Chapter

Innovations in the Surgery of Cerebral Aneurysms: Enhanced Visualization, Perfusion, and Function Monitoring

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Abstract

Surgery of cerebral aneurysms has evolved over the years. Advances regard enhanced intraoperative visualization and monitoring of both function and perfusion. Technological assistance used in oncological or skull base surgery, such as intraoperative neurophysiological monitoring (IONM) or endoscopy, now adopt to vascular surgery. Intraoperative indocyanine green video angiography (ICG-VA) and techniques for its interpretation (squeezing maneuver; entrapment sign), endoscopes, and exoscopes increase visualization. Flow evaluation by microflow probe permits perfusion monitoring; IONM allows functional monitoring. Bypasses replace flow in complex aneurysm cases. Pre-, intra-, and postoperative imaging and flow measurement techniques help in donor selection and follow-up. Despite some progression in the aneurysm clips, the principle has not changed. Innovation and even change of principle in aneurysm exclusion might be desirable. Basic research in aneurysm wall and flow dynamics might in the future change the paradigms of cerebral aneurysm treatment.

Keywords: aneurysm surgery, cerebral aneurysm, bypass, clipping, vascular surgery, indocyanine green video angiography, flow measurement, neurophysiological monitoring, perivascular flow probe, endoscope

1. Introduction

The advent of endovascular treatment determined the crisis of cerebral aneurysm surgery. Endovascular therapy is less invasive and its progression is rapid. Industries' interests and investments potentiate the technological endovascular advancements. Surgical treatment by clipping of intracranial aneurysms is durable and stable in time. There are advances in making surgical treatment safer and offering treatment to the more complicated cases, not amenable to endovascular therapy. Advances and investments in the surgery of cerebral aneurysms are less deafening in the last decade. However, some silent innovative advances are made over the years. Here we present innovations in cerebral aneurysm surgery.

2. Enhanced intraoperative visualization: intraoperative indocyanine green video angiography (ICG-VA) principle and implantation in vascular neurosurgery

Indocyanine green (ICG) is a near-infrared (NIR) fluorescent dye initially approved by the Food and Drug Administration (FDA) in 1956 for the evaluation of the cardiocirculatory and liver function. FDA extended the approval for ophthalmic angiography in 1975. Nowadays, ICG fluorescence is routinely used in ophthalmology for the visualization of the retinal microcirculation. A specific optical setup for near-infrared (NIR) light is necessary for the visualization of the ICG fluorescence. The development of an ICG angiography new system allowed further implementation for the intraoperative visualization of the tissue perfusion in general surgery.

Raabe et al. gave a substantial contribution by implementing ICG angiography use in vascular neurosurgery [1].

The absorption peak of ICG is 805 nm, while the emission peak is 835 nm. Within these two peaks, the endogenous tissue chromophore absorption is low.

NIR light penetrates the tissue from several millimeters to a few centimeters. ICG is injected intravenously, and it bounds in 1–2 s predominantly to globulins (α1-lipoproteins). In the absence of vascular permeability damage, ICG bound to globulins remains intravascular. ICG has a plasma half-life of 3–4 min. It is only excreted by the liver with no metabolization.

Raabe et al. used a laser-fluorescence imaging device (IC-View; Pulsion Medical Systems AG, Munich, Germany), consisting of a NIR laser light source (0.16 W, λ = 780 nm) and a NIR-sensitive digital camcorder.

ICG was injected intravenously in a bolus (standard dose of 25 mg dissolved in 5 ml of water). ICG fluorescence was induced by the NIR light emitted by the laser light source. The digital video camera with optical filtering recorded only the ICG-induced fluorescence signal.

The near-infrared filter was commercially available for surgical microscopes routinely used in neurosurgery, and ICG-VA could be applied in vascular neurosurgery.

For example, intraoperative ICG-VA could be performed using a surgical microscope (OPMI® PenteroTM, The Carl Zeiss Co., Oberkochen, Germany) equipped with a microscope-integrated near-infrared ICG-VA (Carl Zeiss, Infrared 800TM, Meditec, Germany). ICG is injected intravenously in a bolus of 25 mg dissolved in 5 ml of water, and the operating field is illuminated with near-infrared light. Real-time angiographic images are visualized on a video screen and recorded. The images can be replayed. Only the illuminated field is recorded. ICG can be injected multiple times during surgery; thus ICG-VA is repeatable.

3. ICG-VA for accessing aneurysm occlusion after clipping

After Raabe's first report [1], ICG-VA gradually became routinely used in aneurysm surgery. It is used after aneurysm clipping to access whether the aneurysm occlusion is complete. Catheter angiography is the gold standard for cerebral aneurysm diagnosis [2] and for confirming aneurysm occlusion. However, intraoperative catheter angiography requires a programmed setup; is invasive, expensive, and time-consuming, and requires a well-trained staff. It is reserved to particular complicated cases, and it is not intraoperatively routinely used in the surgery of intracranial aneurysms. Furthermore, the time required for an intraoperative angiogram may be sufficient for the establishment of irreversible ischemia. Postoperative residual aneurysms after clipping are reported in a variable range from 4 to 19%

