Rehearsals using patient-specific 3d-printed aneurysm models for simulation of endovascular embolization of complex intracranial aneurysms: 3D SIM Study

Anthony Lebras, Fakhreddine Boustia, Kevin Janot, Estelle Lepabic, Mathilde Ouvrard, Claire Fougerou-Leurent, Jean-Christophe Ferre, Jean-Yves Gauvrit, François Eugene

JoN - Original Research

TITLE

Rehearsals using patient-specific 3d-printed aneurysm models for simulation of endovascular embolization of complex intracranial aneurysms: 3D SIM Study.

AUTHORS

Anthony LE BRAS, MD, PhD, Service de Radiologie, Centre Hospitalier Bretagne Atlantique, France

Fakhreddine BOUSTIA, MD, Service de Radiologie, Centre Hospitalier Universitaire de Rennes, France

Kevin JANOT MD, Service de Radiologie, Centre Hospitalier Universitaire de Tours, France

Estelle LE PABIC, PhD, Service de Biostatistiques, Centre Hospitalier Universitaire de Rennes, France

Mathilde OUVRARD, PhD, Direction de la Recherche, Centre Hospitalier Universitaire de Rennes, France

Claire FOUGEROU-LEURENT,MD, Service de Pharmacologie Clinique, Centre Hospitalier Universitaire de Rennes, France

Jean-Christophe FERRE, MD, PhD, Service de Radiologie, Centre Hospitalier Universitaire de Rennes, France

Jean-Yves GAUVRIT, MD, PhD, Service de Radiologie, Centre Hospitalier Universitaire de Rennes, France

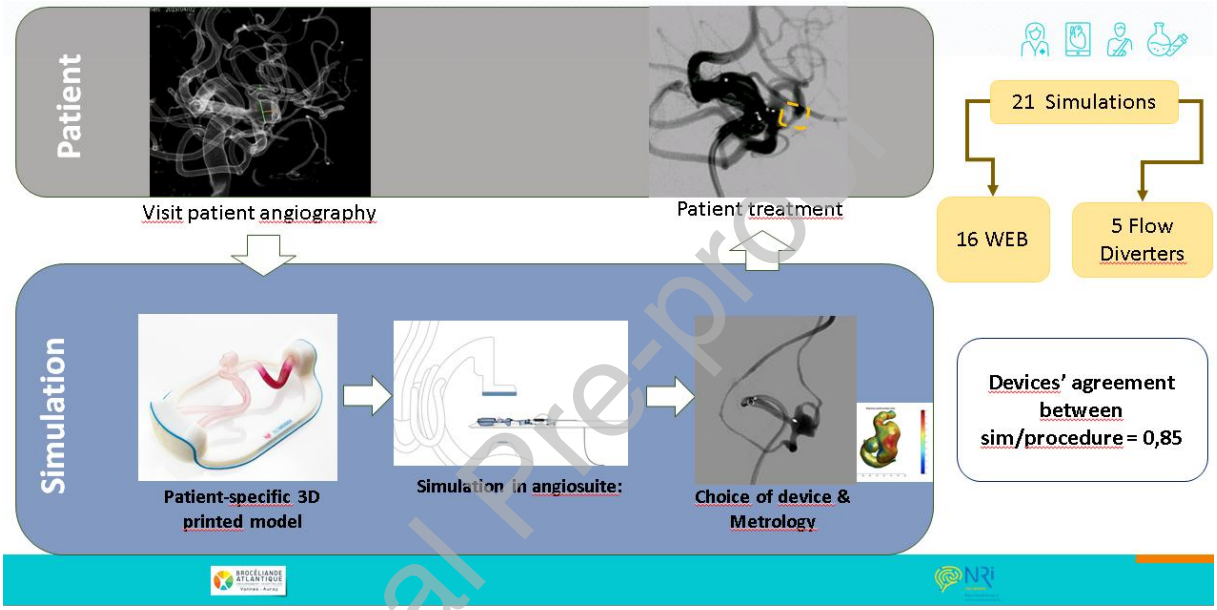
François EUGENE, MD, Service de Radiologie, Centre Hospitalier Universitaire de Rennes, France

HIGHLIGHTS:

- Challenging embolization of complex intracranial aneurysms, with advanced devices (WEB, flow diverters)
- Pre-operative rehearsals could be helpful for advanced device selection
- Patient-specific 3D-printed models bring haptic feedback and reliable model
- Implantation failure of advanced device and radiation dose of procedure could be reduced by EVIAS solution rehearsals

Graphical abstract

REHEARSALS USING PATIENT-SPECIFIC 3D-PRINTED ANEURYSM MODELS FOR SIMULATION OF ENDOVASCULAR EMBOLIZATION OF COMPLEX INTRACRANIAL ANEURYSMS: 3D SIM STUDY



ABSTRACT

Background: In neurovascular treatment planning, endovascular devices to manage complex intracranial aneurysms requiring intervention are often selected based on conventional measurements and interventional neuroradiologist experience. A recently developed technology allows a patient-specific 3D-printed model to mimic the navigation experience. The goal of this study was to assess the effect of pre-procedure 3D simulation on procedural and clinical outcomes for wide-neck aneurysm embolization.

Materials & Methods: In this unblinded, non-randomized, prospective, multicenter study conducted from November 18 through December 20, patients with complex intracranial aneurysms (neck > 4mm or ratio < 2 [1]) were treated by WEB or flow diverter stents (FDS). The primary endpoint was concordance between simulation and procedure, 3D-printed model accuracy as well as embolization outcomes including complications, procedure times, and radiation dose were also assessed. Secondary endpoint was to compare versus a retrospective WEB cohort.

