Acta Neurochirurgica (2024) 166:294
https://doi.org/10.1007/s00701-024-06182-z

ORIGINAL ARTICLE

Complex intracranial aneurysms: a DELPHI study to define associated characteristics

Francesco Diana[1,2,43] · Michele Romoli[3] · Eytan Raz[4] · Ronit Agid[5] · Felipe C. Albuquerque[6] · Adam S. Arthur[7] · Jürgen Beck[8] · Jerome Berge[9] · Hieronymus D. Boogaarts[10] · Jan-Karl Burkhardt[11] · Marco Cenzato[12] · René Chapot[13] · Fady T. Charbel[14] · Hubert Desal[15] · Giuseppe Esposito[16] · Johanna T. Fifi[17] · Stefan Florian[18] · Andreas Gruber[19] · Ameer E. Hassan[20] · Pascal Jabbour[21] · Ashutosh P. Jadhav[6] · Miikka Korja[22] · Timo Krings[23] · Giuseppe Lanzino[24] · Torstein R. Meling[25] · Jaques Morcos[26] · Pascal J. Mosimann[23] · Erez Nossek[27] · Vitor Mendes Pereira[28] · Andreas Raabe[29] · Luca Regli[16] · Veit Rohde[30] · Adnan H. Siddiqui[31] · Rokuya Tanikawa[32] · Stavropoula I. Tjoumakaris[33] · Alejandro Tomasello[1,2] · Peter Vajkoczy[34] · Luca Valvassori[35] · Nikolay Velinov[36] · Daniel Walsh[37] · Henry Woo[38] · Bin Xu[39] · Shinichi Yoshimura[40] · Wim H. van Zwam[41] · Simone Peschillo[42]

Received: 15 April 2024 / Accepted: 2 July 2024

Abstract
Purpose Intracranial aneurysms present significant health risks, as their rupture leads to subarachnoid haemorrhage, which in turn has high morbidity and mortality rates. There are several elements affecting the complexity of an intracranial aneurysm. However, criteria for defining a complex intracranial aneurysm (CIA) in open surgery and endovascular treatment could differ, and actually there is no consensus on the definition of a "complex" aneurysm. This DELPHI study aims to assess consensus on variables defining a CIA.

Methods An international panel of 50 members, representing various specialties, was recruited to define CIAs through a three-round Delphi process. The panelists participated in surveys with Likert scale responses and open-ended questions. Consensus criteria were established to determine CIA variables, and statistical analysis evaluated consensus and stability.

Results In open surgery, CIAs were defined by fusiform or blister-like shape, dissecting aetiology, giant size (≥ 25 mm), broad neck encasing parent arteries, extensive neck surface, wall calcification, intraluminal thrombus, collateral branch from the sac, location (AICA, SCA, basilar), vasospasm context, and planned bypass (EC-IC or IC-IC). For endovascular treatment, CIAs included giant size, very wide neck (dome/neck ratio ≤ 1:1), and collateral branch from the sac.

Conclusions The definition of aneurysm complexity varies by treatment modality. Since elements related to complexity differ between open surgery and endovascular treatment, these consensus criteria of CIAs could even guide in selecting the best treatment approach.

Keywords Brain aneurysm · SAH · Clipping · Coiling · DELPHI

Abbreviations

AICA	Anterior-inferior cerebellar artery
CIA	Complex intracranial aneurysm
EC	External carotid
IC	Internal carotid
MCA	Middle cerebral artery
SCA	Superior cerebellar artery

Extended author information available on the last page of the article

Introduction

Intracranial aneurysms are the main cause of subarachnoid hemorrhage and, when ruptured, are associated with high rates of morbidity and mortality. Following the advancements in the endovascular techniques in recent years, most intracranial aneurysms can nowadays be treated endovascularly, while open surgical cases have followingly been limited to ever more complex cases. [17]. Scientific literature reports that complex intracranial aneurysms (CIA) pose unique diagnostic and therapeutic challenges, [28] but there is not a clear definition of CIA. This ambiguity in defining the complexity of intracranial aneurysms results in a heterogeneous decision-making process.[2, 7, 9, 12, 13, 20, 23, 27, 29–31]. Moreover, criteria for defining a CIA in open surgery and endovascular treatment could differ, and the difference could even guide treatment approaches.

To address this challenge, we used a DELPHI approach to assess consensus on variables to define a CIA among a panel of experienced experts in both neurosurgical and neuroendovascular fields. Specifically, we utilized a modified Delphi process to identify areas of existing consensus rather than to achieve new consensus.

Materials and methods

Expert panel selection

An international panel of 54 operators, operating in high-volume centers (treating over 100 aneurysms per year), were identified from among some of the most experienced neurosurgeons and neurointerventionalists in Europe, North and South America, and Asia (Supplement Table 1). The protocol was approved by the local internal regulatory board (IRB), and all procedures were followed in accordance with the ethical standards of the IRB and the Helsinki Declaration of 1975. An email invitation and information sheet were sent to all potential participants, who then had the option to assent to participation or decline. Fifty participants consented prior to answering the survey questions. Each panelist answered questions related to his own field.

