Postoperative Infarction After Clipping of Unruptured Anterior Communicating Artery Aneurysms: Anatomical Consideration and Type of Infarction Territory

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Abstract

Introduction

An anterior communicating artery is a common location for both ruptured and unruptured intracranial aneurysms and microsurgery is sometimes necessary for their successful treatment. However, postoperative infarction should be considered during clipping due to its complex surrounding structures. This study aimed to evaluate the risk factors of postoperative infarction after surgical clipping of unruptured anterior communicating artery aneurysm and its clinical outcomes.

Methods

Patients who underwent microsurgical clipping of unruptured anterior communicating aneurysm in our hospital were retrospectively analyzed between January 2008 and December 2020. Demographic data, anatomical features of anterior communicating artery complex and aneurysm, surgical technique, character of postoperative infarction, and its clinical course were evaluated.

Results

Notably, 66 of 848 patients (7.8%) had a radiologic infarction and 34 patients (4%) had symptomatic infarction. Univariable and multivariable logistic regression analysis showed that hypertension (OR 2.05; $p<0.05$), previous cerebrovascular accident (OR 2.79; $p<0.05$), posterior projection (OR 3.94; $p<0.01$), aneurysm size (OR 1.16; $p<0.01$), skull base to aneurysm distance (cut-off value 10 mm; OR 3.36, $p<0.01$) were associated with postoperative infarction. In the pterional approach, closed A2 was an additional risk factor (OR 1.98; $p<0.05$). The worst outcome was presented with the infarction of A2 cortical branches (mRS=2.00±1.63).

Conclusion

Hypertension, old cerebrovascular accidents, posteriorly projecting aneurysm, size, and high positioned aneurysms are independent risk factors for postoperative infarction during surgical clipping of unruptured anterior communicating artery aneurysm. Additionally, closed A2 plane is an additional risk factor for postoperative infarction in pterional approach.

Introduction

The anterior communicating artery (ACoA) is a common location for both ruptured and unruptured intracranial aneurysms [8, 10]. Anterior communicating artery aneurysms (ACoAAs) can be treated with neurosurgical or endovascular treatment. Recently, several ACoAAs have been treated with endovascular treatment due to the significant development of endovascular materials, such as stents for coil embolization and flow diverters. However, neurosurgical treatment is still required for aneurysms, which is expected to have incomplete treatment with endovascular treatment [37, 63, 69]. Microsurgical clipping of ACoAAs is challenging because it has a complex relationship with the surrounding structures [8, 10].

Especially, perforating branches from the ACoA complex, such as the recurrent artery of Heubner (RAH), subcallosal artery (SCA), hypothalamic artery (HThA), and medial lenticulostriate artery (MLSA) are important because infarction in these perforators can lead to severe neurologic deficits, such as frontal lobe syndrome, amnesia, motor weakness, or pituitary insufficiency [9, 10, 25, 42, 47, 48, 64]. Therefore, the strategy for treatment of ACoAA should be deliberate to avoid postoperative infarction.

Several studies reported complications and outcomes after the treatment of ACoAAs [6, 22, 24, 30, 36, 44–46, 49, 53, 70]. Postoperative infarction is a well-known complication of neurosurgical treatment and is reported to occur 5.8–71.7% after the treatment of an ACoAA [22, 24, 36, 44–46, 53, 70]. However, most of the studies included ruptured ACoAAs, which may cause difficulty in the analysis of patients' characteristics and anatomical considerations independently because there may be a bias with variables that are generated from subarachnoid hemorrhage (SAH), such as brain swelling, vasospasm, and increased intracranial pressure (IICP) [6, 22, 24, 45, 46, 53, 70]. In contrast, studies which included only unruptured ACoAAs did not evaluate the postoperative infarction or its risk factors specifically [30, 36, 44, 49]. This study is aimed to evaluate the risk factors and clinical outcome of postoperative infarction after surgical clipping of an unruptured ACoAA.

Materials & Methods

This retrospective study was approved by the institutional review board of our medical center. The patient's consent was not required due to the retrospective design of the study.

Inclusion criteria

From January 2008 to December 2020, patients who visited our hospital and for the treatment of an unruptured ACoAA were identified by a retrospective chart review. The inclusion criteria for the study were 1) diagnosis of an unruptured ACoAA; 2) patients who underwent microsurgical clipping; and 3) patients who had a follow-up period more than 6 months after discharge with images and clinical data. The exclusion criteria were 1) patients who visited with subarachnoid hemorrhage or any other ruptured aneurysm history; 2) patients with neurologic deficit; 3) patients with other intracranial deformity, such as arteriovenous malformation, fistula, or tumors; 4) patients who underwent neurosurgical treatment with trapping or clipping with extracranial-intracranial bypass surgery; and 5) patients who had undergone any other neurosurgery that is not related with aneurysm.

Preoperative evaluation

The demographic data of the patients were verified by electronic medical record (EMR), including sex, age, presence of hypertension, diabetes mellitus, dyslipidemia, and history of previous cerebrovascular accident (CVA), including infarction or hemorrhage without neurologic sequelae. All the patients underwent computed tomography angiography (CTA), magnetic resonance imaging (MR), digital subtraction angiography (DSA) to diagnose and evaluate the ACoAA and its relationship with surrounding structures. The size, neck length, and height of aneurysm and presence of fenestration in the ACoA

complex was evaluated using DSA. Based on the method of Matsukawa et al., the projection of the ACoAA was determined as the relationship between the dome projection and reference lines, which are parallel and perpendicular to the sphenoid planum on CTA or DSA (Fig. 1) [40]. It was classified into five groups; 1) anterior 2) superior, 3) posterior, 4) inferior, and 5) multiple, if there are more than two aneurysms that are projecting separately. The relationship of the ACoA complex was also evaluated. The A1 segment of the anterior cerebral artery (ACA) was classified to 1) symmetric, if there were no differences between both A1; 2) asymmetric, if the diameter of a smaller A1 segment was less than 50% of the diameter of the contralateral A1; 3) aplastic, if there is only one dominant A1 segment without any contralateral A1 [29, 34, 71]. Additionally, we measured the distance between the skull base and aneurysm, which is defined as the minimal length from the sphenoid planum to the aneurysm dome using CTA and DSA (Fig. 2).

Neurosurgical treatment

All the patients were treated by three well experienced neurosurgeons from our hospital. All neurosurgical treatments were under general anesthesia. Intraoperative evoked potential (EP) monitoring and indocyanine green video angiography (ICG-VA) were performed during surgery. Surgical clipping was performed with either a pterional approach (Fig. 3) or interhemispheric approach (Fig. 4) for all patients. The presence of intraoperative rupture was investigated using EMR and microscopic intraoperative videos. Additional data were collected for patients who underwent the pterional approach. This included side selection for the approach and relationship of A2 with ACoA complex, which was defined as 1) an opened A2, if the A2 segment of ACA at the approach side is located posteriorly than the contralateral A2; and 2) a closed A2, as the ipsilateral A2 is located anteriorly than the contralateral A2, based on Suzuki et al. (Fig. 5) [26, 60]. As the approach strategy, we selected the pterional approach for the ACoAA with a skull base to aneurysm distance of less than 10 mm, and interhemispheric approach was selected for the ACoAA with a skull base to aneurysm distance of more than 10 mm. Additionally, the pterional approach was considered to be performed from the opened A2 plane to expose the aneurysm easily. However, the strategy was modified if there are variables to consider, such as aneurysm projection, other intracranial aneurysms to clip, or the relationship between perforating arteries.

Postoperative evaluation

After neurosurgical treatment, the clinical status of the patient was identified by EMR and verified if there are any postoperative neurological changes compared to the preoperative status. CT was performed immediately after the surgery and additional CTA was performed 3 days after surgery to verify the complete occlusion of the ACoAA and the status of the surrounding vessels. Additional CTA or MR were performed if there was any neurological alteration during the hospital day. Conventional angiography was performed with patients who had 1) a large size ACoAA; 2) intraoperative complications; or 3) suspected postoperative infarction in CT or MR. At 1 and 6 months after the treatment, an additional CT follow-up was performed. After comparing the pre- and postoperative images, the patients who had newly discovered low density at the postoperative CT or restriction in MR diffusion image, were defined as

having radiologic infarction. Moreover, if patients had a neurological alteration, which corresponds to the territory of radiologic infarction, they were defined as symptomatic infarction. After identifying the postoperative infarction, the branches which corresponded to the infarction were classified by recognizing their territories. The classification of postoperative infarction was divided into five groups, namely, 1) the RAH group; 2) SCA and HThA group; 3) MLSA group 4) A2 early branch group which includes orbitofrontal and frontopolar arteries; and 5) Others group, which do not correspond to arterial territory, but suspected as infarction in CT or MRI, including venous infarction or retraction injury (Fig. 6). The modified Rankin Scale (mRS) were used to evaluate the clinical outcomes at discharge, and 6 months after discharge.