of cases [3–10]. ICG-VA is fast, easily used, and not invasive. It allows immediate assessment of the aneurysm occlusion after clipping, and permits whether necessary clip repositioning or further clip positioning. Although, ICG-VA is inferior to catheter angiography in assessing aneurysm complete occlusion, it is intraoperatively easily used in the cases where intraoperative catheter angiography would not be used routinely. It does not substitute postoperative neuroradiological control of aneurysm complete occlusion but allows to have higher postoperative occlusion rates. Postoperative catheter angiography remains the gold standard for assessment of aneurysm occlusion. Generally, intraoperative ICG-VA is used to access clipping after apparent complete occlusion under the microscope light. Della Puppa et al. showed that despite apparent complete occlusion under microscope visualization, ICG-VA revealed unexpected residual aneurysms in 9% [11]. Roessler et al. in a study of 295 aneurysms clipped with the use of ICG-VA showed an intraoperative clip modification rate of 15% based on ICG-VA data [12]. Thus, ICG-VA is a complementary tool that increases aneurysm occlusion rate, but it does not substitute postoperative digital subtraction angiography (DSA) for the detection of aneurysm remnants [13]. Intraoperative aneurysm puncture, or opening whenever possible, remains the most reliable intraoperative measure to assess complete occlusion.

4. Tools to improve ICG-VA interpretation

Different factors can determine false-negative or false-positive ICG-VA findings. Arteriosclerosis and wall thickening at the clipping site influence false-negative ICG-VA findings [14]. Repeated ICG can determine false-positive results. Also, a small remnant detected in ICG can undergo spontaneous thrombosis and thus may not present a real residual.

4.1 Squeezing maneuver

ICG-VA despite improvement of aneurysm occlusions rate can also show deceptive false-negative results. Della Puppa et al. described a surgical simple maneuver to detect false-negative ICG-VA results after clipping of a cerebral aneurysm [15]. The squeezing maneuver consists of a gentle pinch with bipolar/Cushing bayonet forceps of the dome of a clipped aneurysm when ICG-VA documents its apparent exclusion.

The maneuver is performed during the same ICG injection to confirm the aneurysm exclusion. It is considered positive when, after an initial ICG-VA shows the aneurysm exclusion, a gentle pinch of the slack aneurysm dome with a bipolar or Cushing bayonet forceps under ICG-VA visualization causes the prompt dyeing of the sac, suggesting that the aneurysm is still filling up. The maneuver is considered negative when, after pinching of the clipped dome, the sac does not fill up. The puncture and opening of the sac can confirm whether a flow is still filling the aneurysm. The squeezing maneuver can depict ICG-VA false-negative results.

This permits to readjust the clip or position a second clip to completely exclude the aneurysm during the same procedure. Calcification/atheroma of the wall/neck was predictive of a positive maneuver ($P = 0.001$). This is consistent with Gekka et al. findings several years later, which report false-negative ICG-VA results in atherosclerosis and wall thickening at the clipping site [14].

4.2 ICG entrapment sign

ICG-VA can also show false-positive results, if misinterpreted. When ICG is injected before the final aneurysm clipping, the dye might be entrapped within

the sac by the clip's blades, which would obstacle the dye washout. ICG-VA would show the dye entrapped in the sac. An erroneous interpretation of the data would be to consider the aneurysm unsecured. Della Puppa et al. introduced the ICG entrapment sign as the detection under infrared light of ICG remnants sequestered in the dome [16]. ICG entrapment sign detects dye stasis, and not active filling. It is considered a sign of aneurysm occlusion in the setting of ICG injection prior to final clipping. This may happen if ICG is injected prior to clipping for visualization of perforating arteries near to the sac or detection of atheromas of the neck/dome. This happens more commonly after clip repositioning based on ICG indication.

The squeezing maneuver can detect a false-negative ICG-VA (an unsecured aneurysm despite apparent occlusion after ICG), whereas the ICG entrapment sign can detect a false-positive ICV-VA result (a secured aneurysm under infrared light, despite ICG-VA showing dye).

5. Other ICG-VA uses

5.1 Transdural application

ICG-VA can be used before dural opening in vascular arteriovenous malformations or fistulas to optimize the exposure of the malformation, perform a safe dural opening, and identify dural vascular connections of the lesion [17]. The cases where transdural ICG can help in aneurysm surgery are very rare. These are the cases of distal cortical, generally distal middle cerebral artery (M4) aneurysms. In a case of M4 ruptured aneurysm, ICG-VA allowed transdural aneurysm visualization [18]. This is particularly helpful in an emergency setting, when neuronavigation is not available, to localize the aneurysm and avoid damage while opening the dura.

5.2 Transoptic aneurysm visualization

Other exceptional ICG-VA applications reported are the transoptic aneurysm visualization and occlusion confirmation in a case of an optic splitting aneurysm [19]. An ophthalmic artery aneurysm medially and superiorly projecting, suspicious for an under optic growth, underwent surgery. Initially the aneurysm was not visible. ICG-VA permitted the transoptic aneurysm visualization and after clipping final occlusion.

ICG-VA application was extended in other pathologies [20–26].

5.3 Flow measurement by microflow probe: principle and implementation in neurosurgery

Vascular micro-Dopplers are used in cerebral aneurysm surgery to indicate the flow velocity. They are easy to use and give the surgeon an acoustic signal feedback. The flow velocity is used as a surrogate of the flow quantity. Flow velocity is not the most reliable indicator for flow. Flow quantity is the most reliable flow measure.

Till the 1990s, the intraoperative ultrasonic blood flow probes have been used to quantitatively measure flow only in cardiac, vascular, and transplant surgery. Charbel et al. in the University of Illinois at Chicago first reported in 1997 the implantation of the ultrasonic perivascular micro blood flow probes in the clipping of cerebral aneurysms [27–31].