Delphi study design

We conducted a three-round Delphi process, with all rounds based on surveys (Table 1). All surveys were completed anonymously. In Round 1, we presented a binary closed-ended question (Yes or No), which included clinical and neuroradiological considerations. The aim was to select variables useful in defining a CIA. Structured statements were constructed using a Likert scale based on the Grading of Recommendations Assessment, Development, and Evaluation paradigm [16] and the recommended Delphi approach. [4] Open-ended questions were also included to generate ideas and variables for Round 2.

All statements were developed and agreed upon by three authors (SP, FD, MR). Results of round 1 were summarized and feedback to the participants before Round 2. This feedback allowed the panelists to reconsider their positions considering the collective opinions, as is standard in Delphi studies. Round 2 incorporated the collective results from Round 1 and a structured survey comprising statements that required Likert scale responses (19 items). It excluded variables that did not achieve an agreement in Round 1. In this phase, participants were asked to provide their viewpoints on the definition of a CIA from both surgical and endovascular perspectives. Experts could only participate in Rounds 2 and 3 if they had completed the previous round.

Participants could indicate disagreement (scores 1–2), remain neutral (score 3), or express agreement (scores 4–5) with the statements. Round 3 included statements that did not meet the consensus criteria or did not exhibit stability between rounds. These were re-evaluated for final consensus using a 3-point Likert scale in the concluding survey.

Anonymization was guaranteed by automatically assigning an ID to the survey response, with linkage implemented to compare the evolution of responses across the rounds. Adherence was ensured through email alerts during the steps of the Delphi process.

Consensus criteria and statistical analysis

The primary endpoint for concluding the Delphi process was consensus for at least half of the items. Consensus for a particular statement was defined as being at least 70% within the lowest or highest category (agree, neutral, or disagree) or within a single score on the Likert scale. Agreement without consensus was defined as being at least 50% within the lowest or highest category (agree, neutral, or disagree) or within a single score on the Likert scale.

Between-round stability was assessed using the McNemar change test for dichotomous variables. Permutation testing without replacement over 104 iterations was employed to approximate normality assumptions for Likert items. A p-value of 0.05 was considered significant. Analyses were performed using R Version 4.2.0 (R Core Team, Vienna, Austria).

Results

Panelists

Among 54 operators, fifty constituted the expert panel: 16 open vascular neurosurgeons, 13 interventional neuroradiologists, 12 dual trained neurosurgeons, 3 interventional neurologists, and 3 endovascular neurosurgeons. Ninety-three percent of panelists (26/28) performing open neurosurgical procedures have more than 10 years of experience. Eighty-two (26/32) percent of panelists performing endovascular procedures have more than 10 years of experience (Supplement Table 1).

Round 1

Among all the proposed parameters to define an aneurysm as complex (aneurysm dimension, dome/neck ratio, aspect ratio, neck geometry, sac morphology, the relation between

Table 1 Summary of the three-round Delphi process, conducted entirely through surveys

Round 1 Participants $n = 50$ (85.5%, 57 invited) Statements $n = 18$ items Open fields $n = 2$ End-points Consensus (> 70%) = 10/18	Tied Aneurysm dimension, dome/neck ratio, morphology, neck geometry, wall, and sac characteristics (including wall calcification, intraluminal thrombosis, blood blister-like or dissecting appearance), parent artery/collaterals status, planned treatment and previous treatments affects the aneurysm complexity Not tied Unruptured status and patients' clinical status do not affect the aneurysm complexity. Aneurysm's aspect ratio, ruptured status, sac orientation, location, relation between neck surface and parent artery, presence of hematoma, vasospasm, the angle of bifurcation of the originating branches, and patient's age did not reach a consensus
Round 2 Participants $n = 47$ Statements OS $n = 68$ Statements EVT $n = 70$ End-points Consensus OS (> 70%) = 39/68 Consensus EVT (> 70%) = 31/70	OS complex Fusiform or blood blister-like shape, dissecting aetiology, giant aneurysms (sac size ≥ 25 mm), broad neck encasing parent arteries, neck surface greater than ½ of the parent artery circumference, wall calcification, intraluminal thrombus, collateral branch originating from the sac, aneurysms located at the level of the anterior-inferior cerebellar artery (AICA), superior cerebellar artery (SCA), basilar trunk or basilar tip, treatments in the context of vasospasm and when a bypass (EC-IC or IC-IC) is planned OS no complex Small aneurysms (sac size < 5 mm), small or medium neck (dome-neck ratio ≤ 1.33:1), saccular aneurysm with irregular shape, side wall aneurysms with a neck surface less than ½ of the parent artery circumference, sac orientation, aneurysms located at the level of the middle cerebral artery (MCA) or posterior communicating artery (PComA), and when a single clip is planned EVT complex Giant aneurysms (sac size ≥ 25 mm), very wide neck (dome/neck ratio ≤ 1:1) and collateral branch originating from the sac EVT no complex Small aneurysms (sac size < 5 mm), small or medium neck (dome-neck ratio ≤ 1.33:1), saccular aneurysm with irregular shape, side wall aneurysms, broad neck not encasing parent arteries, a neck surface less than ½ of the parent artery circumference, sac characteristics (wall calcification, intraluminal thrombus, any shape or aetiology), sac orientation, aneurysms located at the level of the internal carotid artery (ICA), posterior communicating artery (PComA) or basilar tip, and when coiling is planned
Round 3 Participants $n = 42$ Statements $n = 7$ Open fields $n = 0$ End-points Consensus (> 70%) = 1/7 Agreement (> 50%) = 3/7	Considerably influence on any treatment Dimension Morphology Location Neck geometry

