Persistent Primitive Olfactory Artery as Novel Collateral Channel to the Anterior Cerebral Artery in Moyamoya Disease

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Background: There are a variety of collateral routes to compensate persistent cerebral ischemia in moyamoya disease. However, there is no report presenting the persistent primitive olfactory artery (POA) as a spontaneous collateral route to the anterior cerebral artery (ACA) in moyamoya disease. *Methods:* We precisely examined cerebral angiography in 84 patients with moyamoya disease to identify the collateral channel through the persistent POA. Its anatomy was evaluated on pre- and postoperative angiography. *Results:* Of 84 patients, four (4.8%) had spontaneous collateral channel through the persistent POA. All of these four hemispheres were categorized into Stage 5. In all four patients, the collateral blood flow arose from the ophthalmic artery and run to the persistent POA through the ethmoidal moyamoya. The persistent POA provided collateral blood flow from the ophthalmic artery to the ACA in all four patients. Superficial temporal artery to middle cerebral artery anastomosis and encephalo-duro-myo-arterio-pericranial synangiosis was performed in three of four patients. After surgery, the collateral channel through the persistent POA completely disappeared or markedly regressed, suggesting a significant improvement of cerebral hemodynamics in the territory of not only the MCA but also the ACA. *Conclusion:* The persistent POA can potentially provide collateral blood flow to the ACA in about 5% of patients with moyamoya disease, and should be recognized as a novel collateral channel in moyamoya disease. The persistent POA may be useful to evaluate therapeutic effects of surgical revascularization on the ACA territory.

Key Words: Persistent primitive olfactory artery—collateral channel—moyamoya disease—surgical revascularization

Introduction

Moyamoya disease is a unique cerebrovascular disorder characterized by progressive stenosis of the terminal portion of the internal carotid artery and its branches unilaterally or bilaterally. The lesion is associated with abnormally dilated perforating arteries (so called moyamoya vessels) which functions as collateral circulation to the ischemic brain.[1,2] In addition, moyamoya disease is well known to have a variety of spontaneous collateral routes, originating from middle meningeal artery (vault moyamoya), ethmoidal artery (ethmoidal moyamoya), posterior pericallosal artery, and posterior cerebral artery. Especially, middle meningeal artery, ethmoidal moyamoya and posterior pericallosal artery play an important role to provide collateral blood flow to the territory of anterior cerebral artery (ACA).[3]

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On the other hands, persistent primitive olfactory artery (POA) is known as one of rare remnant of the fetal intracranial arteries. The incidence of persistent POA is quite low: 0.14%-0.26%.[4,5] Previously, the persistent POA is rarely associated with cerebral aneurysm.[6-8] However, there is no report demonstrating that the persistent POA functions as spontaneous collateral circulation in moyamoya disease. In this report, we present four (4.8%) of 84 patients who was diagnoses as moyamoya disease with a spontaneous collateral channel to the ACA through the persistent POA. In addition, we evaluate the effect of surgical revascularization on this rare collateral, because it is very useful to assess whether our surgical procedure could improve cerebral hemodynamics in the territories of not only the MCA but also ACA or not.

Materials and Methods

We retrospectively analyzed the findings on cerebral angiography in totally 84 patients who were admitted to our hospital between March 2012 and March 2018. There were 27 pediatric (18 years or younger) and 57 adult patients. There were 36 males and 48 females. Clinical diagnosis included transient ischemic attack or headache in 41 patients, ischemic stroke in 19, hemorrhagic stroke in 11, and asymptomatic in 13.