Results : Twenty-one patients were treated, 76% of cases by WEB and 24% by FDS. Concordance between post-simulation and real procedure efficiency was 0.85 [0.69 – 1.00] for size device selection and 0.93 [0.79 – 1.00] for wall-apposition/aneurysm neck closure. Geometrical accuracy of the 3D-printed model showed a mean absolute shift of 0.11 mm. Two complications without major clinical impact were reported with a post-operative mRS similar to pre-procedure mRS for all patients.

Conclusions: Rehearsal using accurate 3D-printed patient-specific aneurysm models enabled optimization of embolization strategy, resulting in reduced procedure duration and cumulative fluoroscopy time which translated to reduced radiation exposure compared to procedures performed without simulation.

KEYWORDS : interventional neuroradiology, simulation, intracranial aneurysm, 3D-printed

INTRODUCTION

Endovascular device strategy for embolization of complex intracranial aneurysms including device selection, sizing and positioning is very dependent on the neurointerventionalist's experience and facilitated using 2D conventional measurements based on 3D rotational angiography. A family of endovascular devices based on flow diversion [2] or disruption [3,4] have been developed to address the difficulty of giant or wide-neck aneurysm embolization. These endovascular devices are challenging to use and need accurate preoperative planning to optimize sizing and landing areas and avoid corrective intervention as well as procedural and peri-procedural complications.

Computed preoperative simulations incorporating some finite elements [5] can help a neurointerventionalist in this purpose, and recent publications [6–8] emphasize the value of these computed simulation tools for flow diverter or disrupter endovascular devices.

However, computed simulation software does not address an important criterion of endovascular embolization which is haptic feedback linked to the handling of endovascular devices during challenging navigation, due to anatomy or to arterial rigidity, as well as during the intra-arterial or intrasaccular device delivery.

With advances in materials and technologies, in vitro simulation based on patient-specific models continues to improve, incorporating fluid dynamics or biomechanical data [9–12].

The use of 3D-printed patient-specific models of intracranial aneurysms enable the neurointerventionalist to plan and perform in vitro the endovascular embolization with the possibility to test different strategies with different sizes and landing zones for the embolization devices [13–15]. The patient can thus benefit from the increased confidence of the neurointerventionalist who will have already performed the in vitro endovascular intervention and integrated each step.

A recent publication reported results from 8 patients with intracranial aneurysms using patient-specific 3D aneurysm models before intervention with novel flow diverter stents (FDS) [16]. Aneurysm structures and features were found to be similar between the 3D models and patients. In addition, simulation was postulated to potentially increase operator confidence and enhance patient outcomes.

In this multicenter open prospective study of patients with wide-neck intracranial aneurysms, we compared the concordance in device selection for adequate wall-apposition/aneurysm neck closure for patients having an in vitro simulation prior to the real procedure. Accuracy of 3D-printed models, embolization outcomes, including wall-apposition/aneurysm neck closure status, per and peri-procedural complications, procedure time and radiation dose, were also investigated.

METHODS

Patient selection: For inclusion in the study, a patient must have presented with a complex wide-neck intracranial aneurysm (neck > 4mm or ratio < 2) requiring intervention to manage

risk of rupture. A multidisciplinary meeting including neurosurgeons, neurointerventionalists and neurologists validated the indication of endovascular preventive treatment. Informed consent for participation in the study was obtained from each patient. The study design was reviewed and approved by the Institutional Ethics Committees of our institutions.

Visit 3D rotational angiography (3DRA): Prior to the endovascular embolization procedure, a diagnostic cerebral angiography of the patient aneurysm, including a 3DRA (voxel = 235 µm3 – matrix = 384), was performed, with 18mL of iodine contrast at 3mL/s, without saline dilution. The 3D volume rendering model (VR) obtained from this visit 3DRA was used first to provide the reference 3D patient-specific model for the metrology assessment (first ten patients) and secondly to print the patient-specific 3D-printed aneurysm model (see paragraph below) for in-vitro simulation.

Metrology: The purpose of metrology was to provide a geometric evaluation of the accuracy of the patient-specific 3D-printed model of the first ten patients. The comparison was performed between the reference 3D VR model obtained from the visit 3DRA and the 3D VR model obtained from the 3DRA of the patient-specific 3D-printed model, with same patients'3DRA injection properties.

This comparison consisted in registration of the two models using an iterative closest point algorithm (ICP) with a least-square matching method. After registration of meshes, each point of the model (obtained from the 3D-model printed 3DRA) was projected on the surface defined by the reference (obtained from the visit 3DRA) in order to calculate the point-to-surface distances [17,18]. This comparison was processed for the first ten patients on the entire set of 5000 points per aneurysm model. The mean, 95% confidence interval (CI), minimum, and maximum were calculated. These data were secondarily separated in two anatomical areas: 1) saccular aneurysm 2) parent and daughter arteries.

Following the registration of the 3DRA VR models, 3D specific points were manually selected on adequate incidences for both models (registered in the same referential) in order to calculate aneurysm-specific geometrical characteristics: maximum dome height, aneurysm neck width as well as the diameters of the parent artery and daughter arteries at the bifurcation (Figure 1). Distance shifts between these measurements for both models were then calculated (mean, standard deviation, absolute maximum).

Patient-specific 3D-printed aneurysm models: Based on images acquired from visit 3DRA, a 3D-printed patient-specific model was produced for the EVIAS system (Biomodex, Paris, France). The segmentation of visit 3DRA was performed with an FDA-cleared and CE-marked system. The printing process merged soft and rigid materials to produce a realistic mechanical behavior of the 3D-printed models. 3D-printed anatomies are made with various flexible photopolymers which allow control of the pliability of the target area, providing precise haptic feedback. The accuracy of the printer was up to 200 µm [16]. Patient-specific 3D models were printed with a Stratatys Multijet printer allowing to lay down material with different biomechanical data including Young modulus. These models were printed according to a patented technology that optimize material distribution in order to fit with biomechanical

datas as kinematic constraint and loading conditions according to physiologic values of a healthy artery based on literature [19]. For example, in the intra-petrous carotid segment of the models, the allocated local deformation was null.

