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CLINICAL ARTICLE

Circulatory arrest and deep hypothermia for the treatment of complex intracranial aneurysms—results from a single European center

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Abstract
Background Vascular neurosurgery faces the controversial discussion about the need for deep hypothermia and circulatory arrest (dh/ca) for the treatment of complex cerebral aneurysms. In this retrospective analysis, we present our experience in the treatment of 26 giant and large cerebral aneurysms under profound hypothermia and circulatory arrest.
Methods All patients were treated surgically under dh/ca. Seventeen patients had aneurysms of the anterior circulation, and nine patients had aneurysms of the posterior circulation. Thrombosis or calcification was found in ten patients. Eleven patients presented with subarachnoid hemorrhage. The seven patients with the longest circulation arrest time were analyzed in detail.
Results Subarachnoid hemorrhage led to hospital admission in 42% (n=11) of cases. The overall mortality was 11.5%, and the overall morbidity was 15%. Ten patients deteriorated transiently but fully recovered. The mean age, Glasgow Coma Score, Fisher, and Hunt and Hess Score correlated significantly with the long-term outcome. Circulation arrest time correlated significantly to the neurological outcome on discharge. All patients with prolonged circulation arrest times had wide aneurysmal necks, and four had adjacent vessels to the dome or the parent vessel included in the neck. We observed a significant increase of neurological deficits immediately postoperatively, but this neurological deterioration resolved over time.
Conclusions We observed neurological deterioration immediately postoperatively in 13 patients, but all patients fully recovered within 6 months except for four patients. A long cardiac arrest time reflected complex pathoanatomical conditions. We conclude that the clipping procedure under deep hypothermia and circulatory arrest remains a pivotal armament in complex vascular neurosurgery.

Keywords Deep hypothermia · Circulatory arrest · Giant aneurysm · Vascular neurosurgery

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Introduction

In recent years, there has been an ongoing controversy in vascular neurosurgery about the need for profound hypothermia and circulatory arrest for the neurosurgical treatment of complex large or giant aneurysms. Improved approaches to the cranial base, revealing full anatomic exposure of the aneurysm and its related structures, and recent advances in neuroradiological interventions apparently seem to distinctively reduce the indication for the interdisciplinary neurosurgical–cardiovascular approach.

All of the authors of the few large series of patients undergoing deep hypothermia and cardiopulmonary bypass for the treatment of intracranial aneurysms and almost all of the reviewers and critics [1, 4, 5, 10, 11, 16, 17, 22, 23, 27, 28] expressly outline the need for the definition of patient characteristics, preoperative clinical and neurological conditions, pathoanatomical factors concerning the cerebral vasculature, and intraoperative paradigms that can be held as useful for the decision of whether to treat a complex large or giant aneurysm conventionally under normothermic conditions or interventionally under profound hypothermia and cardiac standstill.

Besides the general debate as to if and when a benefit is to be expected from this relatively risky and costly interdisciplinary procedure, the experts' opinion that the clipping procedure under profound hypothermia should be reserved for aneurysms arising from the posterior parts of the circle of Willis is a contentious issue [1, 4, 5, 7, 8, 11, 12, 14, 16–19, 22, 27, 28, 30]. Some authors recommend hypothermia and circulatory arrest for aneurysmal malformations of the midbasilar or the basilar apex exclusively [17, 22, 24, 27, 28], whereas Mack et al. presented 66 patients undergoing 66 hypothermic procedures with 33 aneurysms (50%) located in the anterior parts of the circle of Willis, in the largest such series to date [17].

In consideration of this current controversy, we intend to contribute our experience and the lessons learned from our cases as one of the few European Neurosurgical Centers that still uses clipping of complex large and giant aneurysms under profound hypothermia and circulatory arrest in selected cases.

In this context, we present an outcome analysis after a few weeks and after 6 months, postoperatively, in 26 patients who underwent 26 hypothermic procedures with respect to preoperative clinical condition, pathoanatomical facts, intraoperative technical data, and clinical course.

Conceivably, this retrospective analysis represents one of the last large series in this context.

