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Microsurgical treatment strategy for large and giant aneurysms of the internal carotid artery

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ABSTRACT

Objective: We aimed to summarize our microsurgical treatment results for large (10–25 mm) and giant (≥25 mm) intradural internal carotid artery (ICA) aneurysms over a 7-year period at a single institution and to describe our detailed strategy.

Patients and methods: We reviewed the records of 68 patients with 69 aneurysms, including large and giant intradural ICA aneurysms, treated using microsurgical techniques from January 2008 to December 2014. We used adenosine-induced cardiac standstill or retrograde suction decompression for some aneurysm clipping cases and performed bypass surgery if needed.

Results: Fifty-eight large and giant ICA aneurysms (84%) were treated with direct clipping, including 6 aneurysms (9%) clipped using adenosine-induced cardiac standstill and 10 aneurysms (14%) clipped using suction decompression. Eleven unclippable aneurysms (16%) were trapped with extracranial-intracranial bypass. Good or excellent results (modified Rankin Scale scores 0–2) were obtained in 47 patients with unruptured aneurysms (92%) and in 14 patients with ruptured aneurysms (82%) at the 6-month follow-up. Of 17 patients with visual disturbances before treatment, 11 (65%) had improved vision after surgical treatment. A remnant sac was found in 20 cases (29%) on digital subtraction angiography performed immediately postoperatively. At the median follow-up of 22 months, we encountered 3 recurrent aneurysm cases (5%) among the 58 aneurysms that were followed up.

Conclusion: Our study demonstrated that microsurgical treatment of large and giant intradural ICA aneurysms remains competitive to flow-diverting treatment, if the surgeon is prepared to perform multifarious surgical methods, including adenosine administration, retrograde suction decompression, and bypass vascular anastomosis.

1. Introduction

Intradural internal carotid artery (ICA) aneurysms can be defined as aneurysms that occur in the segment between the distal dural ring and the bifurcation of the ICA, with their walls exposed to the arachnoid space. Many giant intracranial aneurysms (47%–55%) have been found to be related to the ICA [1–3]. According to the Unruptured Cerebral Aneurysm Study of Japan, the annual rate of rupture of small (3–4 mm) ICA aneurysms is 0.14% per year, whereas that of large and giant ICA aneurysms is 1.07 and 10.6, respectively [4].

Nowadays, the treatment methods for large (10–25 mm) and giant (≥25 mm) intradural ICA aneurysms include flow diversion and open microsurgery. The advent of flow diverters has caused a reduction in the application of microsurgical treatments for large and giant ICA aneurysms, because flow-diverting treatment is less invasive than the microsurgical approach. However, this novel treatment lacks data about long-term efficiency and durability, as well as long-term results in view of possible complications such as ischemic stroke, delayed rupture, and intraparenchymal hemorrhage [5–9]. Microsurgical treatment remains a competitive therapy for large and giant intradural ICA

Abbreviations: ICA, internal carotid artery; EC-IC, extracranial-intracranial; BTO, balloon test occlusion; SPECT, single-photon emission computed tomography; RA, radial artery; STA, superficial temporal artery; ACP, anterior clinoid process; ECA, external carotid artery; mRS, modified Rankin Scale; DSA, digital subtraction angiography; CTA, computed tomography angiography; GOS, Glasgow Outcome Scale

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aneurysms [10,11].

ICA aneurysms and other anterior circulation aneurysms have different neuroanatomic structures and environments. There are optic nerve and bony structures around an ICA aneurysm, which make large and giant ICA aneurysms more challenging to treat than other aneurysms. In addition, the microsurgical treatment of large and giant intradural ICA aneurysms needs appropriate surgical techniques, and its outcomes depend on the neurosurgeon's experience. In this regard, our study focused on the microsurgical treatment of large and giant intradural ICA aneurysms. We aimed to summarize our microsurgical treatment results for large and giant intradural ICA aneurysms and to describe our detailed strategy.

2. Materials and methods

The institutional review board of our hospital approved this study.

2.1. Inclusion criteria

From January 2008 to December 2014, 3859 patients with a total of 4348 cerebral aneurysms were treated at our medical institution. Among them, we reviewed the records of 1286 patients with a total of 1443 ICA aneurysms, treated using a microsurgical or endovascular approach. Medical records and radiologic images were analyzed retrospectively. The inclusion criteria were as follows: 1) intradural ICA aneurysm, 2) large (10–25 mm) or giant (≥25 mm) aneurysm, 3) clipping with/without extracranial-intracranial (EC-IC) bypass, and 4) trapping with EC-IC bypass. We excluded cases that had only endovascular treatment, or previously treated aneurysm cases. Aneurysms from secondary causes such as moyamoya disease, arteriovenous malformation, trauma, and infection were also excluded.

2.2. Classification of large and giant intradural ICA aneurysms

The trans-segmental property of large and giant ICA aneurysms tends to unite rather than divide ICA segments such as the traditional clinoid, ophthalmic, and communicating segments. In our study, there were many cases in which landmarks were destroyed. We considered the trans-segmental nature of large and giant ICA aneurysms, and classified the aneurysm locations in relation to the position of the aneurysm in the ICA segment and the predominant direction. According to the position of the aneurysm, the location was classified as follows: infra-ophthalmic segment, proximal to the ophthalmic artery origin; para-ophthalmic segment, involving the origin of ophthalmic artery or ophthalmic ICA segment; and terminal segment, distal to the origin of the posterior communicating artery [12]. In terms of the aneurysm dome direction, the location was classified as dorsal, ventral, lateral, medial, or fusiform to the cross section of the ICA [13,14].