Moreover, a blood-mimicking fluid is designed, in combination with a hydraulic system, to simulate blood flow dynamics and to replicate real-world density, viscosity, and body temperature.

Simulation : In vitro simulations were performed by 3 senior neurointerventionalists with 5 to 10 years' experience each with intrasaccular flow disrupter device [Woven EndoBridge (WEB), Microvention, Tustin, CA] or FDS [Pipeline; Medtronic, Dublin, Ireland] procedures. The same practitioner performed both simulation and procedure for a given aneurysm. Device sizes were estimated based on the 3D VR acquired from the patient-models during the simulations. For each simulation the neurointerventionalist had a full portfolio of sizes of WEB and FDS available, to test different sizes or landing zones, if necessary. Once all the simulations were performed, the neurointerventionalist had to select the appropriate device in terms of wall-apposition/aneurysm neck closure and without device overhanging.

All simulations and procedures were performed on biplane Allura (Philips, Eindhoven, Netherlands). (Figure 2)

Procedure : As the EVIAS in vitro simulation system is not approved for endovascular device selection, the study was designed to allow the neurointerventionalist, according to his experience, to choose a different strategy or a different size of device during the real procedure compared to the one selected at the end of the in vitro simulation. Moreover, if the simulation failed with a WEB or a FDS, the neurointerventionalist was allowed to attempt with this type of device during the real procedure according to his experience. Similarly to the simulation the appropriate device was selected according to an optimal wall-apposition/neck closure without device overhanging.

Data collection : Data was collected on demographic (age, sex, smoking status, pre procedural modified Ranking Score) and aneurysm characteristics (location, dome width and height, neck width, dome / neck ratio) (Table 1).

The following measurements were collected: times between visit angiography, in vitro simulation, and real procedure, in vitro simulation and real procedure duration, fluoroscopy time, radiation dose, embolization strategy, number of devices tested / implantation failure rate, immediate complication rate after the procedure (e.g., ischemic stroke, neck embolus, aneurysm perforation), embolization efficiency as measured by wall-apposition (correct or incorrect) for FDS or aneurysmal neck closure (complete, incomplete, residual neck) for WEB, morbidity (mRS > 2 at 3 months), and mortality.

In vitro simulation/procedure duration was measured from the time between the first and last series. The first series was acquired after the positioning of the long sheath and the intermediate catheters in the internal carotid or the vertebral arteries. The end of the procedure was considered the final control run. This calculation was intended to eliminate the time

required for access, from the femoral to the internal carotid/vertebral artery, on which the application of the simulation does not have an impact.

Cohort data : Fluoroscopy time, radiation dose and implantation failure rate were collected retrospectively (unpublished raw data) from 2012 and 2018 from 55 previous WEB cases without simulation at one center using the same imaging equipment (biplane ALLURA, Philips, Eindhoven, Netherlands).

Outcomes evaluated: The primary endpoint was evaluation of agreement between simulation and procedure as assessed by choice of implantable devices (size, positioning). Secondary endpoints included rate of complications, mortality rate, procedure times, irradiation dose, and effectiveness of procedure. The concordance between visit angiography, in vitro simulation and real procedure was examined as described below :

1. Concordance between the device selected following the in vitro simulation and the device implanted during the real procedure
2. The concordance between wall-apposition/aneurysm neck closure at post-simulation and post-procedure.
3. The concordance between device (WEB only) selection from conventional measurements planned after visit angiography and implanted during procedure
4. The concordance between device selection (WEB only) from conventional measurements planned after visit angiography and post-simulation.

Statistical analysis: To describe the data, quantitative results were expressed as mean ± standard deviation (SD) or median and interquartile range (IQR) and qualitative results were expressed in numbers (%). The concordance between in vitro simulation and real procedure was assessed using Cohen's Kappa coefficient with a confidence interval of 95%, with coding variables : device selected (concordances 1,3,4) or wall-apposition/aneurysm neck closure (concordance 2).

All statistical tests had a significance level of 0.05. The statistical analyses were performed using SAS software, v.9.4® (SAS Institute, Cary, NC, USA).

RESULTS

Patients were enrolled in this unblinded, multicenter, non-randomized, prospective study from November 2018 through December 2020, in two university hospitals. Of the 22 patients screened, 21 patients met the study criteria and were treated, and 1 subject was not treated due to a pre-implantation endovascular complication. The mean age (SD) was 56 (10) years, and most patients were women (67%) (Table 1). Half of the patients were current smokers, and 81% had an mRS of 0.

Aneurysms were localized mainly at the internal carotid artery (50%) and at the basilar tip (23%). Aneurysms were predominantly of the saccular morphology. At the diagnostic patient angiography the mean (SD) dome width was 7.59 (1.44) mm, neck width was 5.25 (1.16) mm and dome to neck ratio was 1.63 (0.56).

Table 1. Baseline patient and aneurysm characteristics

Characteristic	**Value**
Age	
Mean ± SD, years	56 ± 10
Sex	
Female, n (%)	14 (66.7%)
mRS score pre-procedure	
0	17 (81.0%)
1	3 (14.3%)
2	1 (4.5%)
Aneurysm Localization	
Internal Carotid	
Subclinoid	1 (4.5%)
Paraophthalmic	1 (4.5%)
Posterior Communicating	7 (31.7%)
Anterior Choroidal	2 (9%)
Anterior Cerebral	
Anterior Communicating	1 (4.5%)
At Anterior Communication Junction	2 (9%)
Middle Cerebral	
Bifurcation	1 (4.5%)
Basilar	
Basilar Tip	5 (22.7%)
Visit (Diagnostic Patient Angiography)	
Size of aneurysm (VR model from visit 3DRA)	
Dome to neck ratio	1.63 ± 0.56
Dome width, mm	7.59 ± 1.44
Dome height, mm	7.41 ± 2.61
Neck width, mm	5.25 ± 1.16
Device	
WEB	15
FDS	5

Notes: Qualitative results are expressed as: total number (missing data) and number (%) for each modality. Quantitative results are expressed as : mean ± standard deviation (median).