Patients and method

Patient population/demographics

Between 1992 and 2007, we operated on 863 cerebral aneurysms, 154 of which were treated endovascularly. A total of 26 (14 males, 12 females) of them were considered for treatment under dh/ca and underwent 26 procedures, of which eight patients had been reported previously [1]. The mean age was 45.6 years (range 17 to 71 years). In five patients (19%), conventional clipping had been attempted previously in our department, while another patient underwent two clipping attempts in another institution before transferring to our institution (see Fig. 1).

Fig. 1 Giant aneurysm of the right MCA after two frustrated clipping attempts elsewhere. The aneurysm was completely clipped under dh/ca

Aneurysm characteristics

Nine of the aneurysms (34%) were located in the posterior circulation, and the other 17 aneurysms (66%) arose from the arteries of the anterior part of the circle of Willis (see Table 1).

Three aneurysms of the posterior circulation were classified as giant aneurysms (>24.9 mm, 33%), and two aneurysms were classified as large (<24.9 cm, 22%). Four aneurysms originated from the basilar artery (BA), and another three aneurysms arose from the posterior communicating artery. The others were comprised of one aneurysm of the vertebral artery and one aneurysm of the anterior inferior cerebellar artery.

One of the BA aneurysms was associated with an arteriovenous malformation and another BA aneurysm with a 2-mm middle cerebral artery (MCA) aneurysm.

Eight aneurysms (47%) of the anterior circulation were classified as giant, whereas seven aneurysms were large.

In the anterior circulation, we found seven aneurysms originating from the MCA, and six were located in the internal carotid artery (ICA). The others included one aneurysm of the anterior communicating artery and three aneurysms of the anterior cerebral artery (ACA).

Overall, a calcification or thrombosis was found in ten aneurysms (34%). The mean size of all aneurysms was 24.8 mm (range 10.0 to 50.0 mm).

All pathoanatomical details are summarized in Table 1.

Specifically, the morphology of the large- (n=8) and regular-sized (n=6) aneurysms was extensively examined

Table 1 Demographical and pathoanatomical details of the cohort

Factor	Population characteristics	
	No. of patients	Mean ± SD
Patient characteristics		
Age in years (mean)	45.6 (17–71)	14.8
Sex		
Male	14 (54%)	
Female	12 (46%)	
Clinical preoperative condition (GCS)		12±4.3 (range 15–3)
Aneurysm characteristics		
Size in millimeter (mean)	24.8 (10–50)	1.2
Anterior	17 (66%)	
Giant	8 (47%)	
Posterior	9 (34%)	
Giant	3 (33%)	
Thrombosed or calcified	10 (31%)	
Location		
Anterior	17	
MCA	7 (41%)	
ICA	6 (35%)	
ACA	3 (18%)	
Acomm	1 (6%)	
Posterior	9	
BA	4 (44%)	
Pcomm	3 (33%)	
VA	1 (11%)	
AICA	1 (11%)	

SD standard deviation, *GCS* Glasgow Coma Scale, *MCA* middle cerebral artery, *ICA* internal carotid artery, *ACA* anterior cerebral artery, *Acomm* anterior communicating artery, *BA* basilar artery, *Pcomm* posterior communicating artery, *VA* vertebral artery, *AICA* anterior inferior cerebellar artery

due to radiological and operative findings, as well as the distribution in the anterior and posterior part of the circle of Willis. Four of the anterior-located (n=6) and both of the posterior-located large aneurysms have a dome/neck ratio of <1 (see Fig. 2); atherosclerotic plaques were described in four and thrombi in two of the six anterior-located large aneurysms, and atherosclerotic plaques were found in one of the posterior-located aneurysms, but no thrombi. One of the two regular-sized, anterior-located aneurysms had a neck wider than the dome and extended atherosclerotic plaques, while the other one included thrombi. Two of the posterior-located, regular-sized aneurysms (n=4) had dome/neck ratios of <1 (see Fig. 3), and two were extremely adherent to the surrounding dura and to the clivus, respectively.

One image of at least one case representing these different aneurysm populations (giant-, large-, and regular-sized) is presented (Figs. 1, 2, and 3).

Clinical presentation

Aneurysmal subarachnoid hemorrhage (SAH) led to hospital admission in 11 patients (42%), whereas 15 patients (58%) presented with an innocent aneurysm that was detected incidentally in the context of the evaluation of a neurological deficit or complaint. SAH occurred in four patients (44%) with aneurysms of the posterior circulation and in seven patients (41%) with aneurysms of the anterior circulation.