Prior to surgical revascularization, cerebral angiography was performed using Seldinger's method via the femoral artery in all 84 patients. Bilateral internal and external carotid angiography and right or left vertebral angiography were performed. Of these, the patients with spontaneous collateral channel through the persistent POA were extracted. Its origin, course, and perfused area were precisely evaluated on cerebral angiography. Their Suzuki's angiographical stage was also recorded. Furthermore, cerebral blood flow was quantitatively measured before and after intravenous injection of acetazolamide, using single photon emission tomography, as reported previously. Cerebral blood flow (CBF) measurement was repeated 3-6 months after surgery, when the subjects underwent surgical revascularization.[9]

Superficial temporal artery to middle cerebral artery (STA-MCA) anastomosis and indirect bypass, encephalo-duro-myo-arterio-pericranial synangiosis (EDMAPS) were performed onto the symptomatic hemispheres or onto those with dense ischemia. Cerebral angiography was repeated 3−4 months after surgery, evaluating the effects of STA-MCA anastomosis and EDMAPS on the collateral channel through the persistent POA.

Results

Of 84 patients with moyamoya disease, four (4.8%) had spontaneous collateral channel through the persistent POA. There were one pediatric and three adult patients. There were three males and one female. The hemispheres with spontaneous collateral channel through the persistent POA were categorized into Stage 5. In all four patients, the collateral blood flow arose from the ophthalmic artery and run into the persistent POA through the ethmoidal moyamoya. Finally, the persistent POA connected the ophthalmic artery and the horizontal portion of the ACA and supplied collateral blood flow to the ACA (Table 1).

STA-MCA anastomosis and EDMAPS were successfully performed in three of four patients. Postoperative course was uneventful. None of them experienced no further cerebrovascular events for 30-52 months after surgery. The remaining one patient was judged as requiring no surgical revascularization and was medically followed up. He was also free from any cerebrovascular event for 63 months after diagnosis. All four patients are presented below:

Case 1

A 14-year-old boy developed generalized seizure and was diagnosed as moyamoya disease. Cerebral angiography revealed that Suzuki's disease stage was Stage 5 and

Table 1. *Summary of four cases with persistent primitive olfactory artery (POA) due to moyamoya disease*

Case	Age	Sex	Clinical presentation	Type	Hemisphere with the persistent POA			Follow-up (months)	Cerebrovascular events
					Disease stage	Treatment	Postop. change of POA		
1	15	Male	TIA	Bilateral	5	STA-MCA + EDMAPS	Disappeared	30	None
2	41	Female	Ishemic stroke	Bilateral	5	STA-MCA + EDMAPS	Disappeared	52	None
3	43	Male	Syncope	Bilateral	5	STA-MCA + EDMAPS	Disappeared	31	None
4	44	Male	Asymptomatic	Bilateral	5	None		63	None

Abbreviations: EDMAPS, encephalo-duro-myo-arterio-pericranial synangiosis; STA-MCA, superficial temporal artery to middle cerebral artery; TIA, transient ischemic attack.