2.3. Preparation for microsurgery

Balloon test occlusion (BTO) and preoperative test for adenosine administration were performed only in patients with unruptured aneurysm.

We performed BTO preoperatively and checked the collateral flow to assess the safety of ICA occlusion. A 5-Fr guiding catheter (Envoy; Codman, Raynham, MA, USA) was placed into the tested ICA. We inflated an occlusion balloon (Sceptor C 4 × 15 mm; Microvention, Tustin, CA, USA) under roadmap guidance in the ICA, and obtained angiograms of the contralateral ICA or vertebral artery with a 4-Fr diagnostic catheter. The procedure was immediately terminated when any clinical sign of ischemia was observed. After 15 min of occlusion, we intravenously injected technetium Tc-99 m bicisate. Then, single-photon emission computed tomography (SPECT) imaging was performed. At our hospital, we do not perform hypotensive challenge during BTO.

In previous reports, there were some complications due to intravenous adenosine injection. Atrial flutter and ventricular tachycardia were reported in patients with a history of myocardial infarction after adenosine-induced cardiac standstill [15]. Pulmonary problems such as bronchospasm can also be induced by adenosine in patients with a history of asthma [16]. Therefore, we evaluated the patients' cardiopulmonary function before surgery for elective adenosine administration. The tests consisted of blood laboratory tests, electrocardiography, chest radiography, pulmonary function test, echocardiography, and thallium-201 myocardial perfusion SPECT [17].

2.4. Microsurgical treatment methods for large and giant intradural ICA aneurysms

The operating field was set up in the same manner for all large and giant intradural ICA aneurysms, with placement of transcutaneous pacemakers as a precaution for asystole caused by adenosine-induced cardiac standstill. We draped the cervical neck as a preparation for proximal control or suction decompression and the non-dominant arm for harvesting of a radial artery (RA). During scalp incision, we dissected an about 8–10 cm length of the superficial temporal artery (STA) from the proximal stump. We also prepared devices for monitoring motor-evoked and somatosensory-evoked potentials, and used microvascular Doppler and indocyanine green angiography for evaluations in the operating room. For the treatment of large and giant intradural ICA aneurysms, we performed pterional craniotomy with removal of the sphenoid ridge. After the dura was opened, the Sylvian fissure was widely split carefully, avoiding venous drainage deterioration to prevent venous infarction. The anterior clinoid process (ACP) was radically drilled off and removed through an intradural or extradural approach. The intradural approach allows better visualization of the ophthalmic segment of the ICA with an aneurysm, easier identification of the optic canal, and the ability to control the extent of anterior clinoidectomy [18,19]. The advantages of the extradural approach include easier identification of the anatomical orientation, shorter procedure time than that of intradural clinoidectomy, and protection from injury of intradural structures such as the optic nerve [20,21]. The preference of neurosurgeons determines the approach of ACP removal at our institute. The distal dural ring was also opened to provide space for temporary proximal clipping.

The microsurgical treatments for large and giant intradural ICA aneurysms can be classified into direct aneurysm neck clipping and trapping of the aneurysm with bypass. Our strategy for large and giant intradural ICA aneurysms is briefly described in the decision flowchart in Fig. 1.

First, we tried direct neck clipping for aneurysm treatment. In some instances, temporary arterial occlusion with clipping was not suitable despite a wide Sylvian fissure opening and ACP removal, such as when a large aneurysm interrupts the scene of the proximal artery and adjacent structures such as the optic nerve, or when severe atherosclerotic change occurs in the proximal artery. In this respect, the use of adenosine can be a good option for proximal control. In some cases, we used adenosine-induced cardiac standstill when we could not perform direct aneurysm clipping owing to non-decreased aneurysm wall tension after temporary clip occlusion of the cervical ICA or intracranial ICA. We administrated adenosine in a test-incremental manner (starting with 6–12 mg) and injected additional doses in a precalculated manner (0.3–0.4 mg/kg) [17]. This regimen was based on several reports about the dose and regimen of adenosine administration [22–27]. If a patient has resistance to adenosine, the retrograde suction decompression technique may also be an alternative in the state of cervical ICA exposure. We inserted a needle and aspirated blood from the ICA in the neck, after temporary trapping with a vascular clamp between the proximal cervical ICA and proximal to the posterior communicating artery [28]. The time for suction decompression did not exceed 3 min under the monitoring of motor-evoked potentials. Therefore, the time of