Eight of those patients with unruptured aneurysms complained about headache (53%), five patients presented with cranial nerve deficits (33%), one patient (6%) showed motor deficit (hemiparesis), and five patients (33%) showed clinical signs of acute increased intracranial pressure and internal hydrocephalus that could be confirmed by computed tomography. In one patient (6%), the aneurysm was detected incidentally by neuroimaging due to evaluation after a minor head trauma.

The patients presenting with aneurysmal SAH were classified according to Hunt and Hess (HH): HH I one patient (9%), HH II three patients (27%), HH III two patients (18%), HH IV four patients (36%), and HH V one patient (9%).

The initial computed tomography was assessed according to the score given by Fisher. Fisher grade II was found in two patients (18%); two patients were scored Fisher grade III (18%), and Fisher grade IV was detected in seven patients (63%).

Fig. 2 Large aneurysm of the right MCA presenting with an extremely wide neck, calcification, and partial thrombosis

The preoperative clinical presentation is described in Tables 2 and 3.

Technical aspects of and employment of dh/ca

The technical aspects of the clipping procedure under dh/ca have been described previously by Aebert and Brawanski [1].

Fig. 3 Regular-sized aneurysm of the BA. Note the wide neck (dome/neck ratio<1)

The aneurysm was exposed as far as safely possible by the neurosurgeon, and a needle probe was inserted for direct measurement of brain temperature. Intraoperatively, the integrity of the intravascular blood flow was checked with the micro-Doppler, intermittently.

After surgical exposure of the femoral vessels, the cannulae were inserted (21 or 23 French). To optimize blood rheology, we accomplished a dilution up to a hemoglobin value of 5 g/dl. Maximal cooling was performed with high pump flows until a brain temperature of 21°C was reached. Then, CPB was stopped, and the venous blood was actively or passively drained by pressure-controlled vacuum-assisted drainage into the venous reservoir.

Postoperatively, a CT scan was obtained in a 24-h interval, and DSA taken during the next few days confirmed complete occlusion of the aneurysm.

Statistical analysis

A neurological impairment score (NIS) was calculated and utilized for statistical analysis. The influence of surgical procedural factors was investigated by recording the cardiac arrest time, time of extracorporeal circulation, cooling time, counts of circulatory arrests per patient, brain temperature, rewarming time, and the number and time of transient clipping procedures. Spearman's rank correlation was used to detect associations between outcome, demographics, accompanying diseases, and surgical procedure. Mann–Whitney rank sum test was performed to detect the influence of SAH or ICH at presentation vs. the incidental detection of the aneurysm, large- vs. giant-size aneurysm, preexisting hypertensive disease, anterior vs. posterior aneurysm localization, and cardiac arrest time. Repeated measurements of the neurological severity score at the different time points were investigated using ANOVA on ranks followed by Dunn's procedure as a multiple-comparison test. p values less than 0.05 were considered statistically significant (SigmaStat 3.01.0, SPSS Inc. Chicago, IL, USA).

Results

Patient selection

The final decision of when to treat an aneurysm surgically under the condition of deep hypothermia and circulatory arrest was dependant on the neuroradiologists' evaluations and the neurosurgeons' appraisements (senior author A.B.) on the first line. The anatomical evaluation included the collateral flow to the aneurysm, wall properties, localization, perforator anatomy, and the form and size of the aneurysmal neck. All of these data were used to gauge the time for exclusion of the aneurysm from circulation during

Table 2 Clinical presentation/anterior circulation

Sex	Age	Lok	Diam	HH	Fisher	GCS	CN	Motor	Hydroceph	Headache
f	25	ACA	1.8	0	0	15	0	0	0	1
m	45	ACA	2	5	4	3	1	N/A	1	1
m	20	ACA	N/A	4	4	8	0	0	1	1
m	41	MCA	4	1	4	15	0	0	0	1
m	40	MCA	4.5	0	0	15	0	0	0	0
f	47	MCA	1.5	0	0	15	0	0	0	0
f	45	MCA	2.5	0	0	15	0	0	0	1
m	66	MCA	5	0	0	15	0	0	0	1
m	39	MCA	4	0	0	15	0	0	0	0
m	52	MCA	3.9	4	4	3	0	0	0	0
m	41	Acomm	2.8	3	2	12	1	0	0	1
f	31	ICA	2	0	0	15	1	0	0	1
f	61	ICA	1.5	3	4	6	0	1	1	1
f	48	ICA	1.5	0	0	15	0	0	0	1
m	26	ICA	3	0	0	15	0	0	0	0
m	17	ICA	1	0	0	15	0	0	0	0
f	56	ICA	2.5	2	3	10	0	0	1	1