the parent artery and neck surface, sac and wall characteristics, parent artery, and collateral branches characteristics, sac orientation, location, rupture or unruptured status, presence of vasospasm, type of planned treatment, and previous treatment), consensus (agreement of over 70% based on ratings) was reached for 10 out of 18 items.

The panelists agreed that the following parameters affect the complexity of the aneurysm: aneurysm dimension, dome/neck ratio, morphology, neck geometry, wall, and sac characteristics (including wall calcification, intraluminal thrombosis, blood blister-like, or dissecting appearance), parent artery/collaterals status, planned treatment, and previous treatments. They also agreed that the unruptured status and patients' clinical status do not affect the complexity of the aneurysm. Aneurysm aspect ratio, ruptured status, sac orientation, location, the relation between the neck surface and the parent artery, presence of hematoma, vasospasm, the angle of bifurcation of the originating branches, and the patient's age did not reach a consensus (Supplement Table 2).

Round 2

Among all statements requiring a Likert scale response (68 for open surgery and 70 for endovascular treatment), a consensus (agreement of over 70% based on ratings) was reached for 39 out of 68 items for open surgery and 31 out of 70 items for endovascular treatment. Results are summarized in Table 2 and reported in Supplement Table 3.

For the open surgery, panelists agreed that aneurysms meeting the following criteria are associated with complexity: fusiform or blood blister-like shape, dissecting aetiology, giant aneurysms (sac size $\geq$ 25 mm), broad neck encasing parent arteries, neck surface greater than half of the parent artery circumference, wall calcification, intraluminal thrombus, collateral branch originating from the sac, aneurysms located at the level of the anterior-inferior cerebellar artery (AICA), superior cerebellar artery (SCA), basilar trunk, or basilar tip, treatments in the context of vasospasm, and when a bypass (EC-IC or IC-IC) is planned. They also agreed that the following criteria are not associated with complexity for open surgery: small aneurysms (sac size < 5 mm), small or medium neck (dome-neck ratio $\leq$ 1.33:1), saccular aneurysm with an irregular shape, side wall aneurysms with a neck surface less than half of the parent artery circumference, sac orientation, aneurysms located at the level of the middle cerebral artery (MCA) or posterior communicating artery (PComA), and when a single clip is planned.

For the endovascular treatment, panelists agreed that aneurysms meeting the following criteria are associated with complexity: giant aneurysms (sac size $\geq$ 25 mm), a very wide neck (dome/neck ratio $\leq$ 1:1), and collateral branch originating from the sac. They also agreed that the following criteria are not associated with complexity for endovascular treatment: small aneurysms (sac size < 5 mm), small or medium neck (dome/neck ratio $\geq$ 1.33:1), saccular aneurysm with an irregular shape, side wall aneurysms, broad neck not encasing parent arteries, a neck surface less than half of the parent artery circumference, sac characteristics (wall calcification, intraluminal thrombus, any shape or aetiology), sac orientation, aneurysms located at the level of the internal carotid artery (ICA), posterior communicating artery (PComA), or basilar tip, and when coiling is planned.

Round 3

Among the seven items (applicable to both open and endovascular treatment) requiring a Likert scale response, agreement (consensus of over 50% based on ratings) was reached for four items. For both open surgery and endovascular treatment, panelists agreed that aneurysm dimension, morphology, location, and neck geometry significantly influence the complexity of the treatment. All the remaining items had consistent scores across the rounds (Supplement Fig. 1).

Discussion

The modified DELPHI methodology used in this study had the aim to assess the consensus extent among experts who are not independent of each other and typically already share common viewpoints of aneurysm management. DELPHI panel achieved consensus on several CIA parameters addressed in the survey. From the perspective of open surgery, the complexity of an aneurysm is defined by its location, size of the sac, and non-saccular shape (either blood blister-like or fusiform). With regard to the size and location, for example, in some neurosurgical series the likelihood of requiring retreatment was linked to both elements, being significantly higher for non-MCA aneurysms larger than 12 mm, compared to MCA aneurysms smaller than 12 mm. [18] In terms of shape, open surgery of blood blister-like aneurysms is associated with a higher risk of poor clinical outcomes, mortality, and periprocedural complications than endovascular treatment. [26] In the case of fusiform aneurysms, both approaches entail high mortality and complication rates, yet open surgery requires multiple and more intricate steps, such as direct clipping, trapping with bypass, proximal occlusion, resection with reanastomosis, transposition, aneurysmorrhaphy with thrombectomy, and wrappin, compared with the endovascular reconstruction or deconstruction of the artery [1, 15]. In addition, the dome/neck ratio holds more significance in endovascular than in surgical treatment. In randomized controlled trials (RCTs), coiling nearly doubled the treatment failure rate of clipping (24.2% vs. 14.5%) of wide-necked aneurysms [8], and single