Statistical analyses

For verifying the risk factors for the postoperative infarctions and its outcomes, all the patients were reviewed retrospectively with the medical records and radiologic findings. A statistical analysis was performed using the IBM® SPSS® software version 28.0.0.0 for Windows. The characteristics between the infarction and non-infarction groups were compared using a two-sample t-test, chi-square, or Fisher's exact test for each variable. Comparison of the characteristics by approach type was also analyzed in the same manner. The risk factors of the postoperative infarction were evaluated by a univariable logistic regression analysis. Additionally, due to a small number or events, the variables with a p-value < 0.01 in the univariable analysis were selected and analyzed with multivariable logistic regression. The separated risk factors of the postoperative infarction for each approach were verified in the same way. Additionally, the patients with radiologic infarction had evaluated the relationship between infarction branches and their prognosis using the chi-square test, Fisher's exact test, or Wilcoxon-signed rank test.

Results

Between January 2002 and December 2020, a total of 9,865 patients with 10,013 intracranial aneurysms visited our medical center for cerebral aneurysm. Among them, 848 patients with 873 unruptured ACoAAs were included in our study and underwent neurosurgical clipping.

The characteristics of 848 enrolled patients are described in Table 1. The mean age of patients was 58.60 ± 9.27 and 489 patients (57.7%) were women. For aneurysm characteristics, anteriorly projecting aneurysm (n = 439, 51.8%) counted the most proportion and posteriorly projecting aneurysm (n = 35, 4.1%) was the least, and 22 patients had ACoAAs with multiple projection. The mean size of the aneurysm was 5.21 ± 2.38 mm and the skull base to aneurysm distance was 9.38 ± 3.43 mm. For the approach type, the pterional approach was performed with 795 (93.8%) patients, and 53 (6.2%) patients had the interhemispheric approach. In our study, 66 patients (7.8%) had a radiologic infarction. There were differences between non-infarction and infarction groups in age, presence of hypertension, previous CVA, posterior projection and aneurysm's size, neck length, height, and skull base to aneurysm distance with clinical significance ($p < 0.05$).

Table 1
Characteristics of treated anterior communicating artery aneurysm patients

	Total (n = 848)	Non-infarction (n = 782)	Infarction (n = 66)	P value
Age (SD)	58.60 (9.27)	58.36 (9.27)	61.44 (8.88)	0.01[a]
Sex				
Men (%)	359 (42.3)	337 (43.1)	22 (33.3)	0.123[b]
Women (%)	489 (57.7)	445 (56.9)	44 (66.7)	
Hypertension (%)	456 (53.8)	408 (52.2)	48 (72.7)	0.001 [b]
Diabetes mellitus (%)	112 (13.2)	103 (13.2)	9 (13.6)	0.915 [b]
Hyperlipidemia (%)	207 (24.4)	191 (24.4)	16 (24.2)	0.974 [b]
Previous CVA (%)	32 (3.8)	25 (3.2)	7 (10.6)	0.002 [b]
Aneurysm				
Projection				
Anterior (%)	439 (51.8)	411 (52.6)	28 (42.4)	0.114 [b]
Superior (%)	203 (23.9)	183 (23.4)	20 (30.3)	0.207 [b]
Posterior (%)	35 (4.1)	26 (3.3)	9 (13.6)	< 0.001 [b]
Inferior (%)	191 (22.5)	179 (22.9)	12 (18.2)	0.379 [b]
Multiple (%)	22 (2.6)	19 (2.4)	3 (4.5)	0.241 [b]
Size				
Maximal diameter (SD)	5.21 (2.38)	5.09 (2.24)	6.67 (3.32)	< 0.001 [a]
Neck (SD)	3.75 (1.39)	3.69 (1.36)	4.40 (1.59)	< 0.001 [a]
Height (SD)	3.83 (2.01)	3.73 (1.89)	4.93 (2.91)	< 0.001 [a]

CVA Cerebrovascular accident; *D/N ratio* Dome to neck ratio; *ACoA* Anterior communicating artery

[a] Two-sample T-test

[b]chi-square test or Fisher's exact test

	Total (n = 848)	Non-infarction (n = 782)	Infarction (n = 66)	P value
D/N ratio (SD)	1.41 (0.46)	1.40 (0.46)	1.51 (0.47)	0.067 [a]
Skull base to aneurysm distance (SD)	9.38 (3.43)	9.18 (3.38)	11.74 (3.18)	< 0.001 [a]
Fenestration of ACoA (%)	58 (6.8)	53 (6.8)	5 (7.6)	0.805 [b]
A1 type				
Symmetric (%)	222 (26.2)	203 (26.0)	19 (28.8)	0.852 [b]
Asymmetric (%)	371 (43.8)	344 (44.0)	27 (40.9)	
Aplastic (%)	255 (30.1)	235 (30.1)	20 (30.3)	
Approach				
Pterional (%)	795 (93.8)	732 (93.6)	63 (95.5)	0.791 [b]
Interhemispheric (%)	53 (6.2)	50 (6.4)	3 (4.5)	
CVA Cerebrovascular accident; *D/N ratio* Dome to neck ratio; *ACoA* Anterior communicating artery				
[a] Two-sample T-test				
[b]chi-square test or Fisher's exact test				

A univariable logistic regression analysis revealed that age, hypertension, previous CVA, posterior projection, size of the aneurysm, neck length, height, and skull base to aneurysm distance were the clinical risk factors for postoperative infarction after surgical clipping (Table 2). For a multiple projecting aneurysm, preliminary analyses for the association between infarctions and projection showed no significant interactions effects among aneurysms projections. In multivariable logistic regression analysis, we included the risk factors with a p-value less than 0.01 in the previous univariable analysis because of the small number of events. Finally, hypertension (OR 2.05; CI [1.14–3.68]; $p < 0.05$), previous CVA (OR 2.79; CI [1.07–7.28]; $p < 0.05$), posterior projection (OR 3.94; CI [1.64–9.44]; $p < 0.01$), size of aneurysm (OR 1.16; CI [1.06–1.28]; $p < 0.01$), skull base to aneurysm distance (OR 1.16; CI [1.07–1.25]; $p < 0.01$) were revealed as the independent risk factors for the postoperative infarction after surgical clipping of the ACoAA. For the size of aneurysm and skull base to aneurysm distance, a receiver operating characteristic (ROC) curve was drawn for the relationship with postoperative infarction. The area under curve (AUC) showed over than 0.5 in both sizes of aneurysm (AUC = 0.651; $p < 0.001$) and skull base to aneurysm distance (AUC = 0.730; $p < 0.001$). Each optimal cut-off value was determined as 5 mm for the size of aneurysm (sensitivity = 0.627; specificity = 0.552), and 10 mm for skull base to aneurysm distance (sensitivity = 0.701; specificity = 0.630) (Fig. 7). When we divided the distance of the skull base

to aneurysms distance of 10 mm more or less, a logistic regression analysis revealed more postoperative infarction in patients with the skull base to aneurysm distance more than 10 mm (OR 3.36; CI [1.83–6.05]; $p < 0.01$)

Table 2
Univariable and multivariable logistic regression analyses of postoperative infarction