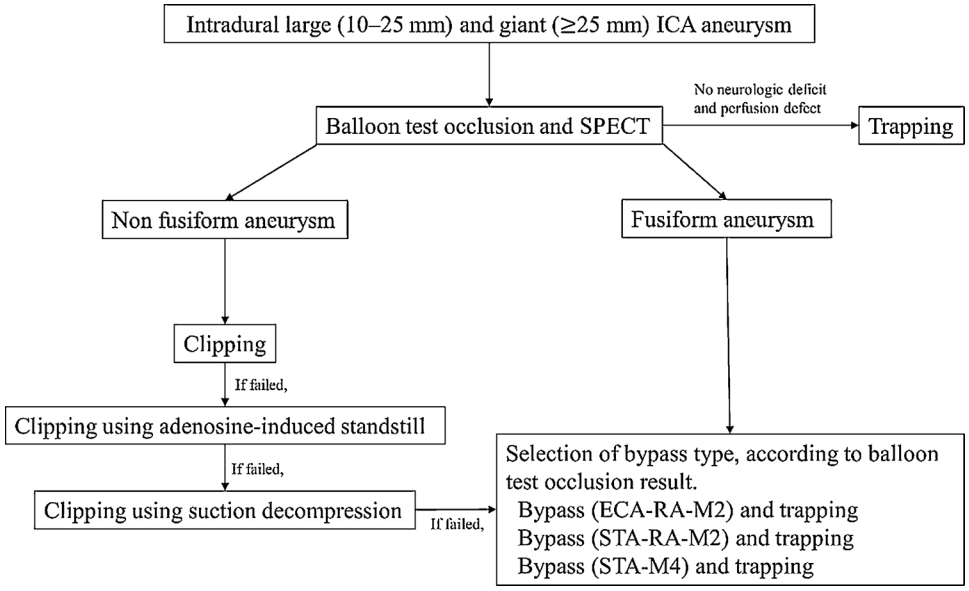

Fig. 1. Flowchart of treatment decision making for large and giant intradural ICA aneurysms.
ICA, internal carotid artery; SPECT, single-photon emission computed tomography; ECA, external carotid artery; RA, radial artery; STA, superficial temporal artery.

Table 1
Baseline characteristics of the patients with large and giant intradural ICA aneurysms.

Clinical aspects		Values (% or range)
No. of patients		68
Men/women		13 (19%)/55 (81%)
Age at treatment, years		57 (34–78)
Clinical presentations	No. of patients with unruptured aneurysms	51 (75%)
	Cranial nerve symptoms (oculomotor nerve palsy, visual deficits)	17
	Headache	12
	Transient ischemic attack	1
	Asymptomatic	21
	No. of patients with ruptured aneurysms	17 (25%)
	Hunt-Hess grade 1	0
	Hunt-Hess grade 2	9
	Hunt-Hess grade 3	7
	Hunt-Hess grade 4	1
	Hunt-Hess grade 5	0
No. of aneurysms		69
Large aneurysm, largest diameter: 10 to < 25 mm		55 (80%)
Giant aneurysm, largest diameter: 25 mm or larger		14 (20%)
Mean aneurysm size, mm		17 (10–37)

ICA, internal carotid artery.

surgical flow arrest was short enough to avoid the need for heparinization. We suctioned up to 50–100 mL of blood during suction decompression. In principle, the aspirated blood was returned to the venous flow, as autotransfusion, in order to prevent anemia.

If aneurysm clipping failed for some reason, we performed trapping with bypass [29]. The type of bypass surgery depended on the BTO result. External carotid artery (ECA)-RA-M2 bypass surgery was performed when the patient could not tolerate BTO. If patients who could tolerate BTO had insufficient collateral flow or a perfusion defect seen in SPECT, we performed a proximal STA-RA-M2 bypass. If patients who could tolerate BTO had sufficient collateral flow but showed a mild perfusion defect in SPECT, we performed an insurance STA-M4 bypass. For the treatment of ruptured aneurysms, we performed ECA-RA-M2 bypass in principle. We attempted ICA trapping in the surgical field if possible, but performed endovascular trapping after bypass surgery when inevitable. Endovascular trapping was another option after scalp closure. We occluded the aneurysmal orifice and the ICA. If the aneurysm neck was near the ophthalmic artery orifice, we occluded the ICA including the ophthalmic artery origin to prevent retrograde flow into the aneurysm in endovascular treatment [30].

2.5. Clinical and radiologic outcome evaluation

For the evaluation of clinical outcomes, we assessed functional outcomes according to the modified Rankin Scale (mRS) [31] at discharge and at the 6-month follow-up. Visual field test and vision acuity evaluation were also performed at the 6-month follow-up, on the basis of a report that showed improvement of visual function in patients who were treated surgically within 3 months of the onset of symptoms [32]. All preoperative digital subtraction angiography (DSA) images were obtained before treatment. Postoperative follow-up DSAs were conducted to detect residual aneurysms in all cases, at 1–5 days after microsurgical treatment.

3. Results

There were the 106 large and giant intradural ICA aneurysms treated with a microsurgical or endovascular approach during the study period. Among them, 68 patients with a total of 69 large and giant intradural ICA aneurysms were treated using microsurgical techniques. A total of 13 men and 55 women with an average age of 57 years were enrolled in this study. The baseline characteristics of the patients are summarized in Table 1.

According to the location of the affected ICA, 3 aneurysms (4%) were infra-ophthalmic, 29 (42%) were para-ophthalmic, and 37 (54%) were terminal-segment aneurysms. In relation to the cross section of the ICA, the aneurysms were classified as follows: 7 aneurysms (10%) had a predominantly dorsal location, 34 (49%) had a ventral location, 7 (10%) had a lateral location, 17 (25%) had a medial location, and 4 (6%) had a fusiform location (Table 2).

Two surgeons (BDK, JSA) performed the microsurgeries (Table 3). A total of 58 large and giant ICA aneurysms (84%) were treated with direct clipping, including 6 aneurysms (9%) clipped using adenosine-induced cardiac standstill and 10 aneurysms (15%) clipped using suction decompression. After adenosine injection, there were no

Table 2
Location of large and giant intradural ICA aneurysms.

Aneurysm group		Aneurysm size		Total no. (%)
		Large (10–25 mm)	Giant (≥25 mm)	
ICA segments	Infra-ophthalmic segment	2	1	3 (4%)
	Para-ophthalmic segment	23	6	29 (42%)
	Terminal segment	30	7	37 (54%)
Direction of the aneurysm dome	Dorsal (superior) wall of the ICA	6	1	7 (10%)
	Ventral (posterior) wall of the ICA	30	4	34 (49%)
	Lateral wall of the ICA	6	1	7 (10%)
	Medial wall of the ICA	13	4	17 (25%)
	Fusiform	0	4	4 (6%)
Total no.		55	14	69

ICA, internal carotid artery.