Table 2 Characteristics tied with complexity of intracranial aneurysms. OS = open surgery, EVT = endovascular treatment

TIED TO COMPLEXITY OF INTRACRANIAL ANEURYSM			
		OS	EVT
Dimension	Giant (≥ 25 mm)	X	X
	Large (≥ 10 mm)		
	Medium (5–10 mm)		
	Small (< 5 mm)		
	Very small (< 3 mm)		
Dome-neck ratio	Small neck (2:1)		
	Medium neck (1.33:1)		
	Wide neck (1:1)		
	Beyond wide neck (< 1:1)		X
Morphology	Regular		
	Multilobate		
	Fusiform	X	
Neck geometry	Side-wall		
	Bifurcation-small neck		
	Bifurcation-wide neck	X	
Neck surface	Neck surface < 1/2 parent artery circumference		
	Neck surface > 1/2 parent artery circumference	X	
Sac features	Wall calcification	X	
	Intraluminal thrombus	X	
	Blood Blister-like	X	
	Dissecting aetiology	X	
Parent artery and collaterals	Parent artery focal stenosis		
	Collateral branch from sac	X	X
	Collateral branch from neck		
Location	Anterior circulation Proximal		
	Anterior circulation Distal		
	Posterior circulation Proximal	X	
	Posterior circulation Distal		
Ruptured status	Ruptured		
	Vasospasm	X	
Planned treatment	Single clip		
	Multiple clips		
	Bypass IC-IC	X	
	Bypass EC-IC	X	
	Intrasaccular devices		
	Coiling		
	Balloon assisted coiling/ID		
	Stent assisted coiling/ID		
	Flow-diverter ± coils/ID		

stent-assisted coiling did not demonstrate any advantage over coiling alone. [5] Consequently, endovascular treatments necessitate other strategies, such as Y-stent-assisted coiling or intrasaccular devices, resulting in high rates of long-term angiographic occlusion with a low incidence of treatment-related complications. [6, 19] However, these results need to be confirmed in RCTs.

Categorizing aneurysms under a broad definition of "complex" may be problematic. Most research or clinical trials do not explicitly classify aneurysms as "complex" or "non-complex", but they use variables associated to the aneurysm complexity, such as location, neck size, aneurysm size, and parent vessel attributes [3].This discrepancy indicates that the term "complex" is more often used in product names or to describe treatment procedures rather than as a clinical or academic classification. Consequently, there may not be a widely accepted or practical definition for "complex" aneurysms, particularly given the rapid advancements in endovascular devices and microsurgical techniques. Why is the definition of a CAI clinically crucial? Firstly, in the context of medical communication, establishing a clear and accurate definition is essential to prevent misunderstandings and foster precise understanding among physicians, including neurosurgeons, neurointerventionalists, anesthesiologists, intensive care physicians, neuroradiologists, neurologists, and others. This clarity becomes paramount in the clinical assessment of cerebral aneurysms, where a classification based on complexity directly impacts treatment decisions. Secondly, the implications extend to the realm of medical research, as studies and investigations may specifically target categories of cerebral aneurysms identified as "complex." This targeted approach proves especially beneficial for the exploration of new medical devices or the comparative analysis of different therapeutic techniques. Thirdly, a well-defined classification system would directly benefit patients, allowing them to make well-informed decisions about their health. Currently, clinical decisions regarding the treatment of brain aneurysms are based on fragmented and incomplete evidence-based foundations. Determining the need for treatment should involve weighing the estimated risks associated with the disease, the treatment, and the patient. However, this is difficult with the currently available scoring systems, [10, 11, 14, 24] that do not consider the risks associated with the treatment. We can also argue that assigning a standard value to the risk of treatment may not fully encompass the complexities involved when patients are considering high-risk preventive interventions. Identifying variables that could fill this gap, enabling the comparison of treatment complexities, is perhaps useful in making informed decisions. Lastly, considering that individualized care necessitates rigorous scientific experience, identifying elements related to aneurysm complexity will help formulate hypotheses to be directly tested, avoiding conclusions based on outdated beliefs or fragile observational data. [21] In many centers, clipping is still preferred over coiling for large aneurysms, based on initial endovascular series, including surgically challenging patients, which indicated a high recanalization rate [22, 25]. Stent-assisted coiling is used for large or wide-necked aneurysms, although the STAT trial showed a higher efficacy of stenting for narrow-necked aneurysms compared to wide-necked ones [5] While we lack randomized experience for relatively old techniques and devices, new technologies, which should require the same prospective experience, are being used in clinical practice.

