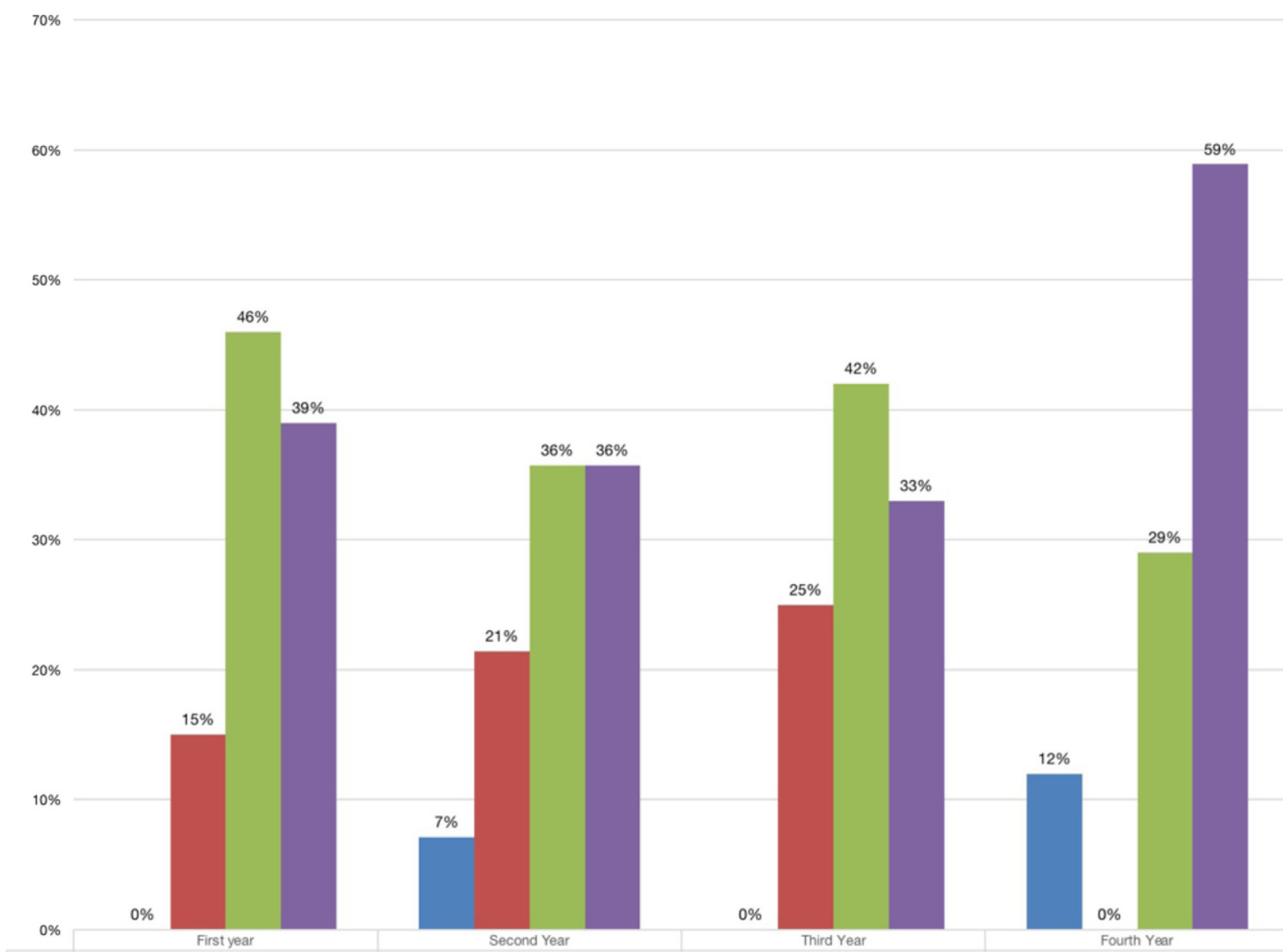
Figure 4. Concordance rate based on different clipping strategy (simple vs. multiple).

for evaluating calcifications, which therefore may not be accurately identified in some cases. For cases of complex clipping (large aneurysms or large neck), the system has a lower planning ability. Concordance score for simple clipping was 3 in 57.1% of cases, and concordance score for multiple clipping was 3 in 19% of cases; thus, average concordance was significantly higher with simple clipping (2.4) than with multiple clipping (1.8) assessed using the t test ($P = 0.018$).