Metrology

For the aneurysm, point-surfaces calculation showed a mean absolute shift of 0.11 mm; 95% of shifts were between -0.22 and 0.36 mm. The absolute maximum shift was 0.75 mm for the aneurysm and 1.04 mm for parent artery and daughter arteries.

For aneurysm-specific geometrical characteristics, shifts between 3D VR models are presented in Table 2. An example of data obtained for patient 008 after registration of the models by ICP algorithm is shown in Fig 1.

Table 2 : Shifts (mm) between geometrical aneurysmal dimension from VR models obtained from 3DRA visit and 3DRA of the 3D-printed patient-specific model.

3DRA visit/ 3DRA printed model	Dome height (mm)	Aneurysm width (mm)	Neck Width (mm)	Parent artery (mm)	Daughter artery 1 (mm)	Daughter artery 2 (mm)
Mean	-0.05	-0.05	-0.09	0.09	0.08	0.12
SD	0.25	0.21	0.18	0.16	0.27	0.16
Absolute Maximum	0.37	0.5	0.40	0.39	0.53	0.32

Procedural and clinical outcomes

At the visit patient angiography, 16 (76.2%) of cases were selected for treatment by WEB, and 5 (23.8%) by FDS.

The concordance, defined by the kappa coefficient (K [95% CI]), between post-simulation and device implanted during the real procedure was 0.85 [0.69 – 1.00] and 0.93 [0.79 – 1.00] for the device selection and the wall-apposition/aneurysm neck closure, respectively (Table - supplementary material)

For the WEB devices:

- K between the device selected from conventional measurement at visit diagnostic angiography and the device implanted during the real procedure was 0.62 [0.15 – 1.00].
- K between the device selected from conventional measurement at visit diagnostic angiography and the device selected post-simulation was 0.47 [0.22 – 0.72].

The percentage of implant failure during the real procedure, whereas in vitro simulation was possible, was reported for 9.5% of the cases (2 patients). For the first case, the neurointerventionalist failed to pass the intermediate catheter through the origin of the ophthalmic artery during the real procedure whereas this issue was considered as not relevant before the simulation and the ophthalmic artery was not printed on the model. For the second case, there was a true mismatch between the device selected following simulation (WEB SL 7x4 mm – complete aneurysm neck closure) and the device chosen during the real procedure (overhanging of the simulation selected device during the real procedure with decision to downsize for a WEB SL 6x4 mm resulting in a residual neck closure).

It must be noted that for one patient, there was a strategy failure during the simulation (failure of positioning of 3 different sizes of WEB), but the neuroradiologist, based on his personal experience, decided to try to implant two different sizes of WEB during the real procedure resulting in implant failure for both and strategy conversion for coiling with remodeling.

The mean number of devices tested was 2.2 per simulation and 1.2 per procedure. The mean (SD) X-ray dose (mGy.cm2) and the mean (SD) X-ray duration (min) were reported for simulation, real procedure and historic cohort (55 patients) in Table 3. Mean (SD) delay (days) between simulation and procedure was 17 (51) days.

Table 3. **Procedural and Clinical Outcomes**

	In Vitro Simulation	**Procedure**	**R WEB Cohort Procedure**
Radiation dose, mGy.cm2	5459.0 ± 10412	150 423 ± 64 590	180 090 ± 75 008
Cumulative fluoroscopy time, min	16.95 ± 10.07	23.05 ± 11.34	30.5 ± 20.4
Number of devices tested, mean	2.2 (Per simulation)	1.2 (Per procedure)	1.3 (Per procedure)
% of implantation failure	1/21 (4,8%)	2/21 (9,5%)	14/55 (25,4%)
Time			
Duration between time guide catheter appropriately positioned and time microcatheter appropriately positioned (i.e., time of catheterization of aneurysm), min	11.62 ± 7.79	18.57 ± 10.25	N/A
Duration between time microcatheter appropriately positioned and time procedure ended (i.e., implantation of devices), min	37.71 ± 21.33	29.43 ± 13.53	N/A
Total procedure duration, min	56.52 ± 24.52	64.86 ± 19.77	N/A
Delay between visit and simulation, days	60.14 ± 52.77		N/A
Delay between visit and procedure, days	76.67 ± 73.57		N/A
Delay between simulation and procedure, days	16.52 ± 51.67		N/A

Safety

The mean mRS post-procedure was identical to the mean mRS pre-procedure. Complications included: 1 post-procedure minor stroke of a top basilar aneurysm with no clinical significance; and 1 peri-procedure ruptured aneurysm with no clinical significance (minor SAH).

DISCUSSION

This study on a small number of patients underlines the potential of in vitro patient-specific simulations with the EVIAS system for optimal preoperative planning. The results showed a potential improvement in term of implantation failure (9.5% post-simulation vs 25.5 in the historic cohort, p = 0,34) adequate device selection, radiation dose and cumulative fluoroscopy duration compared to an historic cohort in which device selection was based on conventional measurements.

In this study, concordance was considered high in device selection and wall-apposition/aneurysm neck closure efficiency between post-simulation and real procedure which indicated that the 3D models reliably reproduced the aneurysm environment allowing device selection consistent with patient anatomy. As in previous studies ([11] - [20]), we evaluated the anatomical accuracy of EVIAS 3D patient–specific printed models (integrating biomechanical data), regarding aneurysm and parent vessels geometric characteristics, validating that they can be used safely for preoperative planning.