Lok localization, *Diam* diameter, *HH* Hunt and Hess, *Fisher* Fisher Score, *GCS* Glasgow Coma Scale, *CN* cranial nerve deficit, *Motor* motor deficit, *Hydroceph* hydrocephalus, *ACA* anterior cerebral artery, *MCA* middle cerebral artery, *Acomm* anterior communicating artery, *ICA* internal cerebral artery

dissection and whether the collapse of the aneurysm dome could be anticipated under the "no-flow condition."

Six patients experienced a former clipping attempt under normothermic conditions (five at our center) that was abandoned intraoperatively.

All 26 patients underwent just one procedure of profound hypothermia and cardiac standstill.

Of the patients presenting with subarachnoid hemorrhage, the median Glasgow Coma Scale (GCS) was 8, and the mean GCS was 8.3 (range 3 to 15). All patients without subarachnoid hemorrhage had a GCS of 15.

Eleven patients suffered from arterial hypertension (41%), two patients had vascular diseases (artery occlusive disease, 7%), and one patient presented preoperatively with coronary heart disease (3%) but was judged operable by the cardiothoracic surgeons. One patient (3%) had an insulin-dependent diabetes mellitus.

Operative data

The surgical technique and perioperative regimen of the clipping procedure under deep hypothermia, and circulatory arrest is described elsewhere [1, 5, 17, 18, 23, 24, 27, 28, 31]. In six patients, we used temporal clipping to reduce the circulation standstill time after we had sufficient anatomical overview. In general, we tried to keep the standstill time as short as possible and used intermittent standstill periods whenever possible.

The mean cardiac arrest time was 23.4 min (range 3.0 to 102 min), the mean brain temperature was 18.4°C (range

Table 3 Clinical presentation/posterior circulation

Sex	Age	Lok	Diam	HH	Fisher	GCS	CN	Motor	Hydroceph	Headache
m	47	Pcomm	1.8	0	0	15	1	0	0	0
f	26	Pcomm	1.2	4	3	8	0	0	1	1
m	70	Pcomm	4.4	0	0	15	1	1	0	0
f	63	AICA	2.5	0	0	15	1	1	0	1
f	49	BA	2	4	4	3	0	0	1	1
f	45	BA	1	2	2	15	0	0	0	1
m	58	BA	1	2	4	13	1	0	0	1
f	71	BA	1.1	0	0	15	0	0	0	1
m	45	Vert	3	0	0	15	1	0	1	1

Note the relatively high number of CN deficits and headaches as initial symptoms

Lok localization, *Diam* diameter, *HH* Hunt and Hess, *Fisher* Fisher Score, *GCS* Glasgow Coma Scale, *CN* cranial nerve deficit, *Motor* motor deficit, *Hydroceph* hydrocephalus, *Pcomm* posterior communicating artery, *PCA* posterior cerebral artery, *BA* basilar artery, *Vert* vertebral artery

18.0°C to 20.0°C), and the mean tympanic temperature was 19.6°C (range 16.2°C to 23.3°C). Temporary clips were placed in six patients, and the mean duration of temporary clipping was 25.3 min (range 2.0 to 45.0 min). The cardiopulmonary bypass was performed in all patients with a mean duration of 136 min (range 45.0 to 240.0 minutes). The average number of circulatory standstills was three per patient, with a range of one to eight standstills per patient.

The mean cooling period lasted for 28.4 min (range 19.0 to 47.0), whereas the rewarming period had a mean duration of 49.9 min (range 28.0 to 123.0).

The complete operative data are presented in Table 4.

The operative records of the seven patients with the longest cardiac arrest times (range 32.0 to 102 min) were extracted, and their preoperative radiological findings were analyzed in detail (Table 5).