The first transit time flowmeters were described in 1962 and 1964 [32, 33]. Limitations in estimating vessel diameter, vessel misalignment, and an unstable zero calibration prevented medical applications [34]. In 1978 Drost et al. presented

the theoretical basis for a flowmeter based on the transit time technique [35, 36]. The transit time flowmeter was introduced in 1983 [36].

The transit time blood volume flowmeter gives a direct measurement of volume flow through the acoustic window of its implanted sensor, independent of flow profile. In contrast, earlier Doppler and transit time ultrasonic flowmeters sense blood velocity, which makes volume flow measurements critically dependent on vessel diameter [35, 36].

The transonic perivascular flow-measuring device includes an electronic flow detection unit with enhanced frequency resolution and volume flow-sensing perivascular probes (Transonic Medical Flowmeter; Transonic Systems, Inc., Ithaca, NY, USA). The perivascular flow probes are manufactured in 1.5, 2, and 3 mm diameter and can be used to measure the average flow volume (mL/min) instantaneously in cerebral vessels.

The flowmeter uses ultrasonic transit time principle to sense liquid volume flow in vessels independent of flow velocity, hematocrit, and turbulence.

The electronic flow-detecting unit is a line-powered flowmeter that automatically identifies the scaling factor and individual calibration factor of the flow probe connected to it. The flow sensors are connected to the flow-detecting unit via a flexible cable.

The ultrasonic transducers transmit ultrasound which helps to sense the volume of blood flowing through the blood vessel in which the sensor is applied.

The flow probe consists of a probe body which houses two ultrasonic transducers and a fixed acoustic reflector. The transducer is positioned around the blood vessel, and then the flow in that vessel is displayed in the digital form. The flowmeter derives an accurate measure of the "transit time," which is the time the wave of ultrasound has taken to travel from one transducer to the other [28].

Practically, a portion of the vessel of interest is dissected from the arachnoid, and the probe is hooked around the vessel under saline irrigation.

The flow appears as a digital display on the detection unit and is registered as positive or negative dependent on the direction of flow in relation to the orientation of the probe. The flow is detected as the volume (mL/min), and the flow volume over time of recording diagram can be printed.

5.4 Flow measurement by microflow probe: application in aneurysm surgery

Quantitative blood flow measurement became essential in blood flow preservation to avoid postoperative ischemic complication in cerebral aneurysm surgery. Amin-Hanjani et al. proposed a baseline evaluation of blood flow in the vessels at risk of flow compromise after clipping (generally the efferent arteries, distal to the aneurysm) and a second flow evaluation of the same vessels after clipping [31]. A reduction of the flow greater than 25% of baseline was considered at risk for ischemic complications, and the clip was repositioned. The data was reproduced by other studies [11, 37, 38]. Flow measurement by microflow probe was also used in other cerebrovascular diseases [39–42].

6. Intraoperative neurophysiological monitoring IONM

IONM routinely used in oncological surgery, over the years, has become essential also in vascular surgery to avoid ischemic complications. Monitoring includes bilateral upper and lower limb motor evoked potentials (MEPs) and somatosensory evoked potentials (SSEPs). Generally, in aneurysm surgery, MEPs are monitored by transcranial electric stimulation, rather than by direct cortical mapping, because

the motor area is not routinely exposed during standard pterional approaches for anterior circulation aneurysms, and it is never exposed with mini invasive approaches. Direct electrical cortical stimulation might also increase the risk of epileptic seizures. For MEP monitoring transcranial electric stimulation is made by electrodes positioned at C1 and C2 according to the 10–20 International System (IS). These electrodes continuously stimulate the motor area during surgery by train stimuli (the pulse trains used are different according to the users; there are reported 4–8 pulse trains) [37, 43]. MEPs are recorded by subcutaneous needle electrodes from the abductor pollicis brevis and abductor hallucis muscles. The baseline MEPs are recorded at the beginning of the surgery, and it is found a compromise with the surgeon between continuous MEP recording and the movements caused by the stimuli tolerated by the surgeon for the dissection and clipping procedure. To avoid false-negative results on MEPs, the stimulus applied for MEP acquisition should be minimal not to activate the distal motor pathways [44]. To avoid false-positive results, brain shift due to the cerebrospinal loss after cisternal opening should be considered.

The reduction of 50% in MEP amplitude or MEP disappearance is considered as an alarm criterion. The surgeon changes the strategy to tempt to recover the MEPs. Temporary clipping is interrupted, or the definitive clip is released. The arterial blood pressure may be increased; local irrigation with saline and papaverine may be tempted. The surgical procedure is temporarily stopped, whenever it is possible (the aneurysm is not intraoperatively ruptured, or it is not opened by the surgeon) to permit the MEPs to recover. The MEP deterioration can be reversible, when the MEPs return to more than 50% of baseline amplitude.

Another methodology of MEP monitoring is by direct cortical stimulation.

Upper limb SSEPs are recorded from C3 and C4 by electrically stimulating the contralateral median nerve at the wrist. Lower limbs are recorded by electric stimulation of the contralateral tibial nerve at the medial malleolus. Recordings from Cz′ and Fz are made according to the 10–20 International System [37].

A total intravenous anesthesia (TIVA) is used. Neuromuscular blockers are not used during surgery, unless extremely necessary. Muscle relaxants are used only for endotracheal intubation.