Furthermore, low concordance between WEB device selection pre-simulation (based on conventional measurements) and post-simulation indicated that experienced interventionalists derived benefit from simulation prior to performing a complex endovascular intracranial intervention. Other recent studies report the necessity of new technologies to optimize FDS or WEB selection by using software based on biomechanical data or aneurysm volume calculation ([21] - [7]) compared to device selection based only on operator experience with conventional measurements.

For example, virtual simulation software, e.g., Sim&Size (Sim&Cure, France) can be utilized to suggest optimal sizing and display the potential degree of wall apposition. In a retrospective study of 189 patients, interventions with the Pipeline Flex Embolization Device using software assistance were associated with fewer corrective procedures, shorter procedure duration, and lower radiation dose [22]. A multicenter study of the same simulation software with the WEB in 186 aneurysms found similar results [8] with an improvement in implantation failure (33% vs 7%). These results are quite similar to ours where an implantation failure rate of 9.5% vs 25% was found.

In vitro simulation using EVIAS technology, in contrast, allow multiple rehearsals of the whole procedure simulation (even access catheter navigability and stability) on an accurate patient-specific anatomy as well as haptic feedback similar to the real procedure.

Our study has several limitations. First, the design of this study does not allow an adequate evaluation of clinical outcome for benefit from multiple rehearsals in vitro-simulation. Indeed, the occurrence of complications during embolization procedure is quite low and the number of patients to include to prove this hypothesis with sufficient power would have been too high in the first patient evaluation of this technology. Second, our study was based in only 2 centers with a small number of practitioners and patients, suggesting that our results have to be interpreted with caution and confirmed by a larger randomized study.

One other limitation of our study was the absence of coiling embolization strategies; however even if 3D in vitro simulation had been studied for microcatheter shaping in coiling embolization technique ([13]-[23]), we decided to evaluate only FDS and WEB devices over coils because device deployment was less operator dependent. The ability of the EVIAS system to properly plan coiling embolization strategy needs to be evaluated. We also choose to evaluated the wall-apposition/aneurysm neck closure instead of Roy Raymond score [24] and Web Occlusion Score [25] in absence of spontaneous thrombosis in simulation and absence of immediate complete occlusion by the end of FDS procedures.

One of the drawbacks of ex-vitro endovascular simulations remains the availabilities of the angiography suite and the neuroradiologist to perform the rehearsals before the real procedure. Indeed, even if the EVIAS system allows a rapid installation with the possibility to quickly change 3D patient-specific cartridges, the whole simulation procedure is time consuming, necessitating integration of this pre-operative planning in the angiography suite workflow. For each complex case, the benefits of realistic rehearsal and training versus cost and time to procedure could be assessed as part of the intervention strategy.

Another drawbacks considerer the medico-economic impact : the cost of patients' specific cartridges were supported by hospitals innovation funds. WEB portfolio for simulations were obtained by combination of devices from our hospital expired, non-human use devices from laboratories, and re-sterilize after patients implantation failure. FDS were obtained with laboratory partnership. Finally, our study didn't demonstrate the ability to reduce the number of devices attempted to implant in procedure, and the cost of its.

CONCLUSION

In summary, this prospective study found that rehearsal using a patient-specific 3D aneurysm simulation prior to endovascular embolization of complex unruptured intracranial aneurysms enabled optimization of treatment device and approach, resulting in reduced procedure duration and thus lower radiation exposure for the patient.

REFERENCES

1 Hendricks BK, Yoon JS, Yaeger K, *et al.* Wide-neck aneurysms: systematic review of the neurosurgical literature with a focus on definition and clinical implications. *J Neurosurg* 2020;**133**:159–65. doi:10.3171/2019.3.jns183160

2 Fiorella D, Kelly ME, Albuquerque FC, *et al.* CURATIVE RECONSTRUCTION OF A GIANT MIDBASILAR TRUNK ANEURYSM WITH THE PIPELINE EMBOLIZATION DEVICE. *Neurosurgery* 2009;**64**:212–7. doi:10.1227/01.neu.0000337576.98984.e4

3 Pierot L, Liebig T, Sychra V, *et al.* Intrasaccular Flow-Disruption Treatment of Intracranial Aneurysms: Preliminary Results of a Multicenter Clinical Study. *Am J Neuroradiol* 2012;**33**:1232–8. doi:10.3174/ajnr.a3191

4 Asnafi S, Rouchaud A, Pierot L, *et al.* Efficacy and Safety of the Woven EndoBridge (WEB) Device for the Treatment of Intracranial Aneurysms: A Systematic Review and Meta-Analysis. *Am J Neuroradiol* 2016;**37**:2287–92. doi:10.3174/ajnr.a4900

5 Ma D, Dumont TM, Kosukegawa H, *et al.* High Fidelity Virtual Stenting (HiFiVS) for Intracranial Aneurysm Flow Diversion: In Vitro and In Silico. *Ann Biomed Eng* 2013;**41**:2143–56. doi:10.1007/s10439-013-0808-4

6 Bouillot P, Brina O, Yilmaz H, *et al.* Virtual-versus-Real Implantation of Flow Diverters: Clinical Potential and Influence of Vascular Geometry. *Am J Neuroradiol* 2016;**37**:2079–86. doi:10.3174/ajnr.a4845

7 Ospel JM, Gascou G, Costalat V, *et al.* Comparison of Pipeline Embolization Device Sizing Based on Conventional 2D Measurements and Virtual Simulation Using the Sim&Size Software: An Agreement Study. *American Journal of Neuroradiology* Published Online First: 2019. doi:10.3174/ajnr.A5973

8 Cagnazzo F, Marnat G, Ferreira I, *et al.* Comparison of Woven EndoBridge device sizing with conventional measurements and virtual simulation using the Sim&Size software: a multicenter experience. *J Neurointerv Surg* 2020;:neurintsurg-2020-017060. doi:10.1136/neurintsurg-2020-017060

9 Khan I, Kelly P, Singer R. Prototyping of cerebral vasculature physical models. *Surg Neurology Int* 2014;**5**:11. doi:10.4103/2152-7806.125858