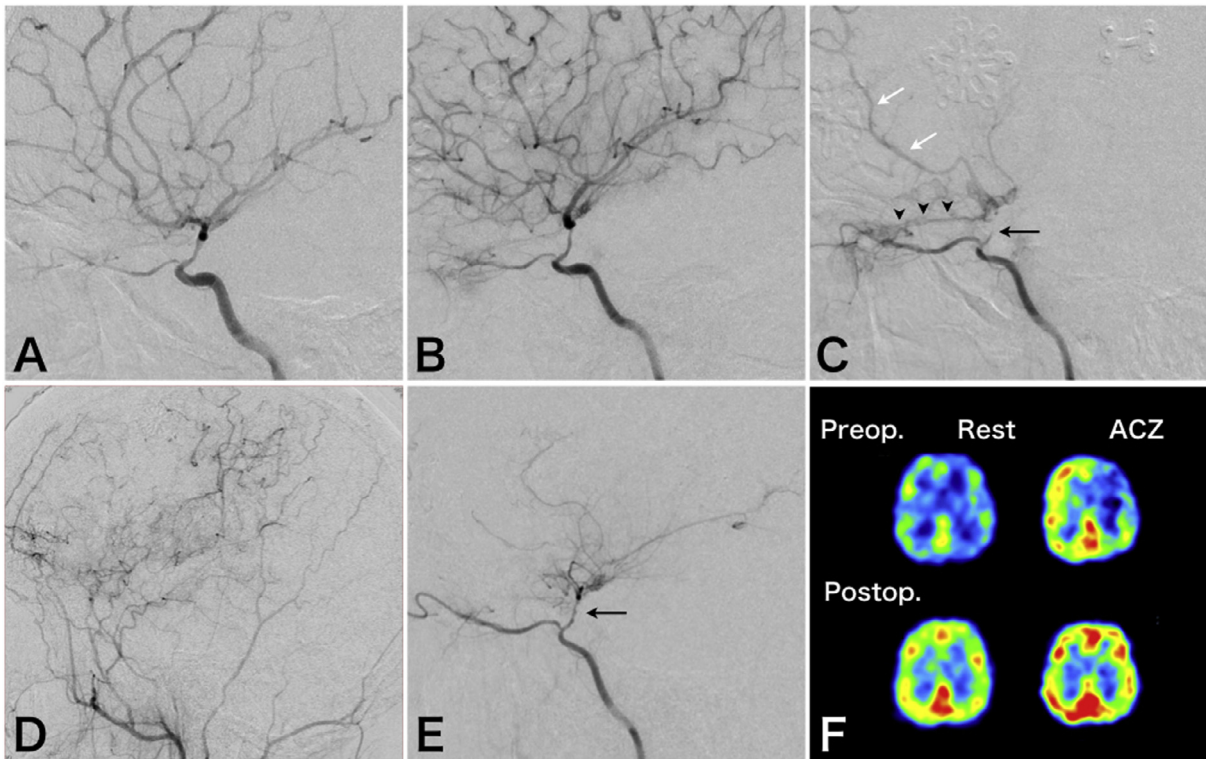

Figure 1. *Radiological findings in Case 1. (A) Lateral view of an initial left internal carotid angiography reveals mild stenosis of the supraclinoid internal carotid artery (Stage 2). (B) Lateral view of the second left internal carotid angiography 3 months later demonstrates no remarkable change. (C) Lateral view of the third left internal carotid angiography 18 months later reveals a complete occlusion of the supraclinoid internal carotid artery (black arrow, Stage 5). The persistent POA is opacified through ethmoidal moyamoya (arrowheads) and connects the ophthalmic artery and ACA (white arrows). (D) Lateral view of left external carotid angiography 4 months after STA-MCA anastomosis and EDMAPS shows well-developed surgical collaterals to the operated hemisphere. (E) Lateral view of left internal carotid angiography 4 months after surgery reveals a partial recanalization of the internal carotid artery (arrow) and complete disappearance of the persistent POA. (F) Pre- and postoperative CBF data before and after intravenous injection of acetazolamide (ACZ) demonstrate that cerebral hemodynamics markedly improves on the left hemisphere, including the ACA territory, after surgery. Abbreviations: ACA, anterior cerebral artery; EDMAPS, encephalo-duro-myo-arterio-pericranial synangiosis; POA, primitive olfactory artery; STA-MCA, superficial temporal artery to middle cerebral artery.*