Treatment complications

No patient was lost to the long-term follow-up of 6 months.

Three patients died during the postoperative period in the intensive care unit. Thus, the treatment-related mortality in our series is 11.5%. All three of them presented with SAH (one patient with Hunt and Hess IV and two patients with Hunt and Hess II; two patients were classified as Fisher IV, and one patient was classified as Fisher III). One patient developed severe pneumonia and was treated with antibiotics and respiratory treatment. However, his pulmonary function rapidly deteriorated, and despite extracorporeal membranous oxygenation, he died due to septicemia on day 5 after the clipping procedure.

The second patient had his giant aneurysm of the basilar artery clipped but developed complete ischemia in the perforator territory, accompanied with a territorial infarction of the right posterior cerebral artery, and he died on day 6 after the clipping procedure.

The third patient died on day 12 after clipping of her large aneurysm of the ICA due to a postoperative infarction of the MCA and ACA territory of the left hemisphere. The transcranial Doppler sonography showed a rapid increase of the blood flow velocity over the left hemisphere, and angiography revealed severe vasospasm in the left MCA and ACA at 3 days after the neurosurgical procedure. Neither the spasmolytic therapy with the calcium antagonist nimodipine nor the intra-arterial spasmolysis with papaverine could prevent that fatal course.

Additionally, four patients developed clinically and radiologically detectable cerebral ischemia. Two of them developed partial infarctions in the MCA territories, and both were treated surgically by decompressive craniectomy. One patient developed partial infarction of left MCA territory and a complete infarction of the left PCA territory. All three of them were classified as Glasgow Outcome Scale (GOS) 3 at discharge and after 6 months. One patient showed new subarachnoidal blood in the quadrigeminal cistern and developed bihemispheric infarctions of the posterior cerebral artery during the clinical course. On discharge, he was classified as GOS 3 and did not recover within 6 months.

Thus, the treatment-related morbidity in our cohort amounts to 15% of all treated patients.

The surgical morbidity and mortality rates due to the location of the aneurysm in the anterior or posterior parts of the circle of Willis are shown in Table 6.

Patient outcome

Fourteen patients (54%) had a worsening of neurological function immediately postoperatively and experienced new neurological deficits. Only four of them had persistent deficits at the 6-month follow-up, whereas 12 patients improved significantly compared to the immediate postoperative status. From all 26 patients, 13 (50%) showed improvement of neurological symptoms at 6 months compared to the preoperative status.

The mean age correlated significantly with the outcome according to the GOS at 6 months ($p=0.008$) but not to the GOS at discharge. Furthermore, the patient group younger than 65 years had a significantly better GOS at 6 months compared to the group older than 65 years ($p=0.015$).

The preoperative GCS correlated significantly with both the GOS at discharge and the GOS at 6 months

Table 4 Intraoperative data related to the dh/ca procedure

Intraoperative feature	Mean	Standard dev.	Range
Cardiac arrest time in min.	23.4	±21.8	3.0 to 102.0
Brain temperature in °C	18.4	±0.6	18.0 to 20.0
Tympanic temperature in °C	19.6	±1.7	16.2 to 23.3
Temporary clipping in minute ($n=6$)	25.3	±14.5	2.0 to 45.0
Cardiopulmonary bypass time in minute	136.0	±51.8	45.0 to 240.0
Counts of cardiac standstill	3	±1.9	1 to 8
Cooling period in minute	28.4	±7.4	19.0 to 47.0
Rewarming period in minute	49.9	+/- 18.2	28.0 to 123.0

Table 5 Pathoanatomical details of the seven patients with extended cardiac arrest time. All of them had a complex structural morphology, four had bled preoperatively, and three had previously experienced a clipping attempt

Initials	Age	Sex	Diameter	Neck	Localization	Wall properties	SAH	Op. attempt prev.	Standstill time
E, M	41	m	4.0	Wide	MCA	Thrombosis, vessels adjacent to dome	Yes	None	68 min
L, E	49	f	2.0	Wide	BA	Irregular shape, Vessel out of neck	Yes	Clipping	34 min
L, L	41	m	2.8	Wide	Acomm	Calcification, Vessel out of neck	Yes	None	32 min
S, M	26	m	3.0	Wide	ICA	Thin wall	No	None	42 min
R, G	58	m	1.0	Wide	BA	Thrombosis	Yes	Clipping	48 min
S, W	45	w	2.5	Wide	MCA	Vessels adjacent to dome	No	Clipping	35 min
S, G	66	m	5.0	Wide	MCA	Irregular shape, thrombosis, and calcification	No	None	102 min

Op. Attempt prev operative attempt previously, *Arrest time* cardiac arrest time

(p=0.024 and 0.003, respectively), and the patients presenting with SAH had a significantly worse GOS at 6 months (p=0.023).