An early experimental study by Branston et al. in 1974 showed that there is a failure of neuronal function in the cortex when the local blood flow falls below about 16 ml/100 g/min. This failure becomes manifest as a progressive reduction in the amplitude of the surface recorded SSEP, and this results in the abolition of the SSEPs if the flow is below about 12 ml/l00 g/min. There is a close relationship between reduced cerebral blood flow (CBF: 12–16 ml/100 g/min) and a reduction in SSEP amplitude or SSEP abolition [45].

MEP monitoring has higher diagnostic accuracy than SSEPs in predicting the occurrence of a postoperative neurological deficit [46].

Li et al. analyzed 92 patients operated for cerebral aneurysms that showed intraoperative MEP deterioration. They found that a MEP deterioration duration greater than or equal to 13 min in intracranial aneurysm surgery was significantly associated with postoperative motor deficits [43].

7. Awake surgery in the surgery of intracranial aneurysms

The principles of neuro-oncological monitoring are being gradually transferred to cerebral aneurysm surgery. In neuro-oncological surgery, the best way to monitor

the neurological and neurophysiological function is by awake surgery. Awake surgery of cerebral aneurysms is controversial for the potential consequences of intraoperative aneurysm rupture. Intraoperative aneurysm rupture does not impact the clinical outcome. This would not be true if the clipping was performed in awake surgery. However, in selected case of clipping of the aneurysms of the dominant hemisphere, the monitoring of the language function and thus awake surgery would be useful. Abdulrauf et al. reported awake surgery in 30 unruptured cerebral aneurysms [47]. In three patients the strategy affected the outcome, since the removal of the temporary clipping determined the reversal of the clinical neurological and neurophysiological changes. One patient developed a neurological damage depending on the clipping, but that could not be reversed by the clip repositioning. Three patients developed hemiparesis without changes in MEPs; thus they were false negatives. The important was the visual testing after final clipping in four patients with internal carotid artery ophthalmic segment aneurysms, and one of these patients required repositioning of the clip. Three patients underwent an intraoperative vessel occlusion test, since the vessel occlusion was part of the permanent treatment of the aneurysm.

8. Blind spot avoidance and mini invasive approaches

8.1 Endoscopic-assisted clipping

The endoscope is mainly used as assistance during microsurgical clipping of intracranial aneurysms. The endoscopic-assisted microsurgery has been promoted by the father of the keyhole approaches Perneczky and by Fries [48]. The endoscope can be used for inspection before clipping; also clipping under endoscopic view and post clipping evaluation to observe the perforator integrity can be performed [49]. The endoscope allows the visualization of the blind spots to the microscope, allows thus the vision around corners, and enhances the visualization. It can potentially ameliorate the quality of treatment. The microscope enables vision in a straight line, while the endoscope enables the visualization of angles. The endoscope can be complementary to the microscope. However, the surgeon must be familiar with the endoscope use, not to cause iatrogenic damage [50].

8.2 Endoscopic ICG-VA

Endoscopic ICG-VA is an important development that combines the benefits of the vision behind the corners of endoscopy and the vessel visualization of ICG-VA [51]. The combination of both is particularly important for the visualization of the perforating arteries hidden in blind spots.

8.3 Pure endoscopic transcranial or endonasal

Purely endoscopic approach to cerebral aneurysms is a potential method in its very beginning. There are case reports of endonasal clipping of aneurysms and of endoscopic transcranial pure approaches.

Radovanovic reports a cadaveric study of a purely endoscopic transpterional port craniotomy to access lesions involving the cavernous sinus and the antero-lateral skull base [52]. In the illustration videos, the author includes clipping of a middle cerebral artery aneurysm through this approach. There are also strictly selected case reports or small series of endoscopic endonasal clipping of anterior

circulation aneurysms [53]. Other case reports regard the pure endoscopic endonasal transclival approach for clipping of posterior circulation aneurysms [54]. These minimally invasive approaches constitute very limited experiences, and they need very deep expertise; otherwise they become dangerous. Safety must never be sacrificed for achieving minimal invasiveness.

8.4 Exoscope

Exoscopes are projected to combine the benefits of neurosurgical microscopes and endoscopes. With the exoscope, the surgeon looks at the monitor while operating, and the entire surgical team has the same view as the primary surgeon. The 3D 4K-HD exoscopes have favorable ergonomics to visualize angles maintaining the surgeon's comfort, maneuverability, and immersive visual experience. The assistant positioning relative to the surgeon can be problematic during surgery. ORBEYE (Olympus, Tokyo, Japan) exoscope has been used in aneurysm surgery with reported excellent visualization of the arterial tree [55], but with a subjective disadvantage in the visualization of bleeding tissue particularly in the muscle or white matter [56]. This new technology is proposed with advantages and limits, and time will tell its exact role in the future.

9. Perforating artery evaluation

The perforating arteries are small twigs of the main cerebral arteries that irrorate the paramedian region of the brainstem, the diencephalon, the basal ganglia, and the internal capsule [57]. Commonly, the perforators are small vessels of less than 1 mm in diameter, except for some lenticulostriate arteries (LSAs) and Heubner arteries larger than 1 mm. They may be multiple and sometimes anastomose. Although the same territory can be supplied by multiple perforators, the consequence of the occlusion of a perforator is unpredictable and more often than not results in a neurological deficit. Perforator infarction was shown as an independent risk factor of poor functional outcome in a series of anterior communicating aneurysms [58]. In the surgery of cerebral aneurysms, it is essential to preserve the perforating arteries. While the flow preservation of a larger artery is easier and eventually the flow can be replaced by revascularization, the perforator damage is more feared and less predictable. The monitoring of the perforators is fundamental. ICG-VA has the advantage of being able to visualize the perforating arteries. As a speculation, it is assumed that flowmetry and SSEPs account for the cortical gray matter function while the MEPs for the subcortical white matter function. Thus, MEPs can be used to evaluate the perforating artery function, and ICG-VA allows their visualization along with endoscopes, exoscopes, and endoscopic ICG-VA that permit the vision behind blind points.