Nevertheless, our method still provides good awareness of the anatomy regardless of the ability to perfectly predict clipping. Similar percentage results in terms of clipping planning were obtained by other authors using simulators based on more advanced VR systems[7-10]; these systems use stereoscopic 3D images with the possibility of manipulating simulated tools inside the model. Stereoscopic vision guarantees a better perception of depth but is associated with high costs and may be unaffordable for some centers. Our models are displayed on a 2D flat monitor. However, with editing functions simulating the movements of the operating microscope, it was easy to understand the relationships between the structures and sense the depth of the operative field.

The various simulation and rehearsal systems proposed have different characteristics and functions. Some simpler systems could be used to improve visuospatial skills (awareness of 3D patient-specific anatomy); other, more complex programs are equipped with haptic feedback systems allowing practical training on the model (drilling, craniotomy, manipulation of instruments with tactile feedback).[10,11,25] Although at the present time it is not easy to identify a clear positive effect on the patient's outcome, we hypothesize that surgical efficiency and performances will benefit from preoperative training based on 3D simulation.[5,9,10,13]

We reported an apparent increase in the concordance rate in the last year of the study (**Figure 5**), suggesting that the 3D planning software with virtual craniotomy improves understanding of the neuroimaging and allows greater



	First year	Second Year	Third Year	Fourth Year
Score 0	0%	7%	0%	12%
Score 1	15%	21%	25%	0%
Score 2	46%	36%	42%	29%
Score 3	39%	36%	33%	59%

Figure 5. Change in the concordance rate in the 4 years of the study.

precision in clipping prediction. This implies an acceleration in the learning curve as well. However, the evaluation of the average concordance (using the t test) shows that the differences between the fourth year and the previous years are not significant. Therefore, this result could be attributed to chance rather than a real increase in the effectiveness of the predictivity of the anatomical study.

Considering the differences between the 2 treating neurosurgeons, we observed a slight nonsignificant difference in average concordance (D.P.: 2.19; R.B.: 2.16; $P = 0.29$). However, it is necessary to specify that R.B. performed fewer procedures but performed the surgeries judged to be of higher complexity (e.g., posterior circulatory aneurysms, giant aneurysms) in which intraoperative management was adjusted according to several variables that were more difficult to predict with preoperative planning.

Limitations

The system we propose has limitations. It does not allow any interaction with the 3D model, and it is displayed on a 2D flat monitor and does not allow parenchymal visualization; therefore it is incomplete. However, it appears to be a useful and low-cost solution that can improve the learning phase of this complex surgery. Moreover, in a period of cost containment, the low costs can be appealing particularly for centers with limited budgets that must nevertheless guarantee adequate surgical results.[29,30] An additional limitation is the design of the study; the preoperative planning was performed by the same surgical team that then performed the actual surgery (which therefore could be influenced by the preoperative planning). A future study will have different surgeons perform the planning (in a blinded manner) and evaluate the differences in concordance between the surgeons who participate in the surgery and those who do not participate.