10 Chivukula VK, Levitt MR, Clark A, *et al.* Reconstructing patient-specific cerebral aneurysm vasculature for in vitro investigations and treatment efficacy assessments. *J Clin Neurosci* 2019;**61**:153–9. doi:10.1016/j.jocn.2018.10.103

11 Anderson JR, Thompson WL, Alkattan AK, *et al.* Three-dimensional printing of anatomically accurate, patient specific intracranial aneurysm models. *J Neurointerv Surg* 2016;**8**:517. doi:10.1136/neurintsurg-2015-011686

12 Kaneko N, Mashiko T, Namba K, *et al.* A patient-specific intracranial aneurysm model with endothelial lining: a novel in vitro approach to bridge the gap between biology and flow dynamics. *J Neurointerv Surg* 2018;**10**:306. doi:10.1136/neurintsurg-2017-013087

13 Ishibashi T, Takao H, Suzuki T, *et al.* Tailor-made shaping of microcatheters using three-dimensional printed vessel models for endovascular coil embolization. *Comput Biol Med* 2016;**77**:59–63. doi:10.1016/j.compbiomed.2016.07.005

14 KONO K, SHINTANI A, OKADA H, *et al.* Preoperative Simulations of Endovascular Treatment for a Cerebral Aneurysm Using a Patient-Specific Vascular Silicone Model. *Neurol Med-chir* 2013;**53**:347–51. doi:10.2176/nmc.53.347

15 Nawka MT, Hanning U, Guerreiro H, *et al.* Feasibility of a customizable training environment for neurointerventional skills assessment. *Plos One* 2020;**15**:e0238952. doi:10.1371/journal.pone.0238952

16 Yamaki VN, Cancelliere NM, Nicholson P, *et al.* Biomodex patient-specific brain aneurysm models: the value of simulation for first in-human experiences using new devices and robotics. *Journal of NeuroInterventional Surgery* Published Online First: 2020. doi:10.1136/neurintsurg-2020-015990

17 Mitton D, Landry C, Véron S, *et al.* 3D reconstruction method from biplanar radiography using non-stereocorresponding points and elastic deformable meshes. *Medical Biological Eng Comput* 2000;**38**:133–9. doi:10.1007/bf02344767

18 Bras AL, Laporte S, Bousson V, *et al.* 3D reconstruction of the proximal femur with low-dose digital stereoradiography. *Comput Aided Surg* 2010;9:51–7. doi:10.3109/10929080400018122

19 Riley WA, Barnes RW, Evans GW, *et al.* Ultrasonic measurement of the elastic modulus of the common carotid artery. The Atherosclerosis Risk in Communities (ARIC) Study. *Stroke* 2018;**23**:952–6. doi:10.1161/01.str.23.7.952

20 Frölich AMJ, Spallek J, Brehmer L, *et al.* 3D Printing of Intracranial Aneurysms Using Fused Deposition Modeling Offers Highly Accurate Replications. *American Journal of Neuroradiology* 2016;**37**:120–4. doi:10.3174/ajnr.a4486

21 Shah KA, White TG, Teron I, *et al.* Volume-based sizing of the Woven EndoBridge (WEB) device: A preliminary assessment of a novel method for device size selection. *Interv Neuroradiol* 2021;:159101992098768. doi:10.1177/1591019920987685

22 Piergallini L, Cagnazzo F, Conte G, *et al.* Virtual simulation with Sim&Size software for Pipeline Flex Embolization: evaluation of the technical and clinical impact. *J Neurointerv Surg* 2020;**12**:968–73. doi:10.1136/neurintsurg-2020-015813

23 Namba K, Higaki A, Kaneko N, *et al.* Microcatheter Shaping for Intracranial Aneurysm Coiling Using the 3-Dimensional Printing Rapid Prototyping Technology: Preliminary Result in the First 10 Consecutive Cases. *World Neurosurg* 2015;**84**:178–86. doi:10.1016/j.wneu.2015.03.006

24 Roy D, Milot G, Raymond J. Endovascular Treatment of Unruptured Aneurysms. *Stroke* 2001;**32**:1998–2004. doi:10.1161/hs0901.095600

25 Fiorella D, Arthur A, Byrne J, *et al.* Interobserver variability in the assessment of aneurysm occlusion with the WEB aneurysm embolization system. *J Neurointerv Surg* 2015;**7**:591. doi:10.1136/neurintsurg-2014-011251