10. Complementary tools

None of the tools described is superior to the others, and their role in improving clinical results in aneurysm surgery is complementary. Della Puppa et al. have described the complementary role of enhanced visualization with ICG-VA and maneuvers and signs to better interpret the data, along with monitoring of function (IONM) and perfusion (flowmetry) [37].

11. Quantitative magnetic resonance angiography and donor selection in bypass surgery for flow replacement

Quantitative magnetic resonance angiography (QMRA) is an MRA that permits blood flow quantification of the major cerebral vessels [59, 60]. QMRA is implemented with a commercially available software called Noninvasive Optimal Vessel Analysis (NOVA) (VasSol, Inc., Chicago, Illinois). MRA creates the cerebral vascular tree. A double-oblique scan is performed using a gated two-dimensional phase-contrast MRA imaged perpendicular to the vessel of interest axis. The software generates a flow report with the mean volumetric flow rate (mL/min) of the vessels of interest. QMRA data have been validated in vivo and have shown proportional differences, around 10% to direct transit time flow measurements [60]. QMRA is reported to be used preoperatively to evaluate the flow of the major vessels in patients with cerebral aneurysm that would require a bypass, when vessel sacrifice is needed to treat the aneurysm [42]. Intraoperatively a flow-based algorithm can be used to determine the flow needed to replace the flow sacrificed. Transit time flow measurements are used for intraoperative measurements. These measurements indicate which is the more appropriate donor graft to be used for the anastomosis. This methodology has shown that superficial temporal artery is often sufficient to replace flow, which renders the surgery easier than using vein or radial artery grafts. QMRA is used in follow-up to detect the bypass flow. The hemisphere flows are calculated and are maintained over time. Details of the algorithm used for calculation of the flow needed to be replaced and the donor flow potential can be found in the paper by Rustemi et al. [42].

12. Intracranial-intracranial bypass

Lawton has rendered popular the intracranial-intracranial (IC-IC) bypass for flow replacement in complex aneurysms [61]. This type of bypass, although more elegant, has several pitfalls and requires very experienced surgeons. IC-IC bypass puts at dangers both the donor and receiving territories. The anastomosis is deep and more difficult to be performed. However, in selected cases and experienced hands, it represents an advancement.

13. Sutureless excimer laser-assisted nonocclusive anastomosis (SELANA)

The ELANA has been developed for intracranial bypass without the need for temporary recipient occlusion. A sutureless variant of the ELANA—the SELANA slide—showed a preclinical success and clinical application started. Unfortunately, it was not shown suitable for clinical applications [62].

14. Future prospective

Many technological innovations now assist the surgeon in the treatment of cerebral aneurysms. Also, different clips are used over the years. However, the clip principle has not changed. A change in occlusion strategy, based on principles other than clipping, might be desirable for the future. There is space for new ideas and new principles. The basic research studies for cerebral aneurysms are focused

on wall analysis and flow stimulations. If advances will become more solid, in the future, cerebral aneurysms will not need neurosurgeons or neuroendovascular radiologists.

15. Conclusions

Surgery of cerebral aneurysms has advanced over the years. Innovations are rapid in this technological era. Many innovations are now routinely used in the clinical practice; others will be soon implemented. The technological innovations currently used in the surgery of cerebral aneurysms are summarized in this chapter. The comprehension of the biology and pathology might in the future render the aneurysm a medical disease.

Conflict of interest

Nothing to declare.

Acronyms and abbreviations

IONM	intraoperative neurophysiological monitoring
ICG-VA	indocyanine green video angiography
ICG	indocyanine green
NIR	near-infrared
FDA	Food and Drug Administration
M4	distal middle cerebral artery
MEPs	motor evoked potentials
SSEPs	somatosensory evoked potentials
IS	International System
TIVA	total intravenous anesthesia
CBF	cerebral blood flow
LSAs	lenticulostriate arteries
QMRA	quantitative magnetic resonance angiography
NOVA	Noninvasive Optimal Vessel Analysis
IC-IC	intracranial-intracranial
ELANA	excimer laser-assisted nonocclusive anastomosis
SELANA	sutureless ELANA

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References

[1] Raabe A, Beck J, Gerlach R, Zimmermann M, Seifert V. Near-infrared indocyanine green video angiography: A new method for intraoperative assessment of vascular flow. Neurosurgery. 2003;**52**:132-139; discussion 139

[2] Rustemi O, Alaraj A, Shakur SF, Orning JL, Du X, Aletich VA, et al. Detection of unruptured intracranial aneurysms on noninvasive imaging. Is there still a role for digital subtraction angiography? Surgical Neurology International. 2015;**6**:175. DOI: 10.4103/2152-7806.170029

[3] Alexander TD, Macdonald RL, Weir B, Kowalczuk A. Intraoperative angiography in cerebral aneurysm surgery: A prospective study of 100 craniotomies. Neurosurgery. 1996;**39**:10-18