Table 3
Treatment modalities for intradural large and giant ICA aneurysms.

Surgical treatments	Unruptured aneurysm cases	Ruptured aneurysm cases	Total (%)
Aneurysm clipping, surgical trapping without bypass	43	15	58 (84%)
with adenosine	5	1	6 (9%)
with suction decompression	7	3	10 (15%)
Aneurysm trapping, surgical Hunterian ligation	9	2	11 (16%)
with ECA-RA-M2 bypass	4	2	6 (9%)
with STA-RA-M2 bypass	3	0	3 (4%)
with STA-M4 bypass	2	0	2 (3%)
Total	52	17	69 (100%)

ICA, internal carotid artery; ECA, external carotid artery; RA, radial artery; STA, superficial temporal artery.

permanent abnormal cardiac events except for self-limited atrial fibrillation. Arterial fibrillation developed in 1 case among 6 aneurysm cases after adenosine injection in our study. The arterial fibrillation was transient, and cardiac enzymes such as troponin-I did not increase. There was also no perioperative complication due to the suction decompression technique. On the other hand, 11 unclippable aneurysms (16%) were trapped with EC-IC revascularization.

3.1. Clinical outcomes after the treatment of unruptured large and giant intradural ICA aneurysms

Overall, the mRS score improved at 6 months after treatment compared with that at discharge (Table 4). There were 47 patients (92%) with good or excellent results (mRS 0–2) after 6 months. Moderate or severe disabilities (mRS 3–4) were observed in 3 patients (6%). Among the 3 patients with bad outcomes, 1 patient had paraplegia due to poliomyelitis in childhood and 1 patient required daily assistance because of sepsis due to postoperative urinary tract infection (Table 5). Only 1 case of severe disability was related to the surgical treatment itself. An elderly woman with a giant aneurysm showed poor collateral circulation in preoperative BTO. There was no neurologic deficit during the examination. She underwent trapping with STA-M4 bypass for aneurysm treatment, although STA-RA-M2 bypass was required. Ischemic stroke occurred after surgery. We observed good bypass flow after surgery, on postoperative angiography. Therefore, the cause of infarction was not technical failure of bypass surgery. This treatment caused insufficient blood flow, resulting in postoperative infarction. One female patient (2%) died after surgery. This patient was treated with direct clipping. She had a giant ICA aneurysm with atherosclerotic change. For aneurysm neck occlusion, we tried several clip placements. She had bleeding around the aneurysm after the clipping, and died (Table 5).

Seventeen patients presented with diplopia, visual field defect, or visual acuity deterioration due to compressive cranial neuropathy before treatment. After surgical treatment, 11 patients (65%) had improved vision; however, 4 patients (24%) had aggravated vision.

3.2. Clinical outcomes after the treatment of ruptured large and giant intradural ICA aneurysms

Good or excellent results (mRS 0–2) after 6 months were achieved in 14 patients (82%). Moderate disability (mRS 3–4) was observed in 2 patients (12%). There was 1 case of severe disability (mRS 5). Three patients with bad outcomes had Hunt-Hess grade 3 or 4.

3.3. Radiologic outcomes after the treatment of large and giant intradural ICA aneurysms

For 58 aneurysms, we used DSA, computed tomography angiography (CTA), or magnetic resonance angiography to detect changes in the treated aneurysms during at least 6 months of follow-up. The other 11 cases were not followed up because of death, patient refusal, or follow-up loss. A remnant sac was found in 20 cases (29%) on immediate postoperative DSA. Among the 58 aneurysms with radiographic follow-up of > 6 months after treatment, 3 regrowth aneurysms

Table 4
Modified Rankin Scale scores at discharge and at the 6-month follow-up.

Modified Rankin Scale score	No. of patients at discharge (%)		No. of patients at 6 months after treatment (%)	
	Unruptured cases	Ruptured cases	Unruptured cases	Ruptured cases
0 (No symptoms)	26 (51%)	6 (35%)	31 (61%)	9 (53%)
1 (No significant disability)	5 (10%)	1 (6%)	3 (6%)	3 (17%)
2 (Slight disability)	11 (21%)	5 (29%)	13 (25%)	2 (12%)
3 (Moderate disability)	6 (12%)	2 (12%)	1 (2%)	0 (0%)
4 (Moderately severe disability)	2 (4%)	2 (12%)	2 (4%)	2 (12%)
5 (Severe disability)	0 (0%)	1 (6%)	0 (0%)	1 (6%)
6 (Death)	1 (2%)	0 (0%)	1 (2%)	0 (0%)
Total no.	51	17	51	17

Table 5
Summary of patients with bad outcomes.

	Case no.	mRS score	Aneurysm size (mm)	Treatment	Remarks
Unruptured aneurysm	2	4	20	Bypass (STA-M4) with surgical trapping	Infarction due to insufficient blood flow
	20	6	17	Clipping	Death due to postoperative ICA wall dissection
	37	4	28	Bypass (STA-M4) with surgical trapping	Sepsis due to postoperative UTI
	41	3	13	Clipping	Paraplegia due to childhood poliomyelitis
Ruptured aneurysm	45	4	14	Clipping	H&H 3
	47	5	12	Clipping	H&H 4
	61	4	30	Bypass (STA-RA-M2) with endovascular trapping	H&H 3

mRS, modified Rankin Scale; H&H, Hunt-Hess grade; SAH, subarachnoid hemorrhage; STA, superficial temporal artery; RA, radial artery; UTI, urinary tract infection.

were found. The overall aneurysm recurrence rate was 5% among the 58 followed-up aneurysms at a median follow-up time of 22 months. Two cases received additional coil embolizations for retreatment, but another case was not treated because of the patient's refusal.