The patients presenting with neurological deficits preoperatively had a significantly worse GOS at 6 months but not at discharge (p=0.038 and p=0.104, respectively).

The Hunt and Hess score on admission as well as the initial Fisher score correlated significantly with the outcome at 6 months (p=0.011 and p=0.01, respectively).

Patients with postoperative neurological deterioration had a significantly longer cardiac arrest time (p=0.044). The other intraoperative paradigms had no significant effect on the neurological outcome.

Hypertension was identified as a negative predictor for the outcome at discharge (p=0.009) but not at 6 months.

A significant increase of neurological deficits immediately postoperatively was observed (p=0.008), but the neurological deterioration resolved over time. At 6 months, there were no significant differences due to the GOS and NIS (see Fig. 4).

We found no correlations between the outcome and the anatomical location of the aneurysm in the anterior or posterior circulation.

Table 6 Morbidity and mortality (distributed in the anterior and posterior parts of the circle of Willis)

Overall surgical mortality	3 (11.5%)
Anterior location	2 (7.5%)
Posterior location	1 (3.8%)
Overall surgical morbidity	13 (50%)
Anterior location	9
Posterior location	4
Permanent neurological deterioration	4 (15%)
Anterior location	3
Posterior location	1
Transient neurological deterioration	10 (38.5%)
Anterior location	7
Posterior location	3

Discussion

Technical aspects of complex aneurysms in general

Approximately 5–7% of all cerebral aneurysms are known to be large (diameter 15–25 mm) or giant (diameter ≥25 mm) [4, 11, 12, 32], and their 2-year mortalities range between 68% and 100% [19, 22, 24].

Large and giant aneurysms are often characterized by complex pathoanatomical conditions, particularly in which the wall properties are altered by intra-aneurysmal thrombosis or calcinosis of the dome and neck [5, 7, 8, 10, 11, 16, 17, 22, 24, 27, 28]. This specific type of aneurysm seems to be caused by a vasculopathy of the outer vessel wall [33]. This disease of the aneurysm wall induced by inflammatory processes seems to grow when the general growth mechanism is not interrupted by an operative treatment of the aneurysm, as data show after coiling. Here, the coils are included in the growing thrombus without much real effect [3]. A variety of perforating arteries can be found in and around the aneurysmal wall of the dome, feeding ambigu-

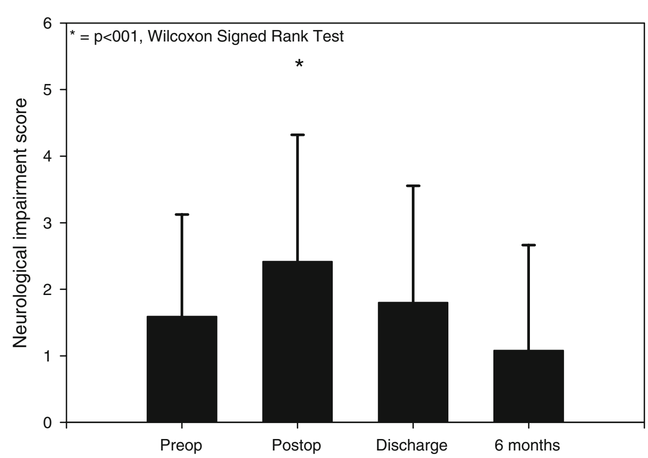

Fig. 4 Neurological impairment after hypothermic circulatory arrest. A total of 54% deteriorated immediately postoperatively, but all of the patients except four recovered during the time course

ous territories that may play an important role distinctively in the aneurysms of the midbasilar artery [8, 11, 19, 29].