Stage 2 on the right and left side, respectively (Fig 1A). He underwent STA-MCA anastomosis and EDMAPS on the right side. The postoperative course was uneventful. Follow-up angiography performed 3 months later showed no significant change in the stenotic lesion of the left internal carotid artery (Fig 1B). One and a half year later, however, he developed transient attacks of motor aphasia and right hemiparesis. Repeat cerebral angiography revealed that the disease stage markedly progressed from Stage 2 to Stage 5 on the left side. The left internal carotid artery was completely occluded at the supraclinoid portion. In addition, left internal carotid angiography demonstrated that the persistent POA became visible through ethmoidal moyamoya and connected the ophthalmic artery and the A1 segment of the ACA, which was not observed before disease progression. The persistent POA provided collateral blood flow from the ophthalmic artery to the ACA, but not to the MCA (Fig 1C). Then, he safely underwent STA-MCA anastomosis and EDMAPS on the left side. Follow-up cerebral angiography performed 4 months after the second surgery demonstrated that surgical collaterals through the external carotid artery developed very well and provided collateral blood flow to the territory of both MCA and ACA (Fig 1D). Left internal carotid artery was partially reopened, but provided blood flow only to the MCA territory. However, the persistent POA was no further observed and supplied no blood flow to the ACA (Fig 1E). CBF and its reactivity to acetazolamide (ACZ) markedly improved on the left side after final surgery, including the left ACA territory (Fig 2F). He is free from any cerebrovascular events and seizure for these 30 months after surgery.

Case 2

A 41-year-old woman delivered a baby through caesarean section. However, she developed mild left hemiparesis 5 days later and was diagnosed as moyamoya disease. On cerebral angiography, disease stage was judged as Stage 6 and Stage 5 on the right and left side, respectively. Left internal carotid angiography demonstrated that the left internal carotid artery was completely occluded just after branching the ophthalmic artery. In addition, the persistent POA was clearly visible through ethmoidal moyamoya and connected the ophthalmic artery and the A1 segment of the ACA, extensively providing blood