3.4. Illustrative cases

3.4.1. Case #1

A middle-aged female patient experienced visual disturbance (right temporal hemianopsia) (Fig. 2). The cerebral angiogram showed a 25-mm giant aneurysm of the right ICA. The aneurysm was a medial-directed, ophthalmic-segment aneurysm. A right fronto-temporal craniotomy was performed followed by intradural removal of the ACP. Despite ACP removal, the surgical corridor was too small to perform temporary clipping. The giant aneurysm limited the available working space. We used adenosine cardiac arrest to aid in aneurysm decompression. We used adenosine 15 mg to generate asystole for about 50 s for clipping. There was minimal residual sac on the postoperative angiogram; however, no recurrence was noted on CTA at 7 months after treatment.

3.4.2. Case #2

A woman in the 5th decade of life experienced visual disturbance (left eye blindness) (Fig. 3). The cerebral angiogram showed a 29-mm

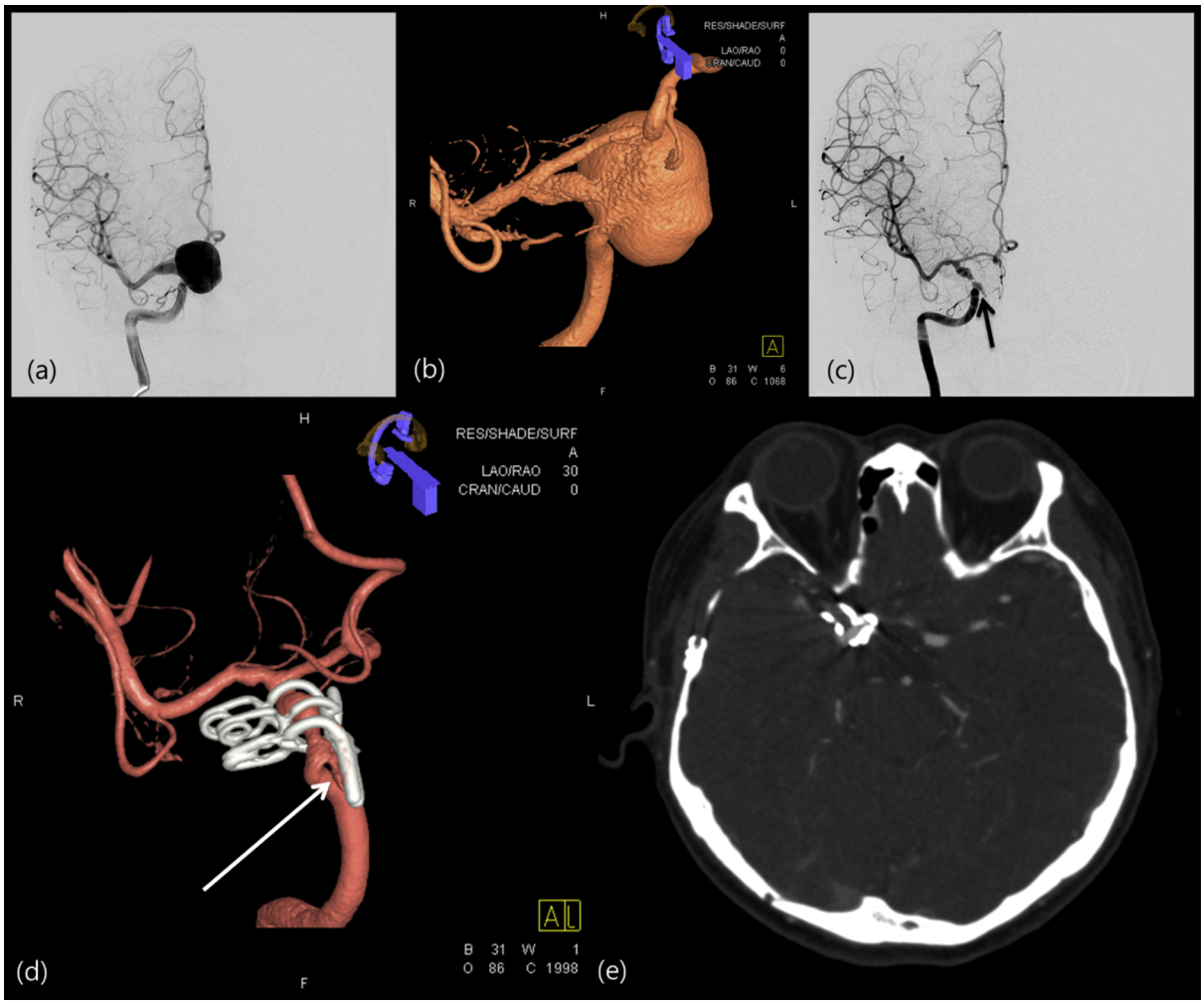

Fig. 2. Evaluation results of a middle-aged female patient who developed visual disturbance.
(a, b) Cerebral angiogram showing a 25-mm giant aneurysm of the right internal carotid artery. The aneurysm was a medial-directed, ophthalmic-segment aneurysm. (c, d) Adenosine 15 mg was used to generate asystole for about 50 s, for clipping. The postoperative angiogram showed minimal residual sac (black arrow and white arrow). (e) No recurrence was seen on the computed tomography angiogram obtained 7 months after treatment.