	Risk of postoperative infarction	
	Univariate (OR, CI [95%])	Multivariate (OR, CI [95%])
Age	1.04 [1.01–1.07] [b]	
Sex		
Men	1	
Women	1.51 [0.89–2.58]	
Hypertension	2.44 [1.40–4.28][a]	2.05 [1.14–3.68][b]
Diabetes mellitus	1.04 [0.50–2.17]	
Hyperlipidemia	0.99 [0.55–1.78]	
previous CVA	3.59 [1.49–8.65] [a]	2.79 [1.07–7.28] [b]
Aneurysm		
Projection		
Anterior	0.66 [0.40–1.10]	
Superior	1.42 [0.82–2.47]	
Posterior	4.59 [2.05–10.26] [a]	3.94 [1.64–9.44] [a]
Inferior	0.75 [0.39–1.43]	
Multiple	1.91 [0.55–6.64]	
Size		
Maximal diameter	1.23 [1.12–1.36] [a]	1.16 [1.06–1.28] [a]
Neck	1.37 [1.17–1.60] [a]	
Height	1.24 [1.12–1.36] [a]	
D/N ratio (SD)	1.49 [0.96–2.30]	
Skull base to aneurysm distance (SD)	1.22 [1.14–1.31] [a]	1.16 [1.07–1.25] [a]

CVA Cerebrovascular accident; *D/N ratio* Dome to neck ratio; *ACoA* Anterior communicating artery

[a]p<0.01

[b]p<0.05

	Risk of postoperative infarction
Fenestration of ACoA (%)	1.13 [0.43–2.92]
A1 type	
Symmetric (%)	1
Asymmetric (%)	0.84 [0.46–1.55]
Aplastic (%)	0.91 [0.47–1.75]
Approach	
Pterional (%)	1
Interhemispheric (%)	0.70 [0.21–2.30]
Intraoperative rupture	3.06 [0.84–11.11]
CVA Cerebrovascular accident; *D/N ratio* Dome to neck ratio; *ACoA* Anterior communicating artery	
[a]p<0.01	
[b]p<0.05	

There was a difference in the proportion of aneurysm projection between the pterional and the interhemispheric groups (Table 3). The interhemispheric approach group had more superiorly projecting aneurysms (n = 24; 45.3%; p < 0.01) and pterional approach group had more inferiorly projecting aneurysms with clinical significance (n = 190; 23.9%; p < 0.01). The size and neck length of aneurysm were larger in the interhemispheric approach group. Additionally, the skull base to aneurysm distance was higher in interhemispheric approach group than the pterionally approached group (13.05 mm vs 9.13 mm; p < 0.01). For the proportion of associated branches of the postoperative infarction, infarction in other territories, which include venous infarction or retraction injury had a higher proportion in the interhemispheric group than the pterional group (p = 0.021).

Table 3
Clinical characteristics by operation procedure

	Pterional (n = 795)	Interhemispheric (n = 53)	P value
Aneurysm			
Projection			
Anterior (%)	411 (51.7)	28 (52.8)	0.873 [a]
Superior (%)	179 (22.5)	24(45.3)	< 0.001 [a]
Posterior (%)	34 (4.3)	1 (1.9)	0.718 [a]
Inferior (%)	190 (23.9)	1 (1.9)	< 0.001 [a]
Multiple (%)	21 (2.6)	1 (1.9)	1 [a]
Size			
Maximal diameter (SD)	5.16 (2.38)	5.98 (2.29)	0.016 [b]
Neck (SD)	3.72 (1.38)	4.18 (1.44)	0.02 [b]
Height (SD)	3.81 (2.01)	4.01 (1.96)	0.493 [b]
D/N ratio (SD)	1.41 (0.47)	1.45 (0.38)	0.497 [b]
Skull base to aneurysm distance (SD)	9.13 (3.30)	13.05 (3.30)	< 0.001 [b]
Intraoperative rupture (%)	15 (1.9)	0 (0.0)	0.31 [a]
Postoperative infarction (%)	63 (7.9)	3 (5.7)	0.791 [a]
RAH (%)	23 (2.9)	0 (0.0)	0.391 [a]
SCA and HThA (%)	25 (3.1)	1 (1.9)	1 [a]
MLSA (%)	19 (2.4)	0 (0.0)	0. 625 [a]
A2 cortical (%)	5 (0.6)	2 (3.8)	0.066 [a]

D/N ratio Dome to neck ratio; *RAH* recurrent artery of Heubner; *SCA* subcallosal artery; *HThA* Hypothalamic artery; *MLSA* Medial lenticulostriate artery; *A2 cortical* Orbitofrontal and frontopolar arteries

[a] chi-square test or Fisher's exact test

[b] Two-sample T-test

	Pterional (n = 795)	Interhemispheric (n = 53)	P value
others (%)	2 (0.3)	2 (3.8)	0.021 [a]
D/N ratio Dome to neck ratio; *RAH* recurrent artery of Heubner; *SCA* subcallosal artery; *HThA* Hypothalamic artery; *MLSA* Medial lenticulostriate artery; *A2 cortical* Orbitofrontal and frontopolar arteries			
[a] chi-square test or Fisher's exact test			
[b] Two-sample T-test			

Additional univariable and multivariable logistic regression analyses for the pterional approached subgroup were performed (Table 4). A univariable analysis showed age, hypertension, previous CVA, posterior projection, size of aneurysm, neck length, height, skull base to aneurysm distance as clinical risk factors for postoperative infarction, which is similar with the total study group. Additionally, for the pterional approached group, a closed A2 plane from the approach side was also a risk factor with clinical significance. In a multivariable analysis, same as the analysis in the total group, we included risk factors with a p-value less than 0.01 in the previous univariable analysis. As a result, hypertension (OR 1.98; CI [1.08–3.63]; $p < 0.05$), posterior projection (OR 4.81; CI [1.98–11.71]; $p < 0.01$), size of aneurysm (OR 1.15; CI [1.04–1.27]; $p < 0.01$), skull base to aneurysm distance (OR 1.21; CI [1.11–1.31]; $p < 0.01$), and closed A2 plane (OR 1.98; CI [1.09–3.59]; $p < 0.05$) revealed as independent risk factors for the postoperative infarction after surgical clipping of the ACoAA with pterional approach. We also evaluated the relationship between interhemispheric approach and postoperative infarction; however, significant risk factors had not been identified.

Table 4
Univariable and multivariable logistic regression analyses of postoperative infarction in patients with pterional approach

	Risk of postoperative infarction	
	Univariate (OR, CI [95%])	Multivariate (OR, CI [95%])
Age	1.05 [1.01–1.08] [a]	1.03 [1.00–1.06]
Sex		
Men	1	
Women	1.33 [0.78–2.28]	
Hypertension	2.30 [1.31–4.05] [a]	1.98 [1.08–3.63] [b]
Diabetes mellitus	1.12 [0.53–2.34]	
Hyperlipidemia	1.07 [0.59–1.94]	
previous CVA	3.10 [1.22–7.91] [b]	
Aneurysm		
Projection		
Anterior	0.68 [0.40–1.14]	
Superior	1.42 [0.80–2.52]	
Posterior	4.71 [2.10–10.60] [a]	4.81 [1.98–11.71] [a]
Inferior	0.73 [0.38–1.40]	
Multiple	1.98 [0.57–6.92]	
Size	1.26 [1.16–1.37] [a]	1.15 [1.04–1.27] [a]
Neck	1.44 [1.22–1.69] [a]	
Height	1.26 [1.14–1.39] [a]	
D/N ratio	1.50 [0.97–2.33]	
Skull base to aneurysm distance	1.28 [1.18–1.38] [a]	1.21 [1.11–1.31] [a]

CVA Cerebrovascular accident; *D/N ratio* Dome to neck ratio; *ACoA* Anterior communicating artery

[a] $p<0.01$

[b] $p<0.05$

	Risk of postoperative infarction	
Fenestration of ACoA	1.20 [0.46–3.13]	
A1 type		
Symmetric	1	
Asymmetric	0.86 [0.46–1.61]	
Aplastic	0.93 [0.48–1.83]	
Approach side		
Right	1	
Left	1.21 [0.72–2.02]	
A2 type		
Opened	1	
Closed	2.25 [1.29–3.93] [a]	1.98 [1.09–3.59] [b]
Intraoperative rupture	3.00 [0.82–10.92	
Multiple aneurysm clipping	1.28 [0.74–2.22]	
CVA Cerebrovascular accident; *D/N ratio* Dome to neck ratio; *ACoA* Anterior communicating artery		
[a] $p<0.01$		
[b] $p<0.05$		