[4] Drake C, Allcock J. Postoperative angiography and the slipped clip. Journal of Neurosurgery. 1973;**39**:683-689

[5] Feuerberg I, Lindquist C, Lindqvist M, Steiner L. Natural history of postoperative aneurysm rests. Journal of Neurosurgery. 1987;**66**:30-34

[6] Macdonald RL, Wallace MC, Kestle JR. Role of angiography following aneurysm surgery. Journal of Neurosurgery. 1993;**79**:826-832

[7] Proust F, Hannequin D, Langlois O, Freger P, Creissard P. Causes of morbidity and mortality after ruptured aneurysm surgery in a series of 230 patients. The importance of control angiography. Stroke. 1995;**26**:1553-1557

[8] Rauzzino MJ, Quinn CM, Fisher WS. Angiography after aneurysm surgery: Indications for selective angiography. Surgical Neurology. 1998;**49**:32-40

[9] Samson D, Hodosh R, Reid W, Beyer CW, Clark WK. Risk of intracranial aneurysm surgery in the good grade patient: Early versus late operation. Neurosurgery. 1979;**5**:422-426

[10] Suzuki J, Kwak R, Katakura R. Review of incompletely occluded surgically treated cerebral aneurysms. Surgical Neurology. 1980;**13**:306-310

[11] Della Puppa A, Volpin F, Gioffre G, Rustemi O, Troncon I, Scienza R. Microsurgical clipping of intracranial aneurysms assisted by green indocyanine videoangiography (ICG-VA) and ultrasonic perivascular microflow probe measurement. Clinical Neurology and Neurosurgery. 2014;**116**:35-40. DOI: 10.1016/j.clineuro.2013.11.004

[12] Roessler K, Krawagna M, Dörfler A, Buchfelder M, Ganslandt O. Essentials in intraoperative indocyanine green videoangiography assessment for intracranial aneurysm surgery: Conclusions from 295 consecutively clipped aneurysms and review of the literature. Neurosurgical Focus. 2014;**36**:E7. DOI: 10.3171/2013.11.FOCUS13475

[13] Riva M, Amin-Hanjani S, Giussani C, De Witte O, Bruneau M. Indocyanine green videoangiography in aneurysm surgery: Systematic review and meta-analysis. Neurosurgery. 2018;**83**:166-180. DOI: 10.1093/neuros/nyx387

[14] Gekka M, Nakayama N, Uchino H, Houkin K. Factors influencing cerebral aneurysm obliteration and reliability of indocyanine green video-angiography. Acta Neurochirurgica. 2018;**160**:269-276. DOI: 10.1007/s00701-017-3379-6

[15] Della Puppa A, Rustemi O, Rossetto M, Gioffrè G, Munari M, Charbel FT, et al. The "squeezing

maneuver" in microsurgical clipping of intracranial aneurysms assisted by indocyanine green videoangiography. Neurosurgery. 2014;**10**:208-212; discussion 212-203. DOI: 10.1227/NEU.0000000000000334

[16] Della Puppa A, Rustemi O, Scienza R. The "ICG Entrapment Sign" in cerebral aneurysm surgery assisted by indocyanine green videoangiography. World Neurosurgery. 2017;**97**:287-291. DOI: 10.1016/j.wneu.2016.10.011

[17] Della Puppa A, Rustemi O, Gioffrè G, Causin F, Scienza R. Transdural indocyanine green video-angiography of vascular malformations. Acta Neurochirurgica. 2014;**156**:1761-1767. DOI: 10.1007/s00701-014-2164-z

[18] Rustemi O, Scienza R, Della Puppa A. Indocyanine green videoangiography application in distal (M4) middle cerebral artery aneurysm surgery. Journal of Neurosurgical Sciences. 2017;**61**:351-354. DOI: 10.23736/S0390-5616.16.03271-9

[19] Rustemi O, Cester G, Causin F, Scienza R, Della Puppa A. Indocyanine green videoangiography transoptic visualization and clipping confirmation of an optic splitting ophthalmic artery aneurysm. World Neurosurgery. 2016;**90**:705.e5-705.e8. DOI: 10.1016/j.wneu.2016.03.010

[20] Della Puppa A, d'Avella E, Volpin F, Rustemi O, Gioffre' G, Scienza R. Indocyanine green videoangiography (ICG-VA) in parasagittal meningiomas surgery. Considerations on veins management and brain function preservation. Acta Neurochirurgica. 2013;**155**:1475-1476. DOI: 10.1007/s00701-013-1784-z

[21] Della Puppa A, Rustemi O, Gioffrè G. Is the intra-operative application of indocyanine green effective in retro-orbital surgery? Acta Neurochirurgica. 2014;**156**:1419-1420. DOI: 10.1007/s00701-014-2001-4

[22] Della Puppa A, Rustemi O, Gioffrè G, Rolma G, Grandis M, Munari M, et al. Application of indocyanine green video angiography in parasagittal meningioma surgery. Neurosurgical Focus. 2014;**36**:E13. DOI: 10.3171/2013.12.FOCUS13385

[23] Rustemi O, Scienza R, Della Puppa A. ICG-VA application in subtemporal transtentorial treatment of a Cognard V dural arteriovenous fistula. Neurosurg Focus. 2016;**40**(Video Suppl 1):V7. DOI: 10.3171/2016.1.FocusVid.15423