Additionally, the size, shape, and location may necessitate a prolonged exclusion from cerebral circulation and thus an increased intraoperative ischemic tolerance during the dissection of the complex structure of the aneurysmal malformation simply because such accommodations would be necessary to gain anatomical orientation and overview in narrow spaces [2, 15].

Intravasal calcinosis and/or thrombosis often complicate full exposure and compromise the complete occlusion of the aneurysm so that a time-consuming removal of the intra-aneurysmal mass and a partial resection of the aneurysm sac are unavoidable for reshaping the parent vessel for the clip application.

Additionally, under special conditions, aneurysms of the posterior circulation as well as of the internal carotid artery arising near the skull base may lack a sufficient collateral supply, such that occlusion of the parent vessel may result in territorial infarction.

We analyzed the cardiac arrest time in relation to the radiological aspects and intraoperative findings (Table 5). All of the seven patients with a standstill time longer than 32.0 min had an aneurysmal neck wider than the parent vessel's diameter that prolonged the anatomical exposure and surgical preparation of the aneurysm.

Additionally, all of the patients with long circulation standstill time had aggravating pathoanatomical properties of the aneurysmal wall, with calcinosis or thrombosis and vessels originating from the neck or an irregularly shaped aneurysmal configuration.

Four of these patients had experienced SAH, and three of them had previously had at least one clipping attempt under normothermic conditions.

Deep hypothermia and circulatory arrest

dh/ca for the treatment of large or giant and complex cerebral aneurysms provide a prolongation of the ischemic tolerance of the brain up to 40 min [6, 9, 10, 13, 20, 25] by the total control and standstill of the systemic circulation. Hence, a "no-flow condition" is established, and the collapse of the aneurysm and the relaxation of the vasculature are obtained through exsanguination. After perforating the aneurysm dome, the thrombus is dissected and can be eliminated by ultrasound aspiration without arterial bleeding.

In their series including 60 patients, Lawton et al. found an overall treatment mortality of 18.3%, a transient deterioration in 15%, and a permanent deterioration of neurological function in 6.7% [14]. In the largest series to date, including 66 patients with large or giant aneurysms, Mack et al. had a treatment-related mortality of 11% [17]. Likewise, we found an overall mortality of 11.5% in our series. Similarly, we found treatment-related permanent, new neurological deficits in four patients; hence, we conclude a treatment-related morbidity of 15%, assuming that the Hunt and Hess score on admission and the initial Fisher score predicted the outcome at 6 months ($p=0.011$ and $p=0.01$, respectively).

However, 14 patients (54%) showed a neurological deterioration immediately postoperatively but with neurological function recovery during the clinical course. After 6 months, 50% (13 patients) had an improved neurological status, six patients remained unchanged in their preoperative neurological condition, four patients deteriorated permanently, and three patients had died.

The role of cerebral revascularization

Some authors favor bypass surgery in the management of complex intracranial aneurysms [4, 7, 10, 11, 20–22, 29], while even recent publications show concern about the relatively high surgical morbidity and mortality. In their series of 15 patients, Park et al. [21] found a surgical morbidity of 20% with bypass patency rates of 86.7% [21]. Sen and Sekhar had 12 out of 30 patients with ischemic events in the treatment of skull base lesions [26]. Likewise, cerebrovascular bypassing reduces or even prevents the rupture but does not relieve the mass effect of the vascular mass, especially when the aneurysm is thrombosed or calcified.

The endovascular approach

With forthcoming expertise in the interventional treatment of complex aneurysms, one can find studies recommending the endovascular treatment with increasing frequency [7, 11]. However, once the mass effect of the (unruptured) aneurysm has led to cranial nerve deficit and neurological disorder, only the removal of the space-occupying lesion can provide success [12, 17, 19, 22].

In their systematic review, Surdell et al. [29] denominate various studies with an endovascular approach in the treatment of complex aneurysmal lesions and summarize the complete occlusion rate to be 57%, associated with 7.7% mortality and 17.2% morbidity.

Treatment due to localization (anterior versus posterior)

Recently, Mack et al. [17] presented a sophisticated workup of 66 patients with complex large and giant aneurysms, equally distributed in the posterior and anterior parts of the circle of Willis. Neither the morbidity nor the mortality differed significantly between the two groups nor could different outcomes be observed. The optimal condition provides a feasible surgical success to all kinds of complex aneurysms, even to those of the anterior circulation. Thus, the employment of dh/ca should not be exclusively reserved for aneurysms of the posterior circulation, but it should be customized to the individual pathoanatomical condition and of course to the medical condition of the patient.