Table 5
Characteristics of postoperative infarction

		Symptomatic Infarction (%)			Modified Rankin Scale (SD)		
	Total (n = 66)	No (n = 32)	Yes (n = 34)	P value	At discharge	After 6 months	P value
RAH (%)	23 (34.8)	12 (37.5)	11 (32.4)	0.661 [a]	0.96 (1.30)	0.78 (1.28)	0.1817 [b]
SCA and HThA (%)	26 (39.4)	6 (18.8)	20 (58.8)	0.001 [a]	1.42 (0.99)	0.96 (0.92)	0.0015 [b]
MLSA (%)	18 (27.3)	12 (37.5)	6 (17.6)	0.098 [a]	0.78 (1.35)	0.67 (1.33)	0.3458 [b]
A2 cortical (%)	7 (10.6)	1 (3.1)	6 (17.6)	0.106 [a]	2.00 (1.63)	1.71 (1.80)	0.3458 [b]
others (%)	3 (4.5)	2 (6.2)	1 (2.9)	0.608 [a]	0.67 (1.15)	0.67 (1.15)	NA

RAH recurrent artery of Heubner; *SCA* subcallosal artery; *HThA* Hypothalamic artery; *MLSA* Medial lenticulostriate artery; *A2 cortical* Orbitofrontal and frontopolar arteries

[a] chi-square test or Fisher's exact test

[b] Wilcoxon-signed rank test

In a total of 66 patients with radiologic infarction after clipping, 34 patients had infarction related symptoms, such as frontal lobe syndrome, amnesia, motor weakness, and pituitary insufficiency. Patients with an infarction in SCA and HThA had a higher tendency to have related neurologic symptoms than other branches with clinical significance (p = 0.01). For clinical outcomes, mRS at hospital discharge showed higher scores in the SCA and HThA infarction group (1.42 ± 0.99) and A2 cortical branches infarction group (2.00 ± 1.63). When we compared the mRS at discharge with that at 6 months after discharge, the SCA and HThA infarction groups showed improvement in mRS (0.96 ± 0.92) with clinical significance (p = 0.015); however, the A2 cortical branches infarction group did not.

Discussion

Surgical clipping vs coiling

Through the development of the endovascular technique over time, the success rate of ACoAA occlusion with endovascular treatment has been increased, followed with the increase in the number of the endovascular treatment. Previous studies reported that clipping had more procedure related injury than coiling [OR: 2.17– 24.42], including postoperative infarction [24, 45, 46]. Although coiling has become an efficient treatment for intracranial aneurysms, a higher recurrence rate and retreatment rate are reported

than surgical clipping in previous reports [43, 58]. Surgical clipping remains a necessary treatment for an aneurysm with specific characteristics. In our hospital, ACoAA expecting incomplete treatment with coiling, such as aneurysm with 1) broad neck (> 4 mm); 2) large or giant size (≥ 10 mm); 3) unfavorable dome to neck ratio 4) fusiform shape; 5) unstable intraluminal thrombus; 6) perforators which are incorporated into the aneurysm neck; 7) aneurysms in multiple locations; or 8) difficulty in proximal access via endovascular approach, had been treated with surgical clipping. These characteristics of ACoAAs may result in a difficult procedure with clipping; however, it is possible to obtain a better outcome using surgery by the development of microsurgical instruments and microscope, application of ICG-VA, and intraoperative EP monitoring.

Risk factors for postoperative infarction

With demographic data, the patients with hypertension (OR 2.05; $p < 0.05$) and previous CVA history (OR 2.79; $p < 0.05$) were independently associated with postoperative infarction. A meta-analysis of association between silent brain infarction and stroke was reviewed [21]. It was reported that even very small cerebrovascular lesions had an association with stroke and mortality. In addition, hypertension is well known as a strong risk factor for stroke [19, 50, 67]. These may also have a high relationship with postoperative infarction. Another hypothesis is that postoperative infarction may be due to the atherosclerotic change of intracranial vessels. Atherosclerosis is known to be one of the major causes of stroke [2]. Additionally, hypertension is a well-known risk factor for intracranial atherosclerosis [1, 66]. Cosar et al. performed an experiment with 12 rabbits with or without atherosclerotic common carotid artery, and evaluated the effect of the temporary clip [14]. The result showed that the microscopic change due to the temporary clip occurred much earlier in the atherosclerotic CCA (in 1 min) than non-atherosclerotic CCA (in 10 min). In our study, the patients with hypertension or previous CVA may have had predisposing intracranial atherosclerosis. Additionally, we usually use temporary clips for most clip surgeries. It may result in a higher tendency of having vessel injury or emboli during manipulation or temporary clipping of parent artery with atherosclerosis, which may need further study. Also, if there are atherosclerotic changes in the aneurysm or its neck, applying a permanent clip on the aneurysm may induce postoperative infarction due to complications, such as shower emboli, slippage of permanent clip, or additional narrowing of inner diameter than outer diameter of parent artery, which are reported in previous studies [3, 13, 51]. These may be the reasons of the postoperative infarction without visible intraoperative complications in the operation field.

The size of the ACoAA is an important factor for the prediction of aneurysm rupture and choice of treatment. An aneurysm with a size less than 7 mm was reported to have a low rupture risk with in ISUIA [68]. However, a high rate of rupture of small cerebral aneurysms has been reported in UCAS [65]. Additionally, it has been reported that the ACoAA has a higher rupture risk than other anterior circulations. In addition, recent studies reported that ACoAAs with a smaller size have a risk of spontaneous rupture [5, 39]. These make it difficult for neurosurgeons to decide whether aggressive treatment is needed for unruptured ACoAAs. Generally, the size of the aneurysm is known to have a relationship with incomplete clipping and intraoperative rupture [15, 28, 56, 61]. Size is also reported to have an association with

postoperative infarction. Swiatnicki et al. reported that an intracranial aneurysm with a size more than 9 mm (OR 1.15; p = 0.003) was independently associated with brain ischemia [61]. Additionally, another study evaluated the perforator infarction during surgical clipping of posterior communicating artery aneurysm, and they also showed aneurysm size (OR 1.18; p = 0.02) as an independent predictor [62]. Only one study reported that surgical clipping of larger ACoAAs may come with worse clinical outcomes, which have an mRS score more than 2 [27]. In our study, the mean ACoAA size was 5.21 mm (± 2.38 mm), which is reasonable for treatment. Additionally, size (OR 1.16; p < 0.01) was a significant risk factor for postoperative infarction, especially with aneurysms larger than 5 mm. A large size of aneurysm may obstruct the surgical view and hard to visualize perforators. Moreover, it is also associated with more adhesion with the surrounding structures, including parent and perforating arteries, and parenchyma. These may increase the risk of manipulating the surrounding structures during dissection and clipping, which results in vessel injury. Careful consideration with a large size aneurysm is needed during surgical clipping.

The surgical clipping of a posterior projecting ACoAA is considered to be the most difficult because it is hidden between interhemispheric fissure and can hide ACoA perforators, which originated from the posterior portion of ACoA complex, such as SCA and HThA [10, 25, 31, 38]. However, there are few clinical data for complications with surgical clipping of posterior projecting aneurysm. Proust et al. reported that ACoAAs projecting posteriorly to the axis of the pericallosal arteries had a higher risk of vessel occlusion than anteriorly projecting ACoAAs, which leads to unfavorable outcomes [53]. Similarly, Ivan et al. reported that superiorly and posteriorly projecting ACoAAs have significantly worse outcomes because it requires opening the junctional triangle, which is the intersection between the distal A1 ACA segment and the proximal A2 ACA segment [27]. Our data showed that posterior projection was a strong risk factor for postoperative infarction than any other projection, especially with the pterional approach. More attention should be given for clipping posteriorly projecting aneurysm.

Several studies had evaluated high positioned ACoAAs; however, unified definition has not been determined [20, 32, 33, 52]. In the pterional approach, a high positioned ACoAA is reported to have an association with postoperative anosmia or residual neck [52, 60]. The distance from the skull base to the aneurysm was measured with various modifications. In our study, Measurement was done from the sphenoid planum to the aneurysm dome because we usually secure the whole plane of aneurysm dome before permanent clipping. Additionally, our results showed that a high positioned ACoAA, especially more than 10 mm, is significantly associated with postoperative infarction. To visualize the aneurysm, additional manipulation of the frontal lobe and resection of the rectus gyrus would be needed. It may result in additional cortical injury and bleeding control, leading to vessel injury. Suzuki et al. reported an additional requirement of A2 manipulation and contusion with high positioned ACoAAs, which supports our opinion [60]. In our study, patients who had surgical clipping via an interhemispheric approach had a higher position of the ACoAA than the pterional approached group; however, there had been no significant relationship with postoperative infarction. It has been reported that the treatment of a high positioned ACoAA via an interhemispheric approach was also associated with complete clipping when compared to the pterional approach [33]. Therefore, we suggest the definition of a high positioned ACoAA as an

aneurysm located more than 10 mm from the skull base, which should be treated via an interhemispheric approach rather than a pterional approach to avoid postoperative infarction.