Limitations

The purpose of the DELPHI method is to establish a consensus on defining the complexity of brain aneurysms to develop data-driven recommendations. Therefore, a DELPHI consensus is by no means intended to replace evidence-based guidelines. This approach could have several limitations. First, the relatively small number of members in the expert panel could potentially have led to biased results, although efforts were made to represent a broad spectrum of specialties and geographic regions. Second, panelists involved in this DELPHI are not independent of each other and typically already share common viewpoints of aneurysm management. Third, the methodology of requiring > 50% agreement for further inclusion in Round 2 could potentially exclude parameters significant to only one specialty group. While the study aimed to identify commonalities across specialties, this approach might not fully capture the specific needs and perspectives of each group. Fourth, the panel consensus represents a snapshot in time, while technologies, particularly in the endovascular field, are constantly evolving. Hence, the results of this study will likely require updates as new devices or better evidence become available.

Conclusions

The definition of aneurysm complexity is associated with the type of treatment, whether open surgery or endovascular. For open surgery, complexity is determined by its location, size, neck geometry, collateral branches originating from the aneurysm sac and the type of treatment required. From an endovascular perspective, complexity is linked to size, dome-neck ratio ≤ 1:1, and collateral branches originating from the aneurysm sac. The guidance derived from these statements may improve the standardization and objectivity of CIA management.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00701-024-06182-z.

Authors contribution Conception and design of the work: FD, SP.

Data acquisition: FD, MR, ER, FCA, ASA, JüBe, JeBe, HDB, JKB, MC, RC, FTC, HD, GE, JTF, SF, AG, AEH, PJ, APJ, MK, VK, TK, GL, TRM, JM, PJM, EN, VMP, AR, LR, VR, AHS, RT, SIT, AT, PV, LV, NV, DW, HW, BX, SY, WHVZ, SP.

Data analysis and interpretation: FD, MR, SP.

Drafting the work: FD, MR, SP.

Critical revision: all authors.

Final approval: all authors.

Dr. Yoshimura reports research grants from Stryker, Siemens Healthineers, Bristol-Myers Squibb, Sanofi, Eisai, Daiichi Sankyo, Teijin Pharma, Chugai Pharmaceutical, HEALIOS, Asahi Kasei Medical, Kowa, CSL Behring; and lecturer fees from Stryker, Medtronic, JoDTNSon & JoDTNSon, Kaneka, Terumo, Biomedical Solutions, Boehringer-Ingelheim, Daiichi Sankyo, Bayer, Bristol-Meyers Squibb.

Dr Ameer E. Hassan—1. Consultant/Speaker: Medtronic, Microvention, Stryker, Penumbra, Cerenovus, Genentech, GE Healthcare, Scientia, Balt, Viz.ai, Insera therapeutics, Proximie, NeuroVasc, NovaSignal, Vesalio, Rapid Medical, Imperative Care, Galaxy Therapeutics, Route 92 and Perfuze. 2. Principal Investigator: COMPLETE study – Penumbra, LVO SYNCHRONISE – Viz.ai, Millipede Stroke Trial—Perfuze, RESCUE—ICAD—Medtronic. 3. Steering Committee/Publication committee member: SELECT, DAWN, SELECT 2, EXPEDITE II, EMBOLISE, CLEAR, ENVI, DELPHI, DISTALS. 4.DSMB—COMAND trial.

Dr Daniel C. Walsh: Consultant/Speaker for BBraun Aesculap, Stryker, Zeiss, GSK plc.

Dr Adnan H Siddiqui Current Research Grants: Co-investigator for NIH—1R01EB030092-01, Project Title: High Speed Angiography at 1000 frames per second; Mentor for Brain Aneurysm Foundation Carol W. Harvey Chair of Research, Sharon Epperson Chair of Research, Project Title: A Whole Blood RNA Diagnostic for Unruptured Brain Aneurysm: Risk Assessment Prototype Development and Testing. Financial Interest/Investor/Stock Options/Ownership: Adona Medical, Inc., Bend IT Technologies, Ltd., BlinkTBI, Inc, Cerebrotech Medical Systems, Inc., Cognition Medical, CVAID Ltd., E8, Inc., Endostream Medical, Ltd, Galaxy Therapeutics, Inc., Imperative Care, Inc., InspireMD, Ltd., InspireMD, Ltd., Instylla, Inc., IRRAS AB, Launch NY, Inc., NeuroRadial Technologies, Inc., NeuroTechnologyInvestors, Neurovascular Diagnostics, Inc., Peijia Medical, PerFlow Medical, Ltd., Q'Apel Medical, Inc., QAS.ai, Inc., Radical Catheter Technologies, Inc., Rebound Therapeutics Corp. (Purchased 2019 by Integra Lifesciences, Corp), RistNeurovascular, Inc. (Purchased 2020 by Medtronic), Sense Diagnostics, Inc., Serenity Medical, Inc., Silk Road Medical, Sim & Cure, SongBird Therapy, Spinnaker Medical, Inc., StimMed, LLC, Synchron, Inc., Three Rivers Medical, Inc.,Truvic Medical, Inc., Tulavi Therapeutics, Inc., Vastrax, LLC, Viseon, Inc. Consultant/Advisory Board: Apellis Pharmaceuticals, Inc., Boston Scientific, Canon Medical Systems USA, Inc., Cardinal Health 200, LLC, Cerebrotech Medical Systems, Inc., Cerenovus, Cordis, Corindus, Inc., Endostream Medical, Ltd, Imperative Care, InspireMD, Ltd., Integra, IRRAS AB, Medtronic, MicroVention, Minnetronix Neuro, Inc., Peijia Medical, Penumbra, Q'Apel Medical, Inc., Rapid Medical, Serenity Medical, Inc., Silk Road Medical, StimMed, LLC, Stryker Neurovascular, Three Rivers Medical, Inc., VasSol, Viz.ai, Inc. National PI/Steering Committees: Cerenovus EXCELLENT and ARISE II Trial; Medtronic SWIFT PRIME, VANTAGE, EMBOLISE and SWIFT DIRECT Trials; MicroVention FRED Trial & CONFIDENCE Study; MUSC POSITIVE Trial; Penumbra 3D Separator Trial, COMPASS Trial, INVEST Trial, MIVI neuroscience EVAQ Trial; Rapid Medical SUCCESS Trial; InspireMD C-GUARDIANS IDE Pivotal Trial.