GLOSSARY

Real Procedure = embolization in real on patient

In vitro Simulation = 3D printed model in vitro simulation

Visit = diagnostic patient angiography

Embolization = in sim or in procedure

Strategy = choosen device

mRS = modified Rankin Scale

WEB = Wowen EndoBridge

FDS = Flow Diverter Stent

3D RA = 3D-rotational angiography

3D VR = 3D volume rendering

DSA = digital substracted angiography

ICP = iterative closest point algorithm

Acknowledgments : CHU Rennes ; Microvention ; Medtronic ; Biomodex

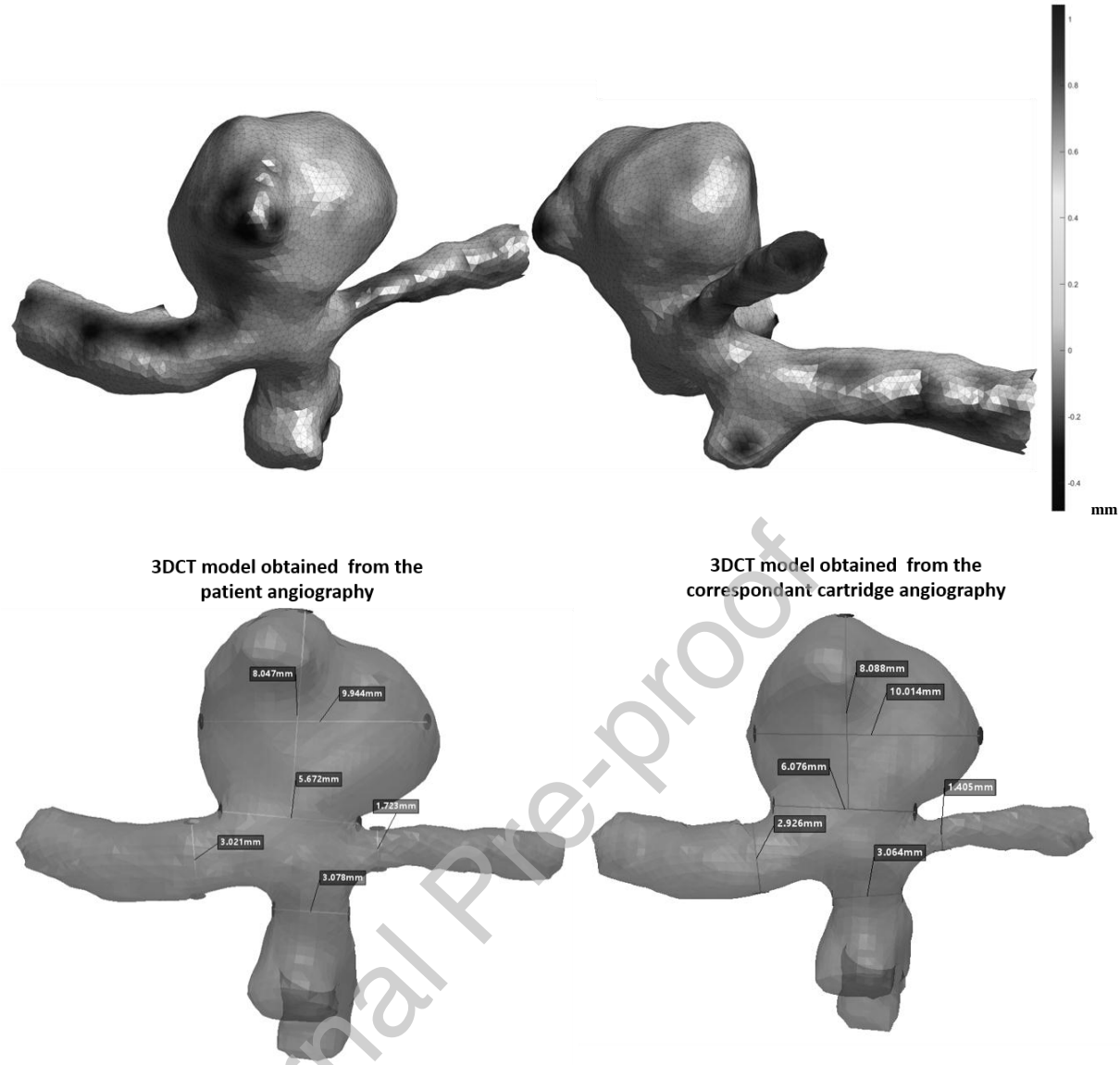
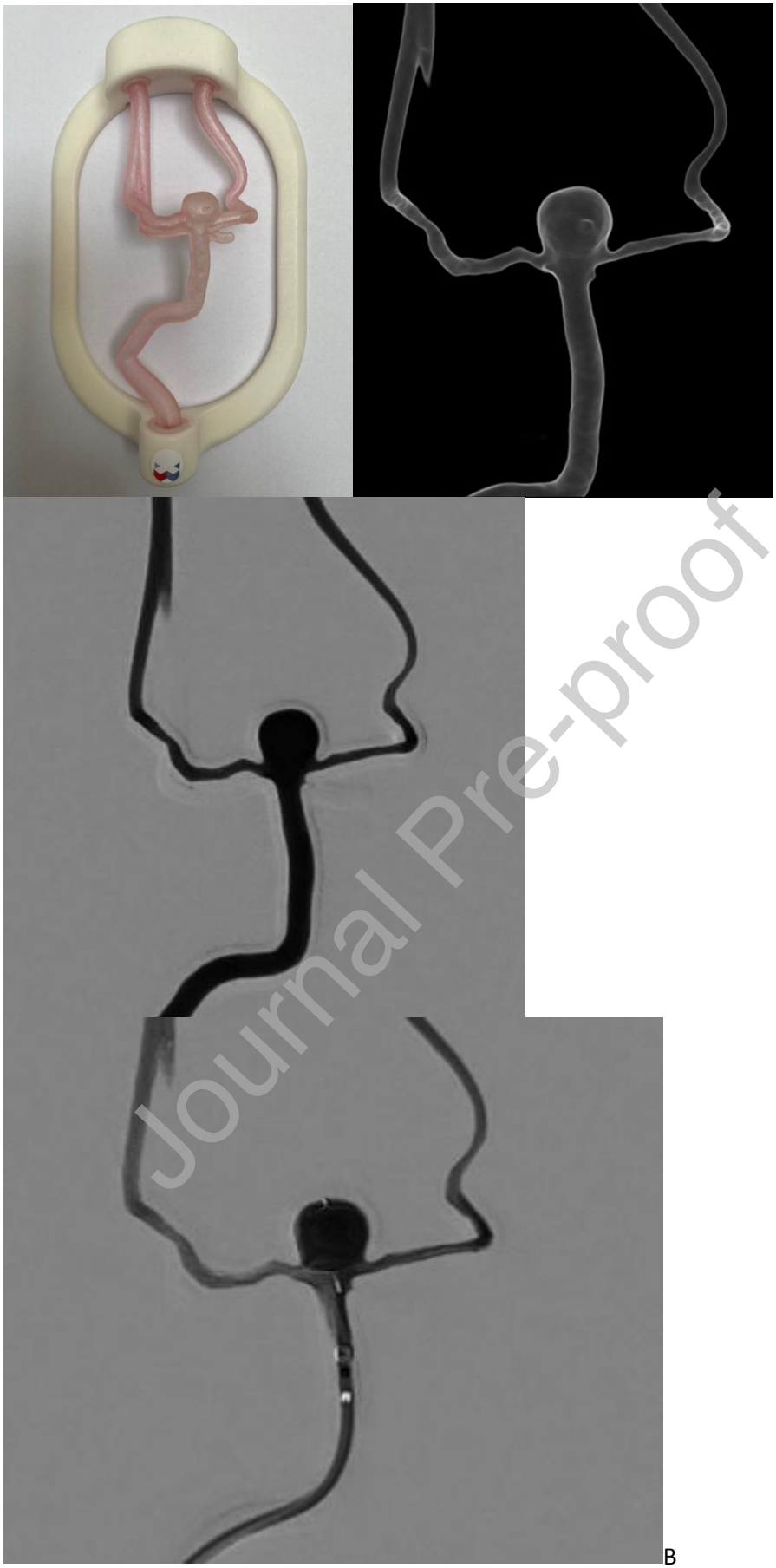
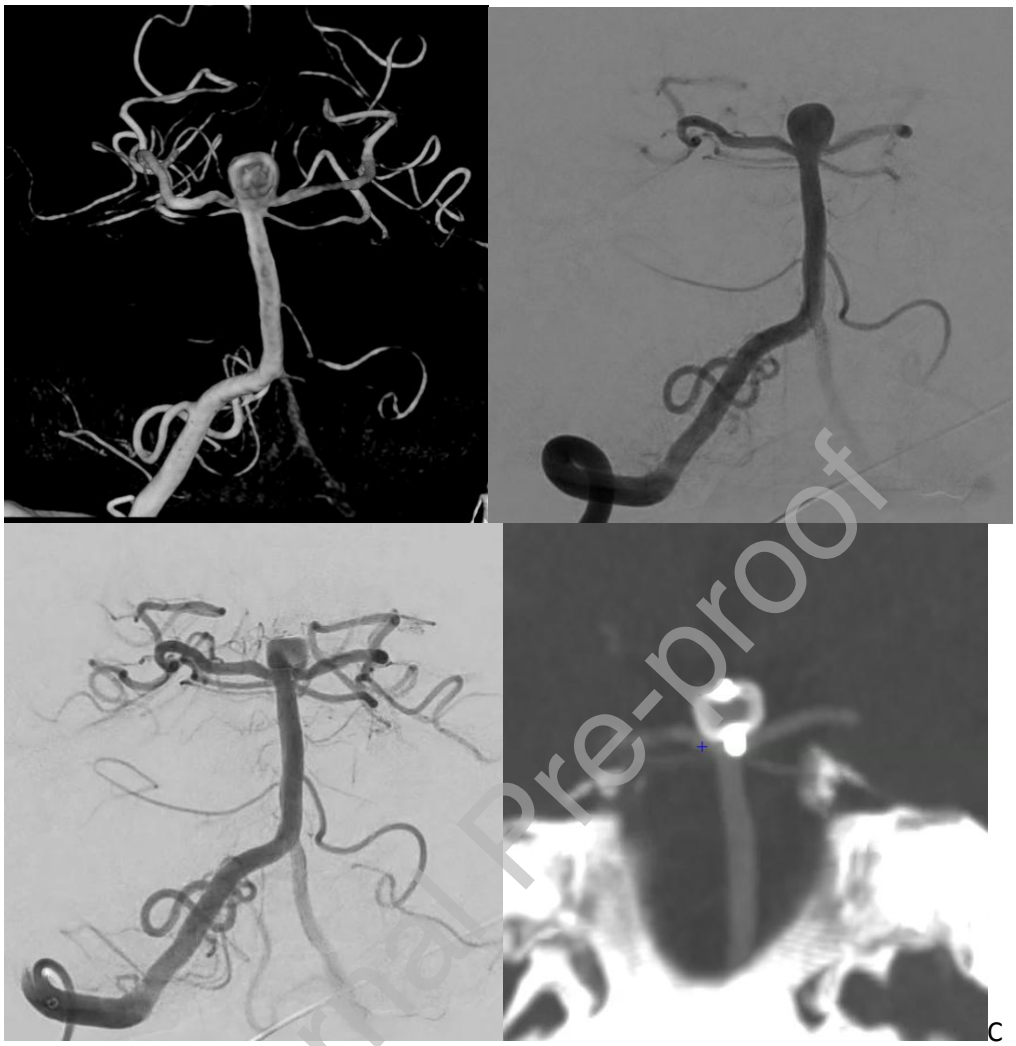


Figure 1 : Registration of the 3DRA VR models of patient 008, 3D specific points were manually selected on adequate incidences for both models (registered in the same referential) in order to calculate aneurism specific geometrical characteristic's: maximal dome height, aneurysm neck width as well as the diameters of the parent artery and daughter arteries at the bifurcation

A



B



C

Fig 2. (A) Simulation with aneurysm model set-up in angiosuite room. (B) Cartridge of 3D-printed model (upper) ; surface rendered 3D-rotational angiogram (3DRA) (middle) and DSA (middle) demonstrating the 3D-printed model in working projection for navigation in a 7.5mm top basilar intracranial aneuvrysm ; DSA in working projection (bottom) showing WEB SL 9x4 position in 3D-printed model with complete aneuvrysm neck closure.

(C) Surface rendered 3D-rotational angiogram (3DRA) (left upper) and DSA demonstrating (right upper) working projection for navigation in his 7.5mm top basilar IA during procedure in patient ; DSA in working projection (left bottom) showing WEB SL 9x4 position in 3D-printed model with complete aneuvrysm neck closure and MIP rendered CTangiogram at day 1 (right bottom) showing complete aneuvrysm neck closure.