Several suggestions were proposed for side selection with the pterional approach. It includes several factors, such as non-dominant hemisphere, projection of aneurysm, dominant A1, and accompanying aneurysms. In our study, an approach from the closed A2 plane showed as an independent risk factor for postoperative infarction (OR 1.98, CI [1.09–3.59], p = 0.024). Considering the anatomical structure of the ACoA complex, an approach from the closed A2 plane requires an additional manipulation of the frontal lobe and A2 due to an obstructed surgical view. Suzuki et al. reported that an approach from the closed A2 plane with a superior directing ACoAA had a higher tendency to have rectus gyrus resection, residual neck, damage of RAH and other perforators, and contusion, which supports our opinion [60]. Hyun et al. also studied 19 superior directing ACoAA, and insisted that a closed A2 plane had a higher incidence of rectus gyrus resection [26]. However, they did not show clinical significance with postoperative infarction, which may be due to the small sample size. Our study showed that an approach from a closed A2 plane has a relationship with postoperative infarction regardless of any projection of the ACoAA, which differs from previous studies and emphasizes the importance of the A2 fork.

Some studies proposed a strategy for side selection by correlating the projection of aneurysm with the A2 fork. They suggested the opening of the A2 plane for superior projection, and closed A2 plane for posteriorly projecting aneurysm [11, 16]. The result of their strategy showed a good clinical outcome with convincing mRS or GOS for more than 88–90.2% of the enrolled patients. Another study showed that the surgical clipping of ACoAAs via supraorbital eyebrow keyhole approach showed no relationship between the A2 plane and postoperative complication [4]. These studies may also be useful to select an approach strategy with preventing postoperative infarction and further evaluation should be needed.

Some studies suggested a right-sided approach, which is believed to avoid retraction of the dominant lobe and provide convenience for most of the right-handed surgeons [16, 57]. However, in our study, there was no significant difference in the postoperative infarction with either approach side. It may be due to our strategy for left-sided approach. We prefer to perform an extended craniotomy to manipulate with convenience for right-sided surgeons and to reduce frontal and temporal lobe retraction. Additionally, it may also reduce the risk of postoperative infarctions. Similar results were also found in previous studies [26, 60].

Clinical outcomes after postoperative infarction

Prognosis of the postoperative infarction was observed to vary with each branch of the ACoA complex. Complications of the postoperative infarction presented as frontal lobe syndrome, amnesia, motor weakness, or pituitary insufficiency. mRS at discharge was the highest in the infarction at A2 cortical branches (mRS = 2.00 ± 1.63), which include orbitofrontal and frontopolar branches, and followed by the infarction at SCA and HthA (mRS = 1.42 ± 0.99).

RAH arises near the A1-ACoA-A2 junction and MLSA originated from the A1 of the anterior cerebral artery [10, 18, 72]. RAH supplies the thalamus, anterior lenticular nucleus, lateral globus pallidus, anterior caudate nucelus, and anterior crus of the internal capsule [10]. Additionally, MLSA supplies the globus pallidus and medial portion of the putamen [54]. Infarction in RAH and MLSA can usually present with weakness in the contralateral face and upper limb [10, 64]. In our study, the infarction in RAH was usually restricted in the head of the caudate nucleus, and the MLSA infarction was mostly presented as a lacunar infarction in the medial portion of the globus pallidus. Infarction in these territories showed good clinical outcomes with an mRS less than 2. They had not been associated with poor outcomes after aneurysm surgery in previous study [55]. Stein et al. reported that the injury localized to the head of the caudate nucleus was presented with vomiting, headache, neck stiffness, and decreased conscious level without neurological focal sign [59]. Additionally, injury in the caudate nucleus showed good clinical outcomes in most studies, which support our results [35, 59].

The SCA and the HThA are known to originate from the posterior region of ACoA. The SCA supplies the genu of corpus callosum, lamina terminalis, anterior commissure, fornix, and septum pellucidum. Additionally, the HThA supplies the hypothalamus and the lamina terminalis [10]. In our study, the infarction of SCA was usually involved the genu of the corpus callosum, and the symptomatic infarction had involved more at the fornix and the anterior commissure, which is similar to previous studies [17, 23, 47]. The fornix is known to be the component of the Papez circuit and plays an important role in the memory formation and consolidation [17, 42]. Additionally, the injury in the fornix may have presented with the memory disturbance, which also affected the clinical outcome. The HThA infarction was rare and presented with pituitary insufficiency. However, for these branches, the mRS after 6 months from discharge has been decreased when compared to the mRS at discharge. The preservation of SCA and HThA during ACoAA clipping is important; however, the infarction of the involved territory may be more critical, and may need further study.

The orbitofrontal artery is the first branch of the A2 segment and supplies the rectus gyrus and medial orbital gyri [41]. Injury of the orbitofrontal area, especially the ventromedial orbitofrontal cortex is known to cause behavioral changes, which is known as the “frontal lobe syndrome” [7, 12]. Our results showed a similar neurologic outcome with previous studies and mRS at discharge and 6 months after discharge showed worse outcomes than other arteries, which require additional care.

Limitations

This study has some limitations. First, a selection bias may have occurred due to the retrospective design of the study. Second, due to the poor documentation of the records, we did not investigate the duration of temporary clipping, range of rectus gyrus resection, which might affect the outcome of postoperative infarction. Third, the precise evaluation of postoperative anosmia, which is a common complication of ACoAA clipping and influence the clinical outcome, had not been performed. Finally, we measured the mRS for the overall clinical outcome; however, it is inaccurate for measuring mild cognitive impairment or amnesia, which needs suitable neuropsychologic tests. Further research is needed in the future.

Conclusion

To our knowledge, this is the first study that has evaluated the anatomical risk factors of the postoperative infarction, especially with respect to unruptured ACoAAs. According to our results, hypertension, previous CVA, posteriorly projecting aneurysm, aneurysm size, high positioned aneurysm (skull base to aneurysm distance > 10 mm) are the independent risk factors for postoperative infarctions during the surgical clipping of an unruptured ACoAA. Additionally, the closed A2 plane is an additional risk factor for the postoperative infarction during the pterional approach. The A2 fork and aneurysm height should be considered in the approach selection for clipping an unruptured ACoAA. Infarction in the A2 cortical branches, SCA and HThA should be provided with more attention in regard to their neurologic outcomes.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose

Availability of data and material

Our data and materials are prepared to send relevant documentation or data in order to verify the validity of the results

Code availability

Not applicable

Ethics approval

This retrospective study was approved by the institutional review board of our medical center.

Consent to participate

This retrospective study was approved by the institutional review board of our medical center and the patient’s consent was not required due to the retrospective design of the study.