Funding This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Data availability Not applicable.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate All authors.

Consent for publication All authors.

Conflicts of interest/competing interests The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

References

1. Anson JA, Lawton MT, Spetzler RF (1996) Characteristics and surgical treatment of dolichoectatic and fusiform aneurysms. J Neurosurg 84(2):185–193
2. Aydin K, Puthuran M, Onal Y et al (2023) The angiographic and clinical follow-up outcomes of the wide-necked and complex intracranial aneurysms treated with LVIS EVO–Assisted coiling. Neurosurgery 92(4):827–836
3. Becske T, Kallmes DF, Saatci I et al (2013) Pipeline for uncoilable or failed aneurysms: results from a multicenter clinical trial. Radiology 267(3):858–868
4. Beiderbeck D, Frevel N, von der Gracht HA, Schmidt SL, Schweitzer VM (2021) Preparing, conducting, and analyzing Delphi surveys: Cross-disciplinary practices, new directions, and advancements. MethodsX 8:101401
5. Boisseau W, Darsaut TE, Fahed R et al (2023) Stent-assisted coiling in the treatment of unruptured intracranial aneurysms: a randomized clinical trial. Am J Neuroradiol 44(4):381–389
6. Cagnazzo F, Limbucci N, Nappini S, Renieri L, Rosi A, Laiso A, di Carlo DT, Perrini P, Mangiafico S (2019) Y-Stent-Assisted coiling of wide-neck bifurcation intracranial aneurysms: a meta-analysis. Am J Neuroradiol 40(1):122–128
7. Chen S-Q, Li L, Gao B-L, Wu Q-W, Shao Q-J, Wang Z-L, Zhang K, Li T-X (2023) Safety and effect of pipeline flex embolization device for complex unruptured intracranial aneurysms. Sci Rep 13(1):4570
8. Darsaut TE, Findlay JM, Bojanowski MW et al (2023) A pragmatic randomized trial comparing surgical clipping and endovascular treatment of unruptured intracranial aneurysms. Am J Neuroradiol 44(6):634–640
9. Diana F, Pesce A, Toccaceli G, Muralidharan V, Raz E, Miscusi M, Raco A, Missori P, Peschillo S (2022) Microsurgical clipping versus newer endovascular techniques in treatment of unruptured anterior communicating artery-complex aneurysms: a meta-analysis and systematic review. Neurosurg Rev 45(2):1089–1100
10. Etminan N, Brown RD, Beseoglu K et al (2015) The unruptured intracranial aneurysm treatment score. Neurology 85(10):881–889
11. Fahed R, Darsaut TE (2017) The Delphi Oracle and the management of aneurysms. J Neurointerv Surg 9(e1):e1–e2
12. Fan F, Fu Y, Liu J et al (2022) Multiple Pipeline Embolization Devices for the Treatment of Complex Intracranial Aneurysm: A Multi-Center Study. Front Aging Neurosci. https://doi.org/10.3389/fnagi.2022.905224
13. Gómez-Amador JL, Valencia-Ramos CG, Sangrador-Deitos MV et al (2023) Roadmapping technique in the hybrid operating room for the microsurgical treatment of complex intracranial aneurysms. J Cerebrovasc Endovasc Neurosurg 25(1):50–61
14. Greving JP, Wermer MJH, Brown RD et al (2014) Development of the PHASES score for prediction of risk of rupture of intracranial aneurysms: a pooled analysis of six prospective cohort studies. Lancet Neurol 13(1):59–66
15. Griffin A, Lerner E, Zuchowski A, Zomorodi A, Gonzalez LF, Hauck EF (2021) Flow diversion of fusiform intracranial aneurysms. Neurosurg Rev 44(3):1471–1478
16. Guyatt GH, Oxman AD, Kunz R, Vist GE, Falck-Ytter Y, Schünemann HJ (2008) What is "quality of evidence" and why is it important to clinicians? BMJ 336(7651):995–998
17. Haverkamp C, Kaier K, Shah M, von zur Mühlen C, Beck J, Urbach H, Meckel S (2024) Cerebral aneurysms: Germany-wide real-world outcome data of endovascular or neurosurgical treatment from 2007 to 2019. J Neurointerv Surg 16(4):365–371
18. Jabbarli R, Pierscianek D, Wrede K, Dammann P, Schlamann M, Forsting M, Müller O, Sure U (2016) Aneurysm remnant after clipping: the risks and consequences. J Neurosurg 125(5):1249–1255
19. Pierot L, Szikora I, Barreau X et al (2023) Aneurysm treatment with the Woven EndoBridge (WEB) device in the combined population of two prospective, multicenter series: 5-year follow-up. J Neurointerv Surg 15(6):552–557
20. Ravina K, Rennert RC, Brandel MG, Strickland BA, Chun A, Lee Y, Carey JN, Russin JJ (2021) Comparative Assessment of