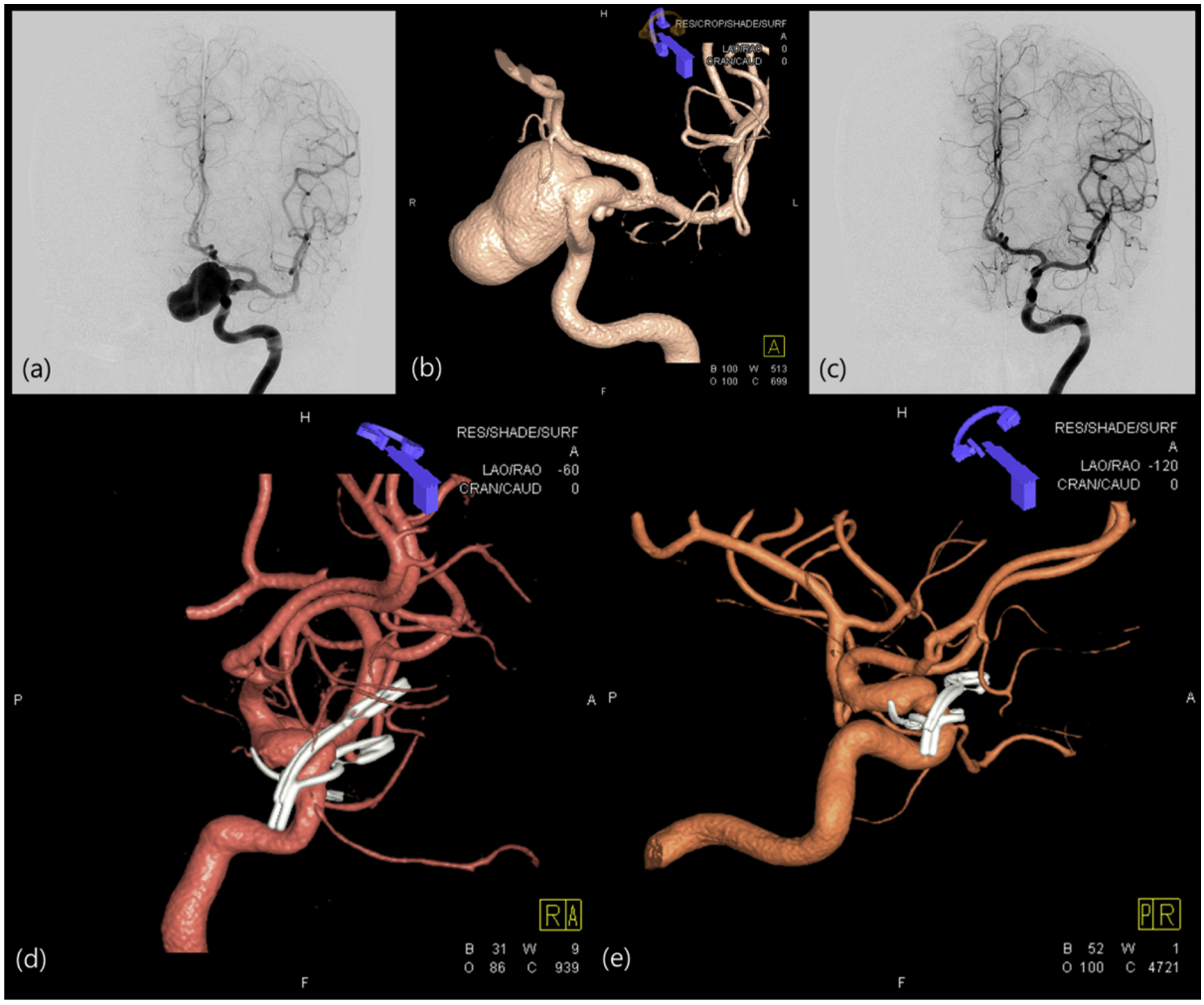

Fig. 3. Evaluation results of a female patient in the 5th decade of life who presented with left eye blindness.
(a, b) Cerebral angiogram showing a 29-mm giant aneurysm of the left internal carotid artery. The aneurysm was a medial-directed, ophthalmic-segment aneurysm. (c, d) Suction decompression was done for clipping of the aneurysm. There was no residual aneurysm on the postoperative angiogram. (e) No recurrence was seen on 41-months follow-up digital subtraction angiography after treatment.

giant aneurysm of the left ICA. The aneurysm was a medial-directed, ophthalmic-segment aneurysm. The ACP was removed through an intradural approach. The surgical corridor was too small to have space for temporary clipping. First, we started adenosine injection with a 6 mg dose. Then, we escalated the dose up to 21 mg to achieve 20–30 s of asystole. However, we could not decompress the aneurysm after adenosine injection owing to the patient's adenosine resistance. Therefore, we decided to perform retrograde suction decompression. After clamping the proximal ICA, we trapped the aneurysm through a temporal clipping on the ipsilateral ICA distal to the neck of aneurysm. A No. 18 angiocatheter was introduced into the proximal ICA to aspirate retrograde collateral flow, resulting in aneurysm collapse. Moreover, this helped in dissecting the structures around the aneurysm and in clipping the aneurysm. There was no residual aneurysm on postoperative angiogram and no recurrence on DSA at 41 months follow-up.