Consent to publish

This retrospective study and approved by the institutional review board of our medical center. The patient's consent was not required due to the retrospective design of the study.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Hyun Taek Rim, Jae Sung Ahn, Jung Cheol Park, Joonho Byun, Seungjoo Lee, Wonhyoung Park. The first draft of the manuscript was written by Hyun Taek Rim and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

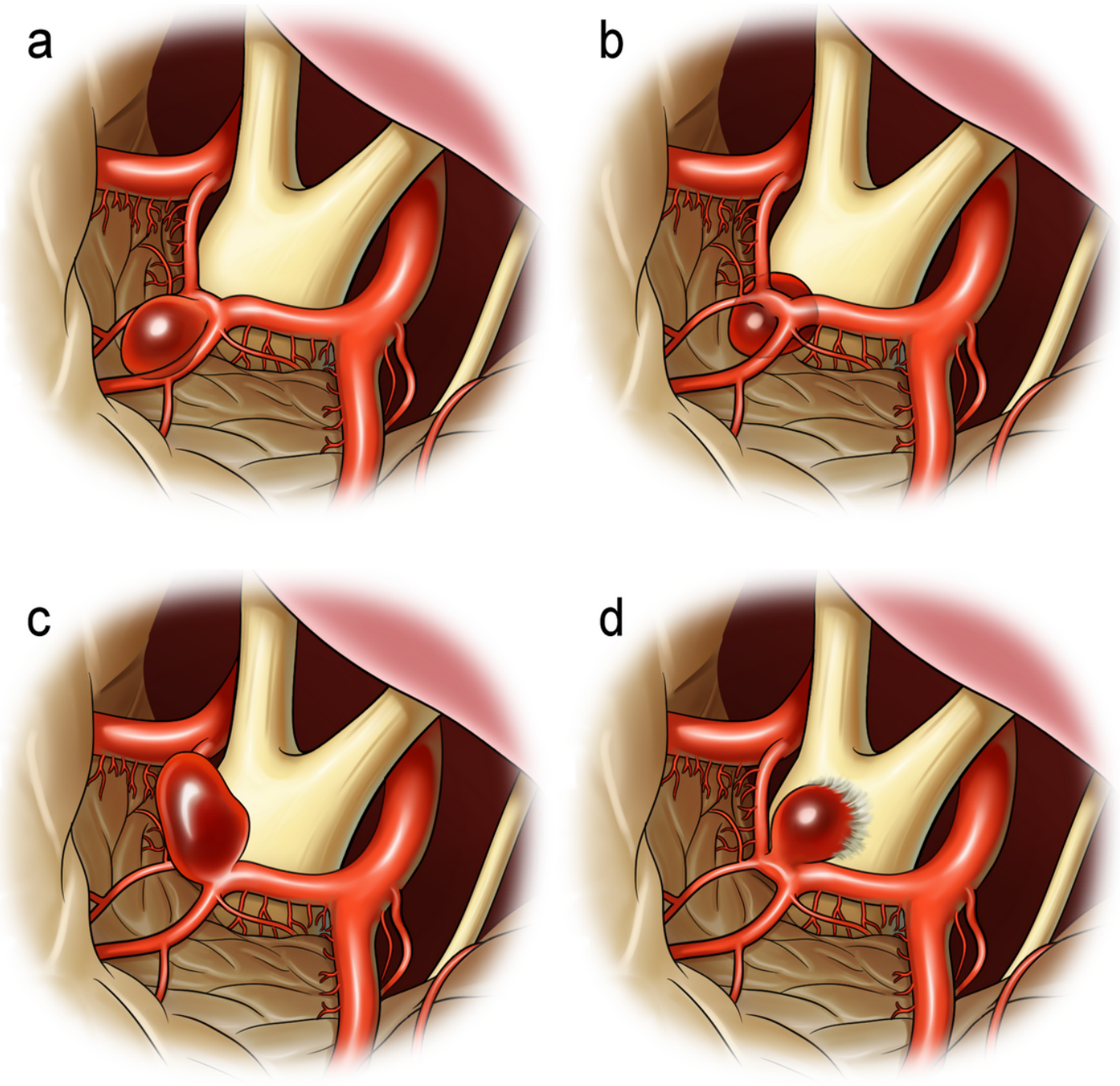

Figure 1

Classification of ACoAA projection a) superior projection. b) posterior projection. c) anterior projection. d) inferior projection

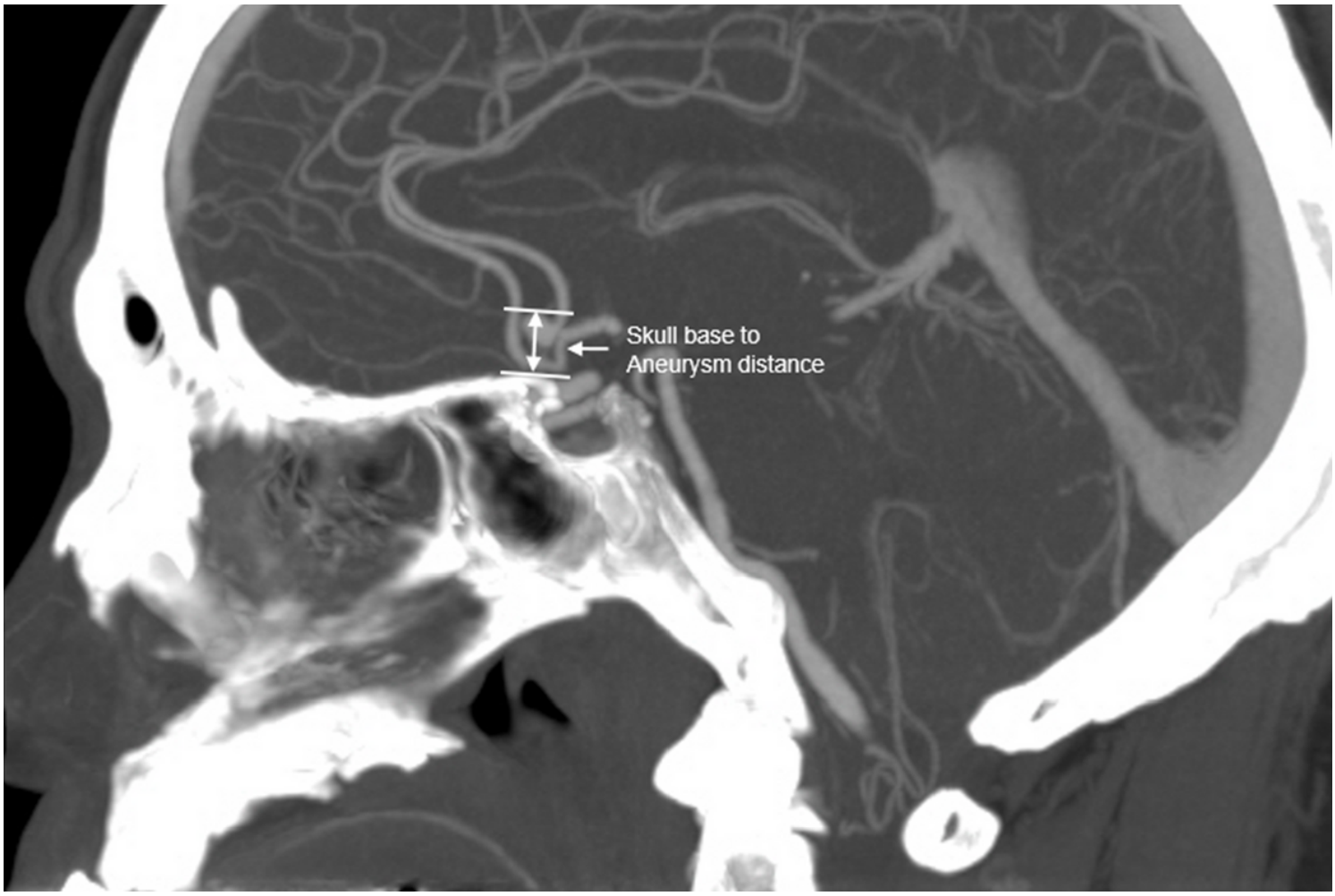

Figure 2

Illustration of skull base to aneurysm distance, which is defined as the minimal length from the sphenoid planum to the aneurysm dome using CTA or DSA.