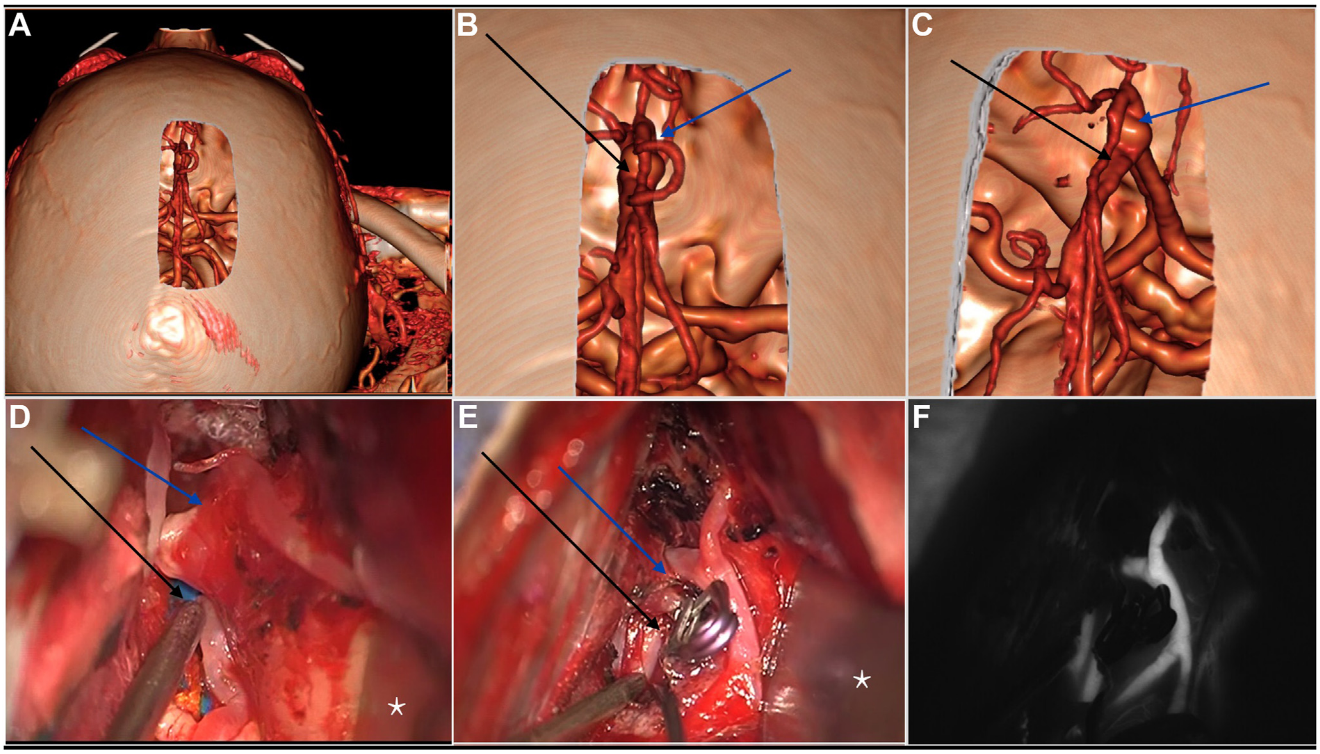


Figure 6. Example of an A3 segment anterior cerebral artery aneurysm. (**A**) Three-dimensional reconstruction with right frontal paramedian craniotomy. (**B**) Magnification to simulate vision of the operating microscope; the callosomarginal artery obstructs the vision of the neck. (**C**) The model was rotated to observe the neck through an unobstructed lateromedial view (in the model it is not possible to mobilize the parenchyma and arteries to visualize the underlying structures). (**D**) The spatula enlarges the interhemispheric fissure and medially displaces the parenchyma and the callosomarginal artery, exposing the neck with the opposite angle of view to that of the simulation. (**E**) Surgical vision after clip placement. (**F**) Indocyanine green videoangiography confirming complete exclusion of the aneurysm and patency of the pericallosal artery and callosomarginal artery. Concordance score was 1. The *black arrow* indicates the angle between the aneurysm and the pericallosal artery. The *blue arrow* indicates the angle between the aneurysm and the callosomarginal artery. The *white star* represents the spatula.

CONCLUSIONS

In our experience, the use of 3D CTA with virtual craniotomy provided a useful low-cost solution to plan clipping strategy for cerebral aneurysms. It helps the surgeon to study patient-specific vascular anatomy. Although this method has some technical limitations, it can be used in all centers, particularly when complex and expensive simulation and rehearsal systems are not available.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Domenico Policicchio: Conceptualization, Methodology, Investigation, Writing – original draft. **Riccardo Boccaletti:** Supervision. **Gina Casu:** Investigation. **Giosuè Dipellegrini:** Visualization, Writing – original draft. **Artan Doda:** Methodology, Data curation. **Giampiero Muggianu:** Investigation, Formal analysis. **Filippo Veneziani Santonio:** Formal analysis, Writing – review & editing.

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