[24] Rustemi O, Scienza R, Della Puppa A. Intra-operative devascularization of petroclival meningiomas by ICG-VA-guided Bernasconi & Cassinari artery identification. Acta Neurochirurgica. 2016;**158**:427-428. DOI: 10.1007/s00701-016-2704-9

[25] Rustemi O, Scienza R, Della Puppa A. Utility of indocyanine green videoangiography in subcortical arteriovenous malformation resection. Neurosurgical Focus. 2017;**43**(Video Suppl 1):V10. DOI: 10.3171/2017.7.FocusVid.1774

[26] Scerrati A, Della Pepa GM, Conforti G, Sabatino G, Puca A, Albanese A, et al. Indocyanine green video-angiography in neurosurgery: A glance beyond vascular applications. Clinical Neurology and Neurosurgery. 2014;**124**:106-113. DOI: 10.1016/j.clineuro.2014.06.032

[27] Hoffman WE, Charbel FT, Ausman JI. Cerebral blood flow and metabolic response to etomidate and ischemia. Neurological Research. 1997;**19**:41-44

[28] Charbel FT, Hoffman WE, Misra M, Hannigan K, Ausman JI. Role of a perivascular ultrasonic micro-flow

probe in aneurysm surgery. Neurologia Medico-Chirurgica (Tokyo). 1998;**38**(Suppl):35-38

[29] Charbel FT, Hoffman WE, Misra M, Ostergren L. Ultrasonic perivascular flow probe: Technique and application in neurosurgery. Neurological Research. 1998;**20**:439-442

[30] Charbel FT, Gonzales-Portillo G, Hoffman WE, Ostergren LA, Misra M. Quantitative assessment of vessel flow integrity for aneurysm surgery. Technical note. Journal of Neurosurgery. 1999;**91**:1050-1054

[31] Amin-Hanjani S, Meglio G, Gatto R, Bauer A, Charbel FT. The utility of intraoperative blood flow measurement during aneurysm surgery using an ultrasonic perivascular flow probe. Neurosurgery. 2006;**58**:ONS-305-ONS-312; discussion ONS-312

[32] Franklin DL, Ellis RS, Rushmer RF. Ultrasonic transit time flowmeter. IRE Trans Biomed Eng. 1962:44-49

[33] Plass KG. A new ultrasonic flowmeter for intravascular application. IEEE Transactions on Biomedical Engineering. 1964;**BME-ll**:154-156

[34] Lundell A, Bergqvist D, Mattsson E, Nilsson B. Volume blood flow measurements with a transit time flowmeter: An in vivo and in vitro variability and validation study. Clinical Physiology. 1993;**13**:547-557

[35] Drost CJ. Vessel diameter-independent volume flow measurements using ultrasound. Proceedings of San Diego Biomedical Symposium. 1978;**17**:299

[36] Barnes RJ, Comline RS, Dobson A, Drost CJ. An implantable transit-time ultrasonic blood flow-meter. The Journal of Physiology. 1983;**34**:2

[37] Della Puppa A, Rossetto M, Volpin F, Rustemi O, Grego A, Gerardi A, et al. Microsurgical clipping of intracranial aneurysmsassistedbyneurophysiological monitoring, microvascular flow probe, and ICG-VA: Outcomes and intraoperative data on a multimodal strategy. World Neurosurgery. 2018;**113**:e336-e344. DOI: 10.1016/j.wneu.2018.02.029

[38] Pasqualin A, Meneghelli P, Musumeci A, Della Puppa A, Pavesi G, Pinna G, et al. Intraoperative measurement of arterial blood flow in aneurysm surgery. Acta Neurochirurgica. Supplement. 2018;**129**:43-52. DOI: 10.1007/978-3-319-73739-3_7

[39] Della Puppa A, Scienza R, Rustemi O, Gioffré G. Can the efficacy of indocyanine green videoangiography in cerebral arterio-venous malformations surgery be further improved? Neurosurgery. 2014;**75**:E732-E734. DOI: 10.1227/NEU.0000000000000531

[40] Della Puppa A, Rustemi O, Scienza R. Intraoperative flow measurement by microflow probe during surgery for brain arteriovenous malformations. Neurosurgery. 2015;**11**:268-273. DOI: 10.1227/NEU.0000000000000741

[41] Della Puppa A, Rustemi O, Scienza R. Intraoperative flow measurement by microflow probe during spinal dural arteriovenous fistula surgery. World Neurosurgery. 2016;**89**:413-419. DOI: 10.1016/j.wneu.2016.02.043

[42] Rustemi O, Amin-Hanjani S, Shakur SF, Du X, Charbel FT. Donor selection in flow replacement bypass surgery for cerebral aneurysms: Quantitative analysis of long-term native donor flow sufficiency. Neurosurgery. 2016;**78**:332-341; discussion 341-342. DOI: 10.1227/NEU.0000000000001074

[43] Li Z, Fan X, Wang M, Tao X, Qi L, Ling M, et al. Prediction of postoperative motor deficits using motor evoked potential deterioration duration in intracranial aneurysm surgery. Clinical Neurophysiology. 2019;**130**:707-713. DOI: 10.1016/j.clinph.2019.02.010

[44] Guo L, Gelb AW. The use of motor evoked potential monitoring during cerebral aneurysm surgery to predict pure motor deficits due to subcortical ischemia. Clinical Neurophysiology. 2011;**122**:648-655