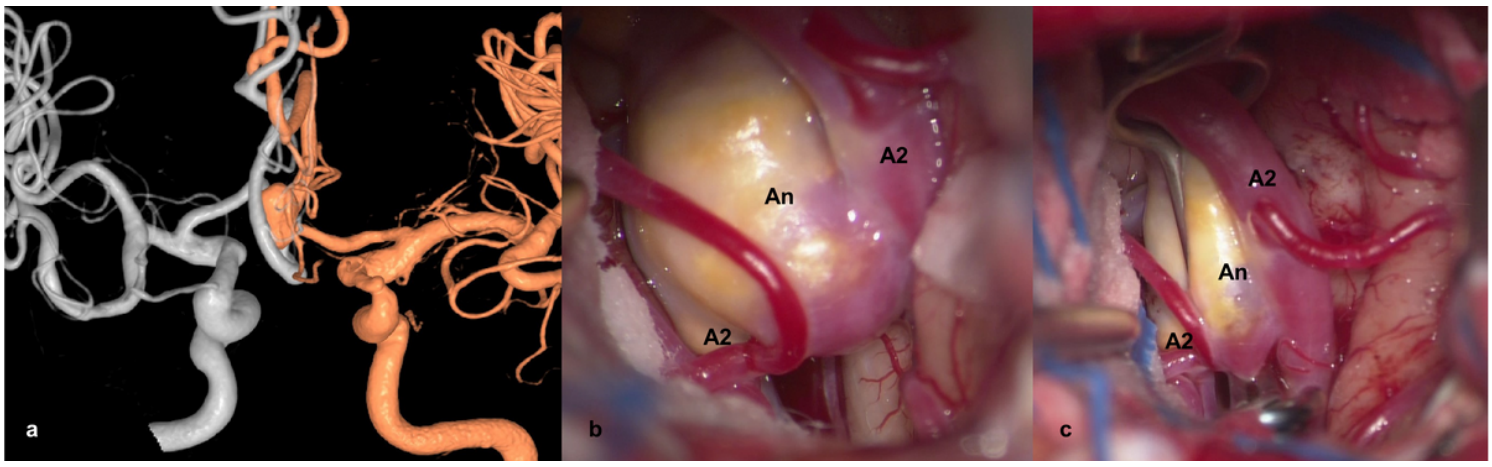

Figure 3

a) Three dimentional angiogram of 69 year old female patient with an anteriorly projecting anterior communicating artery aneurysm. Due to its broad neck, it was determined to treat the aneurysm with

mircrosurgical clipping. b) Pterional cranotomy was performed from the opened A2 plane (right side) and rectus gyrus was aspirated to visualize the aneurysm dome. c) The aneurysm was clipped with multiple clips preserving the surrounding structures. An, aneurysm; A1, A1 portion of the left anterior cerebral artery; A2, A2 portions of both anterior cerebral arteries

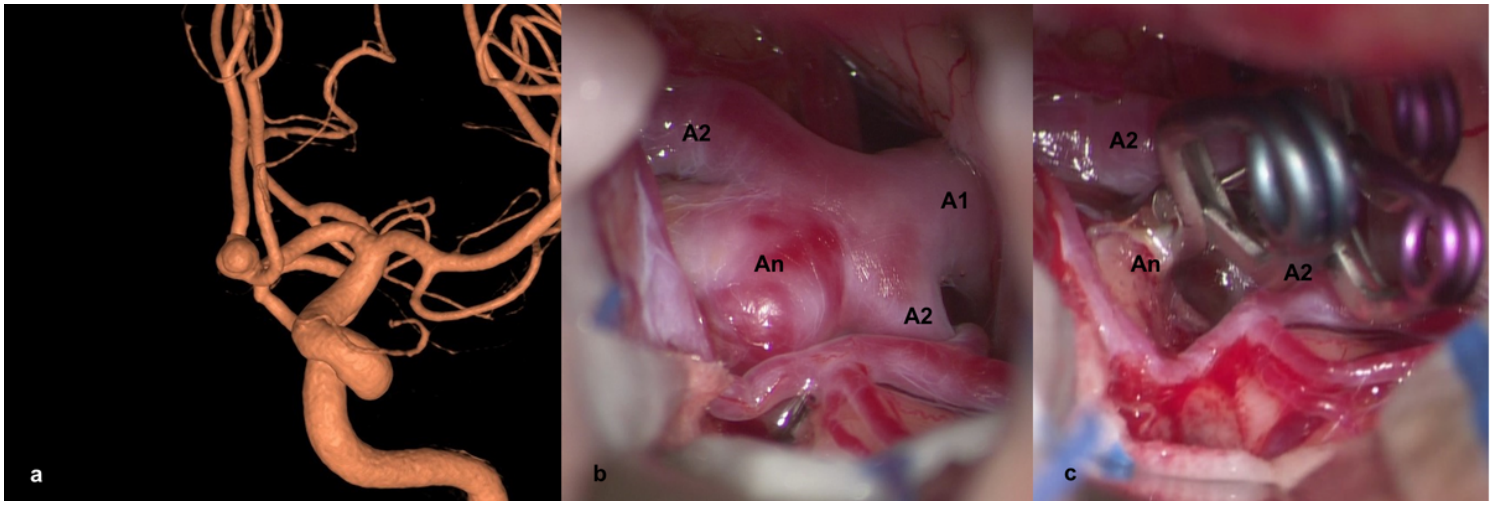

Figure 4

a) Three dimentional angiogram of 75 year old patient with an anteriorly projecting anterior communicating artery aneurysm. The aneurysm had a large size with a broad neck and was expected to havedifficult proximal access by endovascular treatment. b) Microsurgical treatment was determined with interhemispheric approach because aneurysm was higher than 10 mm from the sphenoidal planum. c) The aneurysm had severe adheison with Rt. A2 portion of ACA, fenestrastrated clip was used avoiding Rt. A2 occlusion, and an additional clip was applied at the remnant neck. An, aneurysm; A2, A2 portions of both anterior cerebral arteries.

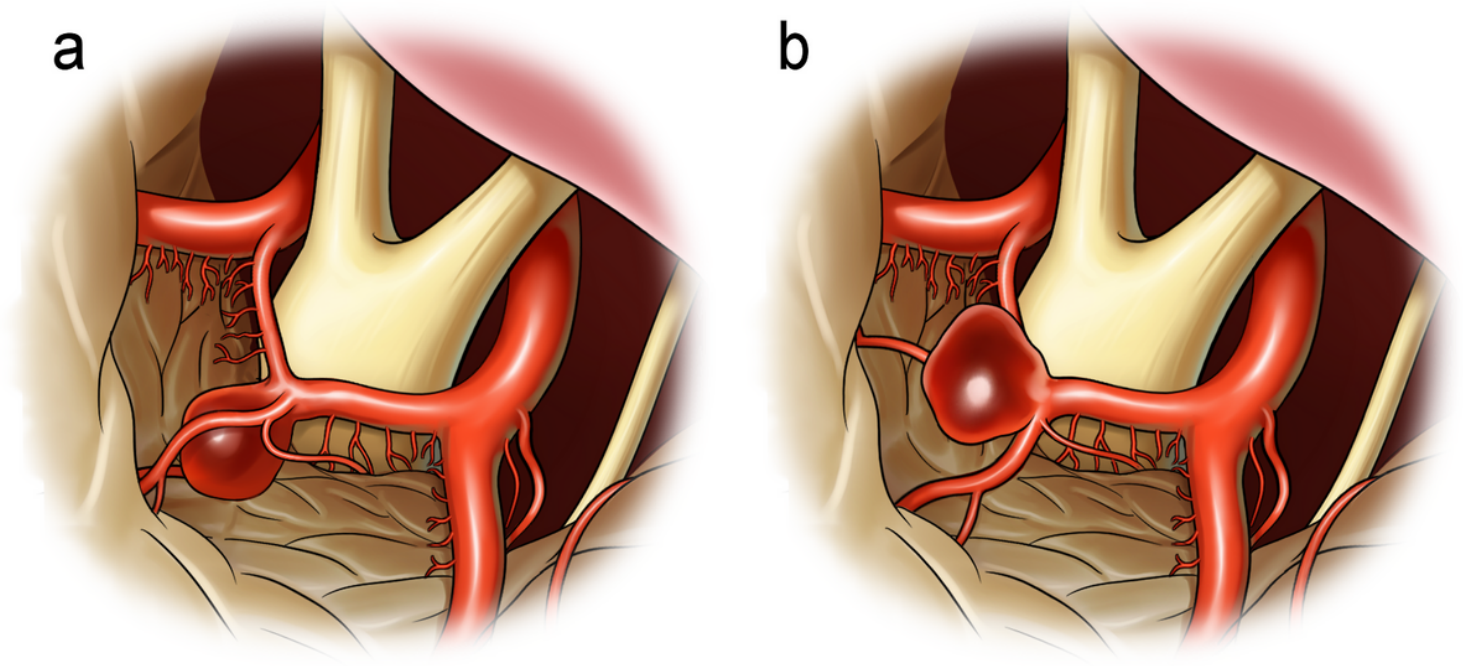

Figure 5

Relationship of A2 fork. a) Surgical view from the closed A2, as the ipsilateral A2 is located anteriorly in comparison with the contralateral A2. b) Surgical view from the opened A2 plane, which the ipsilateral A2 segment is posterior to the contralateral A2.