3.4.3. Case #3

An elderly woman presented with visual disturbance (bitemporal hemianopsia) (Fig. 4). A giant aneurysm of the left ICA was detected, with the longest diameter being 37 mm. The stump of the STA was dissected during surgery. We initially used suction decompression; however, we could not reduce the tension of the aneurysm wall. Atherosclerotic change and calcification of the aneurysm wall tightened the aneurysm wall tension, which was not reduced by suction decompression. Therefore, we decided to trap the aneurysm. The RA was subsequently harvested. Then, we performed STA-RA-M2 bypass. We loaded 300 mg aspirin immediately after surgery, followed by daily 100 mg aspirin. There was no residual aneurysm on the immediate postoperative angiogram and no recurrence on CTA at 7 months after treatment.

4. Discussion

4.1. Clinical outcomes after the treatment of unruptured large and giant intradural ICA aneurysms

Large and giant intradural ICA aneurysms are very difficult to treat. The clinical outcomes of large and giant ICA aneurysms were not favorable until the 1990s [33,34]. Good outcomes (83%–100%) after microsurgical treatment of large and giant ICA aneurysms have been recently reported [10,11]. Among them, Mattingly et al. reported good outcomes (Glasgow Outcome Scale [GOS] score 4–5) in 18 patients (100%) who underwent microsurgery of large and giant ophthalmic ICA-segment aneurysms [35]. The results of flow-diverting treatment for large and giant ICA aneurysms are also noteworthy. There were 5.6% (6 of 107) patients who had major ipsilateral stroke or neurologic death by day 180 in a multicenter trial for the pipeline treatment of large or giant ICA aneurysms [36]. In our study, there were 47 patients

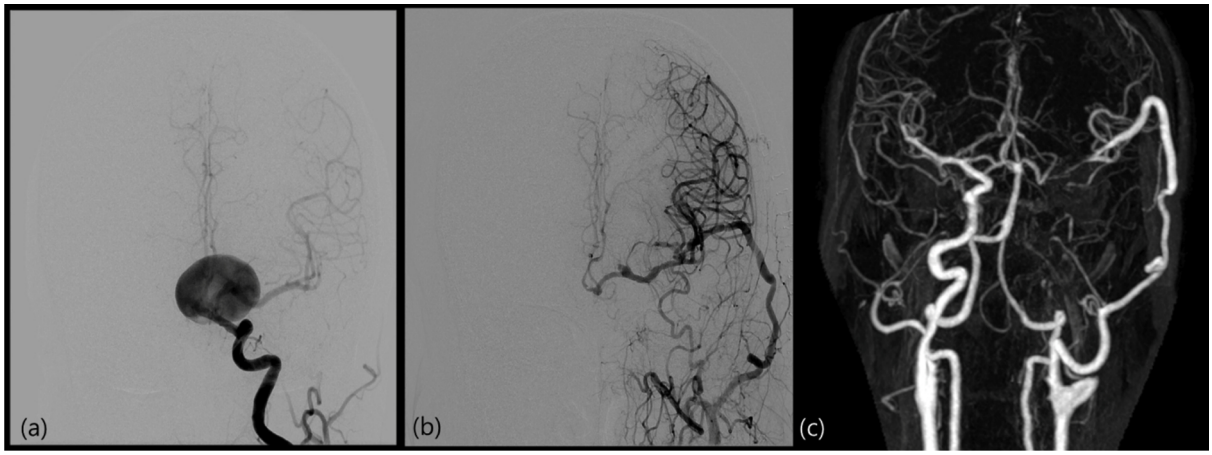

Fig. 4. Evaluation results of an elderly female patient who presented with visual disturbance (bitemporal hemianopsia).
(a) A giant aneurysm of the left internal carotid artery was detected. The largest diameter was 37 mm. Suction decompression was performed first; however, it could not reduce the tension of the aneurysm wall. The aneurysm was trapped after superficial temporal artery-radial artery-M2 bypass. (b) No residual aneurysm was seen on the immediate postoperative angiogram (c) No aneurysm recurrence was observed on computed tomography angiography at 7 months after the treatment.

(92%) with good outcomes (mRS 0–2) postoperatively. This result was similar to that of previous studies.

Large and giant intradural ICA aneurysms can lead to cranial nerve deficits such as visual field defect, visual acuity deterioration, and diplopia. There were 17 patients with visual deficits due to the aneurysmal mass effect in our study. Among them, 11 patients (64.7%) had improved vision after surgical treatment. This result was similar to the surgical results (73.9%–79.0%) of previous studies [35,37]. The visual outcomes were better (64%) after flow diversion than after conventional coiling for large and giant aneurysms of the ICA in the Pipeline for Uncoilable or Failed Aneurysms trial [38]. Flow-diverting devices might potentially be considered an alternative treatment for large and giant ICA aneurysms with neuro-ophthalmologic symptoms.

4.2. Clinical outcomes after the treatment of ruptured large and giant intradural ICA aneurysms

The cumulative rebleeding rate of giant intracranial aneurysms at 14 days has been reported to be 18.4% in the natural history of these aneurysms [39,40]. Therefore, the treatment of ruptured large and giant ICA aneurysms should be considered to prevent rebleeding.