Extracranial-to-Intracranial and Intracranial-to-Intracranial In Situ Bypass for Complex Intracranial Aneurysm Treatment Based on Rupture Status: A Case Series. World Neurosurg 146:e122–e138
21. Raymond J, Darsaut TE (2023) Understanding categories or subgroups and a common clinical reasoning error: the example of aneurysm size and neck width. Neurochirurgie 69(6):101491
22. Raymond J, Roy D, Bojanowski M, Moumdjian R, L'Espérance G (1997) Endovascular treatment of acutely ruptured and unruptured aneurysms of the basilar bifurcation. J Neurosurg 86(2):211–219
23. Rennert RC, Nguyen VN, Abedi A, Atai NA, Carey JN, Tenser M, Amar A, Mack WJ, Russin JJ (2023) Combined open revascularization and endovascular treatment of complex intracranial aneurysms: case series. Front Neurol. https://doi.org/10.3389/fneur.2023.1102496
24. Rinkel GJE, Algra A, Greving JP, Vergouwen MDI, Etminan N (2017) PHASES and the natural history of unruptured aneurysms: science or pseudoscience? J Neurointerv Surg 9(6):618
25. Roy D, Raymond J, Bouthillier A, Bojanowski MW, Moumdjian R, L'Espérance G (1997) Endovascular treatment of ophthalmic segment aneurysms with Guglielmi detachable coils. AJNR Am J Neuroradiol 18(7):1207–1215
26. Tan H, Zhang T, Huang G, Li Z, Wang Z, Cheng M, Liu L, Liu L (2023) Endovascular intervention vs. microsurgery on the prognosis of anterior circulation blood blister-like aneurysm: a cohort study. Front Neurol. https://doi.org/10.3389/fneur.2023.1103138
27. Toccaceli G, Diana F, Cagnazzo F, Cannizzaro D, Lanzino G, Barbagallo GMV, Certo F, Bortolotti C, Signorelli F, Peschillo S (2020) Microsurgical Clipping Compared with New and Most Advanced Endovascular Techniques in the Treatment of Unruptured Middle Cerebral Artery Aneurysms: A Meta-Analysis in the Modern Era. World Neurosurg 137:451-464.e1
28. Togashi S, Shimizu H (2022) Complex intracranial aneurysms, pp 225–238. https://doi.org/10.1007/978-3-030-87649-4_12
29. Wang X, Han G, Wang H, Shang Y, Shi M, Wang X, Bao J, Wang Z, Tong X (2023) Cerebral revascularization for complex middle cerebral artery aneurysms: surgical strategies and outcomes in a single center. Neurosurg Rev 46(1):68
30. Xue T, Deng R, Gao B, Wang Z, Ma C, You W, Zhu Y, Chen Z, Wang Z (2021) Intraoperative indocyanine green video angiography (ICG–VA) with FLOW 800 software in complex intracranial aneurysm surgery. Chin Neurosurg J 7(1):28
31. Zhang J, He L, Xia X, Zhang L, Yu K (2023) Braided stent-assisted coil embolization versus laser engraved stent-assisted coil embolization in patients with unruptured complex intracranial aneurysms. Clinics 78:100202

Authors and Affiliations

Francesco Diana[1,2,43] · Michele Romoli[3] · Eytan Raz[4] · Ronit Agid[5] · Felipe C. Albuquerque[6] · Adam S. Arthur[7] · Jürgen Beck[8] · Jerome Berge[9] · Hieronymus D. Boogaarts[10] · Jan-Karl Burkhardt[11] · Marco Cenzato[12] · René Chapot[13] · Fady T. Charbel[14] · Hubert Desal[15] · Giuseppe Esposito[16] · Johanna T. Fifi[17] · Stefan Florian[18] · Andreas Gruber[19] · Ameer E. Hassan[20] · Pascal Jabbour[21] · Ashutosh P. Jadhav[6] · Miikka Korja[22] · Timo Krings[23] · Giuseppe Lanzino[24] · Torstein R. Meling[25] · Jaques Morcos[26] · Pascal J. Mosimann[23] · Erez Nossek[27] · Vitor Mendes Pereira[28] · Andreas Raabe[29] · Luca Regli[16] · Veit Rohde[30] · Adnan H. Siddiqui[31] · Rokuya Tanikawa[32] · Stavropoula I. Tjoumakaris[33] · Alejandro Tomasello[1,2] · Peter Vajkoczy[34] · Luca Valvassori[35] · Nikolay Velinov[36] · Daniel Walsh[37] · Henry Woo[38] · Bin Xu[39] · Shinichi Yoshimura[40] · Wim H. van Zwam[41] · Simone Peschillo[42]