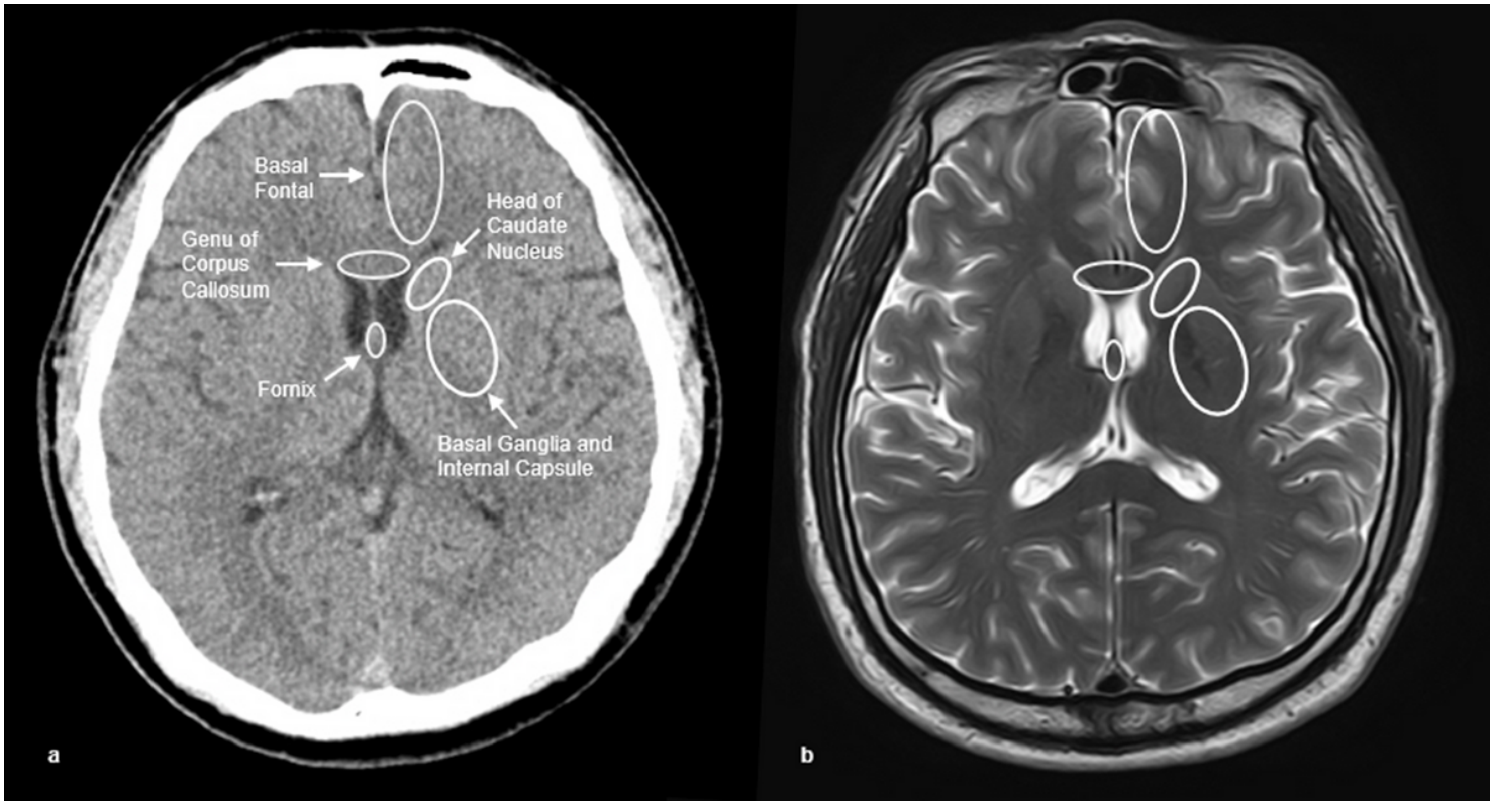

Figure 6

Territory of postoperative infarction. Anatomical location of infarction in CT or MR was verified and correspoding arterial territories were reviewed. The classification was divided into 5 groups, 1) RAH group; 2) SCA and HThA group; 3) MLSA group 4) A2 early branch group; and 5) Others

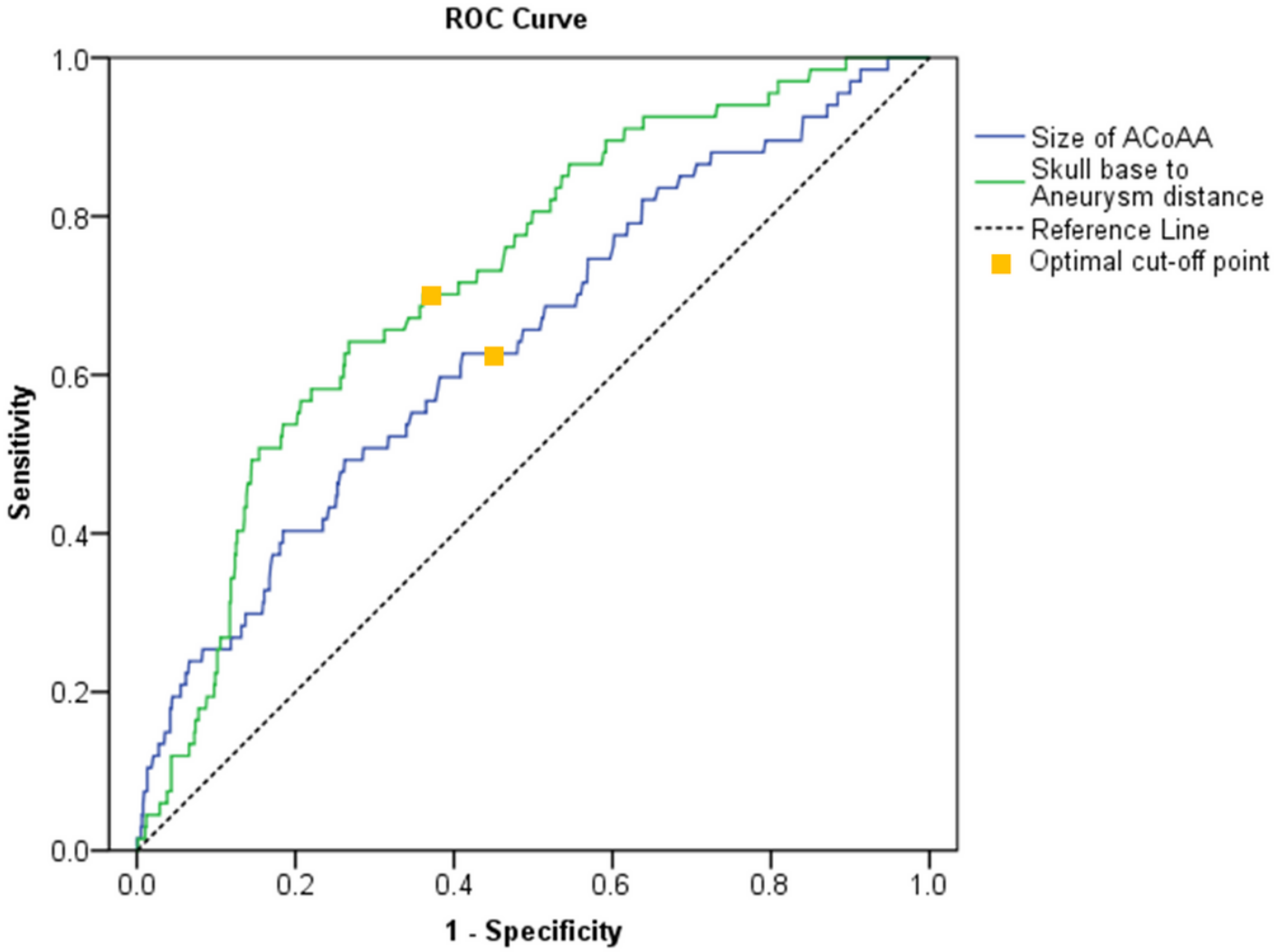

Figure 7

Receiver operating characteristics for the prediction of radiologic infarction. The optimal cut-off point for the size of anterior communicating artery aneurysm (ACoAA) was 5 mm with a sensitivity of 0.627 and specificity of 0.552. Additionally, the optimal cut-off point of the skull base to aneurysm was 10 mm with a sensitivity of 0.701 and specificity of 0.630.