In contrast to this reference, Ponce and Spetzler revisited 105 patients who underwent dh/ca in a 21-year interval (unpublished data) and recommend dh/ca only for aneurysmal lesions of the posterior parts of the circle of Willis [17]. The argument is based on the postulate that complete control of the ICA becomes achievable by cervical exposure, orbitozygomatic approach combined with anterior clinoidectomy, petrous ICA exposure, and temporary balloon occlusion. These procedural advances may decrease the necessity of dh/ca; however, they do not solve the issue of prolonged ischemic tolerance whenever it is necessary for the operative procedure.

Conclusion

The treatment of complex large and giant aneurysms still remains a matter of discussion. Different approaches are customized but neither the neurosurgical treatment with bypassing, advanced craniotomy, and deep hypothermia and circulatory arrest nor the endovascular occlusion has yet been established as the gold standard.

Prospectively, the therapy of patients presenting with complex aneurysmal lesions will depend on the neurosurgeons' and endovascular radiologists' skills and preferences, as well as their expertise and lessons learned.

In our opinion, endovascular therapy will increasingly replace the operative treatment, and only under very special circumstances will the preparation and occlusion of large and giant aneurysms under deep hypothermia and circulatory arrest remain one pivotal armament in this most complex setting.

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Comments

The authors present their experience in the use of deep hypothermic circulatory arrest (DHCA) in the treatment of large and giant aneurysms of the intracranial circulation, over a period of 16 years. The technique was applied in a little less than 4% of the overall number of aneurysms surgically treated.

Large and giant aneurysms can be formidable lesions to tackle with from the surgical standpoint. Given the evidence regarding the dismal natural history of these aneurysms when left untreated, a therapeutic attitude is well granted. Because most of these more complex lesions may require a long period of temporary local circulatory shutdown, extraordinary measures of cerebral protection may have to be called into action. DHCA is at the extreme end of these protective measures as it entails not only the mobilization of a complex technology and expert team of different surgical specialties not available across the board but mainly and foremost because it exposes the patient to a non negligible morbidity and mortality risk.

A balance has to be found between the use of regular protective measures and these extreme solutions. Evolving surgical and neuroradiological technique has significantly changed the landscape of decision-making in a reasonable number of cases. The use of bypass (prophylactic or therapeutic, low or high flow) or techniques of aneurysmectomy and local re-implantation of arteries has in some cases avoided the need for alternative DHCA. As stated by the authors this applies mostly to anterior circulation aneurysms where exposure is less of a problem or to aneurysms for which more elaborate skull base techniques may be of use in securing effective proximal control. Therefore the trend is to restrict the use of DHCA to larger and more complex looking mostly posterior circulation aneurysms.

What is not accountable in any published series and therefore cannot be taken as a general recommendation for anyone individually tackling with these ferocious lesions and envisaging the use of DHCA, is the personal view one has of each particular case, which is going to mold your singular attitude. This is based on one's own experience in using all of the above-mentioned techniques and the results achieved with each and every one of them. Once the use of a technique is implemented and the confidence grows along with number of cases done it is hard to stay away from using the same strategy repeatedly. This change will only happen (when and if it needs to happen) if concomitantly one will develop further expertise, not only form the shear standpoint of surgical technique, but also in managing to adapt one's way of looking at the problem by using a possibly different surgical strategy.

According to the above statement it would have been interesting to know what the percentage of large and giant aneurysms treated with DHCA in this series was when compared to aneurysms clipped under conventional cerebral protective measures, use of bypass and vessel re-implantation.

Despite the fact that endovascular treatment of intracranial aneurysms has become an alternative and rather effective way of treatment, in certain cases with results better than the surgical ones, I think that the existing evidence and the evolving practice argue contrarily to author's last statement implying that the future of the treatment of giant aneurysms is endovascular.

Regardless of the fact that there is no novelty in the material and the conclusions presented I still think it is important that the results of series such as this one be published. They represent a very useful piece of information reflecting single center/surgeon experience or in my understanding, 'local or individual evidence based medicine'.

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