[45] Branston NM, Symon L, Crockard HA, Pasztor E. Relationship between the cortical evoked potential and local cortical blood flow following acute middle cerebral artery occlusion in the baboon. Experimental Neurology. 1974;**45**:195-208. DOI: 10.1016/0014-4886(74)90112-5

[46] Thomas B, Guo D. The diagnostic accuracy of evoked potential monitoring techniques during intracranial aneurysm surgery for predicting postoperative ischemic damage: A systematic review and meta-analysis. World Neurosurgery. 2017;**103**:829-840.e3. DOI: 10.1016/j.wneu.2017.04.071

[47] Abdulrauf SI, Vuong P, Patel R, Sampath R, Ashour AM, Germany LM, et al. "Awake" clipping of cerebral aneurysms: Report of initial series. Journal of Neurosurgery. 2017;**127**:311-318. DOI: 10.3171/2015.12.JNS152140 Erratum in: J Neurosurg. 2017;127:445

[48] Perneczky A, Fries G. Endoscope-assisted brain surgery: Part 1—Evolution, basic concept, and current technique. Neurosurgery. 1998;**42**:219-224; discussion 224

[49] Fischer G, Oertel J, Perneczky A. Endoscopy in aneurysm surgery. Neurosurgery. 2012;**70**:184-190; discussion 190-191. DOI: 10.1227/NEU.0b013e3182376a36

[50] Taniguchi M, Takimoto H, Yoshimine T, Shimada N, Miyao Y, Hirata M, et al. Application of a rigid endoscope to the microsurgical management of 54 cerebral aneurysms: Results in 48 patients. Journal of Neurosurgery. 1999;**91**:231-237

[51] Nishiyama Y, Kinouchi H, Senbokuya N, Kato T, Kanemaru K, Yoshioka H, et al. Endoscopic indocyanine green video angiography in aneurysm surgery: An innovative method for intraoperative assessment of blood flow in vasculature hidden from microscopic view. Journal of Neurosurgery. 2012;**117**:302-308. DOI: 10.3171/2012.5.JNS112300

[52] Andrade-Barazarte H, Patel K, Turel MK, Doglietto F, Agur A, Gentili F, et al. The endoscopic transpterional port approach: Anatomy, technique, and initial clinical experience. Journal of Neurosurgery. 2019;**22**:1-11. DOI: 10.3171/2018.10.JNS171898

[53] Xiao LM, Tang B, Xie SH, Huang GL, Wang ZG, Zeng EM, et al. Endoscopic endonasal clipping of anterior circulation aneurysm: Surgical techniques and results. World Neurosurgery. 2018;**115**:e33-e44. DOI: 10.1016/j.wneu.2018.03.093

[54] Enseñat J, Alobid I, de Notaris M, Sanchez M, Valero R, Prats-Galino A, et al. Endoscopic endonasal clipping of a ruptured vertebral-posterior inferior cerebellar artery aneurysm: Technical case report. Neurosurgery. 2011;**69**:onsE121-onsE127; discussion onsE127-128. DOI: 10.1227/NEU.0b013e318223b637

[55] Khalessi AA, Rahme R, Rennert RC, Borgas P, Steinberg JA, White TG, et al. First-in-man clinical experience using a high-definition 3-dimensional exoscope system for microneurosurgery. Operative Neurosurgery (Hagerstown).

2019;**16**:717-725. DOI: 10.1093/ons/opy320

[56] Langer DJ, White TG, Schulder M, Boockvar JA, Labib M, Lawton MT. Advances in intraoperative optics: A brief review of current exoscope platforms. Operative Neurosurgery (Hagerstown). 2019. pii: opz276. DOI: 10.1093/ons/opz276

[57] Djulejić V, Marinković S, Milić V, Georgievski B, Rašić M, Aksić M, et al. Common features of the cerebral perforating arteries and their clinical significance. Acta Neurochirurgica. 2015;**157**:743-754; discussion 754. DOI: 10.1007/s00701-015-2378-8

[58] Yamamoto Y, Fukuda H, Yamada D, Kurosaki Y, Handa A, Lo B, et al. Association of perforator infarction with clinical courses and outcomes following surgical clipping of ruptured anterior communicating artery aneurysms. World Neurosurgery. 2017;**107**:724-731. DOI: 10.1016/j.wneu.2017.08.086

[59] Zhao M, Charbel FT, Alperin N, Loth F, Clark ME. Improved phase-contrast flow quantification by three-dimensional vessel localization. Magnetic Resonance Imaging. 2000;**18**:697-706

[60] Calderon-Arnulphi M, Amin-Hanjani S, Alaraj A, Zhao M, Du X, Ruland S, et al. In vivo evaluation of quantitative MR angiography in a canine carotid artery stenosis model. AJNR. American Journal of Neuroradiology. 2011;**32**:1552-1559. DOI: 10.3174/ajnr.A2546

[61] Abla AA, Lawton MT. Anterior cerebral artery bypass for complex aneurysms: An experience with intracranial-intracranial reconstruction and review of bypass options. Journal of Neurosurgery. 2014;**120**:1364-1377. DOI: 10.3171/2014.3.JNS132219

[62] van Doormaal TPC, de Boer B, Redegeld S, van Thoor S, Tulleken CAF, van der Zwan A. Preclinical success but clinical failure of the sutureless excimer laser-assisted non-occlusive anastomosis (SELANA) slide. Acta Neurochirurgica. 2018;**160**:2159-2167. DOI: 10.1007/s00701-018-3686-6