✉ Simone Peschillo
simone.peschillo@gmail.com

1 Interventional Neuroradiology, University Hospital Vall d'Hebron, Barcelona, Spain

2 Stroke Research Group, Vall d'Hebron Research Institute, Barcelona, Spain

3 Neurology and Stroke Unit, Department of Neuroscience, Bufalini Hospital, Cesena, Italy

4 Department of Radiology, New York University Langone Health, New York, NY, USA

5 Division of Neuroradiology, JDMI, University Health Network, Toronto, Canada

6 Department of Neurosurgery, Barrow Neurological Institute, St. Joseph's Hospital and Medical Center, Phoenix, AZ, USA

7 University of Tennessee, Semmes-Murphey Neurologic and Spine Clinic, Memphis, TN, USA

8 Department of Neurosurgery, Medical Center, University of Freiburg, Freiburg, Germany

9 Interventional Neuroradiology Department, CHRU, Bordeaux, France

10 Department of Neurosurgery, Radboud University Medical Centre, Nijmegen, Netherlands

11 Department of Neurosurgery, Hospital of the University of Pennsylvania, Penn Medicine, Philadelphia, USA

12 Department of Neurosurgery, Grande Ospedale Metropolitano Niguarda, Milan, Italy

13 Department of Interventional Neuroradiology, Alfried Krupp Hospital Ruttenscheid, Essen, Germany

14 Department of Neurosurgery, University of Illinois at Chicago, Chicago, IL, USA

15 Department of Diagnostic and Therapeutic Neuroradiology, University Hospital of Nantes, Nantes, France

[16] Department of Neurosurgery, University Hospital of Zurich, University of Zurich, Zurich, Switzerland

[17] Department of Neurosurgery, Icahn School of Medicine at Mount Sinai, New York, NY, USA

[18] Department of Neurosurgery, Iuliu Hatieganu" University of Medicine and Pharmacy, Cluj County Clinical Emergency Hospital, Cluj-Napoca, Romania

[19] Department of Neurosurgery, Johannes Kepler University, Neuromed Campus, Kepler Universitätsklinikum, Linz, Austria

[20] Department of Neurology, Valley Baptist - University of Texas Rio Grande Valley, Harlingen, TX, USA

[21] Department of Neurosurgery, Thomas Jefferson Hospital, Philadelphia, PA, USA

[22] Department of Neurosurgery, University of Helsinki and Helsinki University Hospital, Helsinki, Finland

[23] Interventional and Diagnostic Neuroradiology, University of Toronto & Toronto Western Hospital, Toronto, ON, Canada

[24] Department of Neurologic Surgery, Mayo Clinic, Rochester, MN, USA

[25] Department of Neurosurgery, Rigshospitalet, Copenhagen, Denmark

[26] Vivian L. Smith Department of Neurosurgery, UTHealth Houston Neurosciences, Houston, TX, USA

[27] Department of Neurosurgery, New York University School of Medicine, New York, NY, USA

[28] Division of Neurosurgery, Departments of Surgery & Medical Imaging, St. Michael's Hospital, University of Toronto, Toronto, ON, Canada

[29] Department of Neurosurgery Inselspital, Bern University Hospital and University of Bern, Bern, Switzerland

[30] Department of Neurosurgery, University Medical Center Göttingen, Georg-August-University, Göttingen, Germany

[31] Department of Neurosurgery, Jacobs School of Medicine and Biomedical Sciences, University at Buffalo, Buffalo, NY, USA

[32] Department of Neurosurgery, Stroke Center, Sapporo Teishinkai Hospital, Sapporo, Hokkaido, Japan

[33] Department of Neurological Surgery, Thomas Jefferson University Hospital, Philadelphia, PA, USA

[34] Department of Neurosurgery, Charité-Universitätsmedizin Berlin, Berlin, Germany

[35] Neuroradiology Unit, Ospedale San Carlo, Milan, Italy

[36] Clinics of Neurosurgery, Vascular and Endovascular Neurosurgery, University Hospital Pirogov, Sofia, Bulgaria

[37] King's College Hospital NHS Foundation Trust, London, UK

[38] Department of Neurosurgery, Donald and Barbara Zucker School of Medicine at Hofstra/Northwell, Manhasset, NY, USA

[39] Department of Neurosurgery, Huashan Hospital, Fudan University, Shanghai, China

[40] Department of Neurosurgery, Hyogo Medical University, Nishinomiya, Japan

[41] Department of Radiology and Nuclear Medicine, School for Cardiovascular Diseases (CARIM), Maastricht UMC+, Maastricht, The Netherlands

[42] Endovascular Neurosurgery, Guido Guglielmi Endowed Chair in Endovascular Neurosurgery, Unicamillus International University of Health Sciences, Rome, Italy

[43] Department of Scienze della Vita, Della Salute e delle Professioni Sanitarie Link Campus University, Rome, Italy