The rate of good outcomes after microsurgical treatment for ruptured large and giant ICA aneurysms was about 83%–90% in previous reports. Previous studies reported mixed results of ruptured and unruptured aneurysm cases, but addressed a large proportion (58%–73%) of ruptured aneurysms. Xu et al. reported that the GOS score was 4 or 5 at discharge in 84% of their patients, and the Rankin Outcome Scale score was 0–2 in 90% of the patients at the 6-month follow-up [11]. In the study of Eliava et al., good or excellent results (GOS 4–5) at discharge were achieved in 69 patients (83.1%); 11 patients (13.3%) remained severely disabled (GOS 3); and 3 patients died (3.5%) [10]. We used microsurgical treatment for 17 patients with ruptured large and giant ICA aneurysms. Our treatment results demonstrated a good outcome rate of 82%. Three patients (18%) had a bad outcome (mRS 3–6) postoperatively. These patients presented with bad initial states (Hunt-Hess grade 3 or 4). There was no case of bad outcome due to the surgery itself.

There was a limitation in a study about flow-diverting treatment for ruptured large and giant aneurysms, because flow diversion has an aneurysm rupture risk owing to the need for dual antiplatelet medication. Flow-diversion cases for ruptured blood blister aneurysms have been reported. These reports showed favorable clinical outcomes in 68%–76% of cases [41,42]. A recent meta-analysis for ruptured intracranial aneurysms treated with flow-diverter stents demonstrated that the treatment-related complication rate was 17.8% [43]. In a recent study, Brinjikji et al. suggested a method of acute-stage aneurysm coiling followed by planned flow diversion. The outcome of staged flow-diverting treatment for ruptured complex and large/giant cerebral aneurysms was good (mRS 0–2) in 25 cases (80.6%) [44].

4.3. Radiologic outcomes after the treatment of large and giant intradural ICA aneurysms

In the past, the complete occlusion rate was usually a low and the recurrence rate was high for large and giant ICA aneurysms. Recent surgical treatments at other centers demonstrated complete occlusion rates of about 52.9%–100% on postoperative cerebral angiography and low recurrence rates (0%–18.8%) [35,45,46]. In our study, 71% had complete occlusion at immediate postoperative angiographic follow-up, and the rate of recurrence requiring treatment was 5%.

Flow-diverting treatment showed similar occlusion and recurrence results to those of surgical treatment. Complete aneurysm occlusion rates of about 71.0%–86.8% at 1-year angiographic follow-up were reported in recent studies on the pipeline treatment of large or giant ICA aneurysms [36,47]. The 5-year follow-up period of the Pipeline for Uncoilable or Failed Aneurysms study showed a 95% complete occlusion rate [48]. In a recent report, the outcomes of flow-diverting treatment for intracranial aneurysms included a 3.0% retreatment rate [8].

4.4. Microsurgical strategies

The most important aspect of aneurysm surgery is the proximal control of the parent artery. Another important aspect of large and giant aneurysm surgery is the need to overcome the aneurysm wall tension for clipping. However, proximal control of large and giant intradural ICA aneurysms is very difficult owing to bony structures around the parent artery and structures including the optic nerve [35,49]. For proximal control, cervical ICA exposure through neck dissection should be considered.

In this respect, adenosine injection can be a good method for proximal control and softening of the aneurysm wall tension with or without cervical ICA exposure. Transient cardiac standstill is a novel method for decompression of the aneurysm to facilitate clip placement in these situations. Retrograde suction decompression was considered another alternative method for decompressing the aneurysm locally. Retrograde suction decompression is useful for large and giant paraclinoid aneurysms because it decompresses the fundus and neck of the

aneurysm without direct puncture of the lesion intracranially [50]. However, retrograde suction decompression could lead to complications such as atheromatous plaque embolization and arterial dissection [50]. Trapping after bypass should also be considered in patients in whom aneurysm wall tension could not be reduced using adenosine and suction decompression because of an atherosclerotic vessel wall. Severe atherosclerosis makes the aneurysm wall thick and firm, and results in slippage of the aneurysm clip despite retrograde suction decompression. Especially, bypass surgery and trapping of aneurysms were required in cases that have an atherosclerotic plaque at the aneurysm neck, which interfered with aneurysm wall collapse.

Microsurgical treatment of large and giant ICA aneurysms is still useful when flow diversion is difficult to consider because of economic or medical reasons, as is true in some countries. We demonstrated our proper microsurgical methods for the treatment of large and giant intradural ICA aneurysms in this study. Because many unexpected situations are encountered during the surgical treatment of large or giant aneurysms of the ICA, multifarious surgical methods are needed in the neurosurgeon's armamentarium. It is crucial to use the proper surgical method according to the appropriate indication. Moreover, regardless of the selected treatment method, it is important to be prepared to perform other surgical methods. The death of aneurysm surgery has yet to come in the treatment of large and giant intradural ICA aneurysms. Ausman claimed that there is a need for continuous collaboration between surgeons and neuro-interventionists [51]. Surgical treatment would be valid as long as flow diverters have a limitation in ruptured aneurysm treatment, as well as complications such as delayed rupture and intraparenchymal hemorrhage.

4.5. Limitations

This study has some limitations. First, there may be bias due to the retrospective and single-center nature of the study. Second, the follow-up modalities were not standardized because of the different preferences and skills of clinicians in our cerebrovascular team.

5. Conclusion

Microsurgical treatment should be considered when flow diversion is difficult to perform because of economic or medical reasons. Our study demonstrated that microsurgical treatment of large and giant intradural ICA aneurysms remains competitive to flow-diverting treatment, if the surgeon is prepared to perform multifarious surgical methods, including adenosine administration, retrograde suction decompression, and bypass vascular anastomosis.

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Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Conflict of interest

The authors declare that they have no conflict of interest.

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