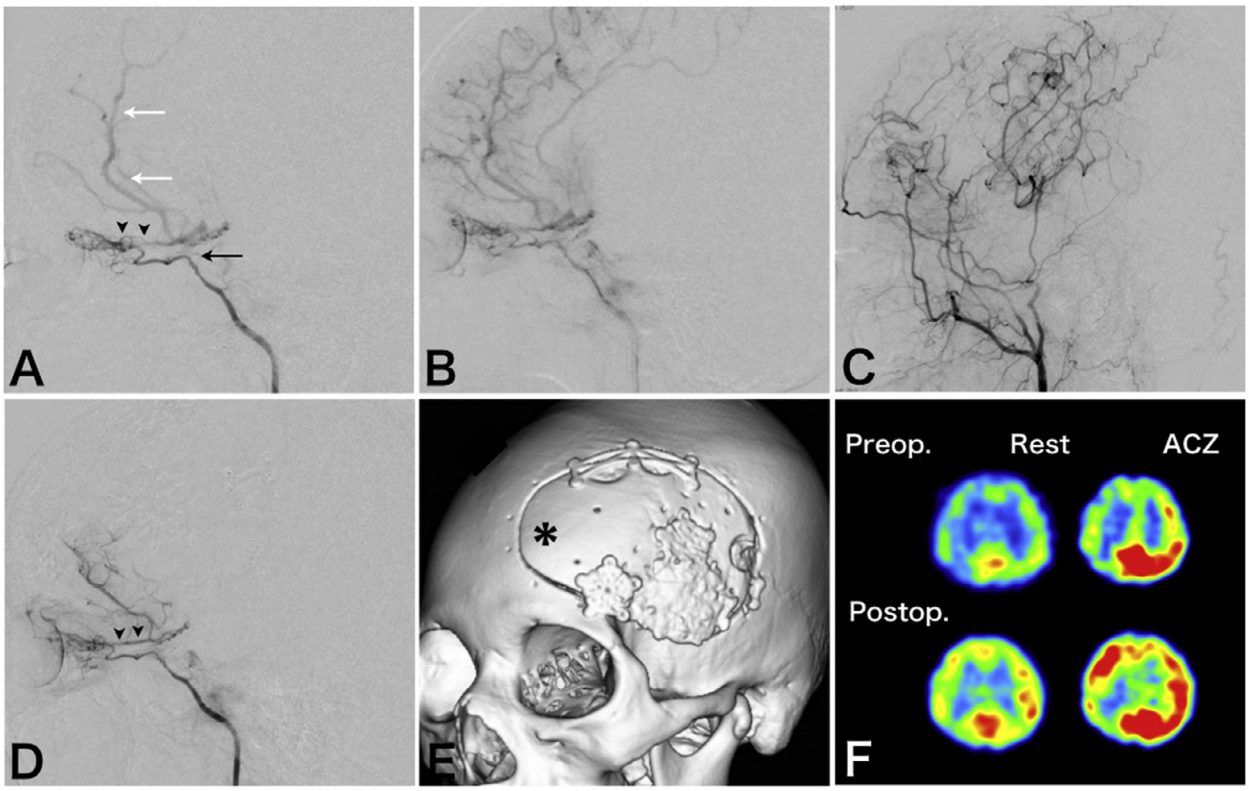

Figure 2. *Radiological findings in Case 2. Early (A) and late arterial phase (B) on lateral view of left internal carotid angiography reveal a complete occlusion of the internal carotid artery just after branching the ophthalmic artery (black arrow, Stage 5). The persistent POA is opacified through ethmoidal moyamoya (arrowheads) and connected the ophthalmic artery and ACA (white arrows). (C) Lateral view of left external carotid angiography 4 months after STA-MCA anastomosis and EDMAPS shows well-developed surgical collaterals to the operated hemisphere. (D) Lateral view of left internal carotid angiography 4 months after surgery reveals a marked diminishment of the persistent POA (arrowheads). Note a limited blood flow supply to the ACA through the persistent POA. (E) Postoperative 3D skull CT demonstrate the extent of craniotomy for surgery. Note a wide craniotomy extending to the medial frontal area for encephalo-pericranio-synangiosis (*). (F) Pre- and postoperative CBF data before and after intravenous injection of acetazolamide (ACZ) demonstrate that cerebral hemodynamics markedly improves on the left hemisphere, including the ACA territory, after surgery. Abbreviations: ACA, anterior cerebral artery; CT, computed tomography; EDMAPS, encephalo-duro-myo-arterio-pericranial synangiosis; POA, primitive olfactory artery; STA-MCA, superficial temporal artery to middle cerebral artery.*

flow from the ophthalmic artery to the ACA (Fig 2A and B). She underwent STA-MCA anastomosis and EDMAPS on both sides. Postoperative course was uneventful. Follow-up cerebral angiography performed 4 months after surgery demonstrated that surgical collaterals through the external carotid artery developed very well and provided collateral blood flow to the territory of both MCA and ACA (Fig 2C). The persistent POA was still observed, but the extent of blood flow to the ACA was markedly diminished (Fig 2D). Using 3D CT, the extent of craniotomy for STA-MCA anastomosis and EDMAPS on the left side is shown on Fig 2E. CBF and its reactivity to ACZ markedly improved on both sides after surgery, including the left ACA territory (Fig 2F). She is free from any cerebrovascular events for these 52 months after surgery.

Case 3

A 43-year-old man developed syncope attack and was diagnosed as moyamoya disease. On cerebral angiography, disease stage was judged as Stage 5 and Stage 4 on the right and left side, respectively. Right internal carotid angiography demonstrated that the right internal carotid artery was completely occluded just after branching the ophthalmic artery. Ethmoidal moyamoya provided collateral blood flow to the base of frontal lobe, and the persistent POA was also visible through ethmoidal moyamoya and connected the ophthalmic artery and the A1 segment of the ACA. The persistent POA provided blood flow from the ophthalmic artery to the ACA (Fig 3A). He underwent STA-MCA anastomosis and EDMAPS on both sides. Postoperative course was uneventful. Follow-up cerebral angiography performed 3 months after surgery demonstrated that surgical collaterals through the external carotid artery developed very well and widely provided collateral blood flow to the territory of both MCA and ACA (Fig 3B). Ethmoidal moyamoya markedly diminished and the persistent POA no further supplied blood flow to the ACA (Fig 3C). CBF and its reactivity to ACZ markedly improved on both sides after

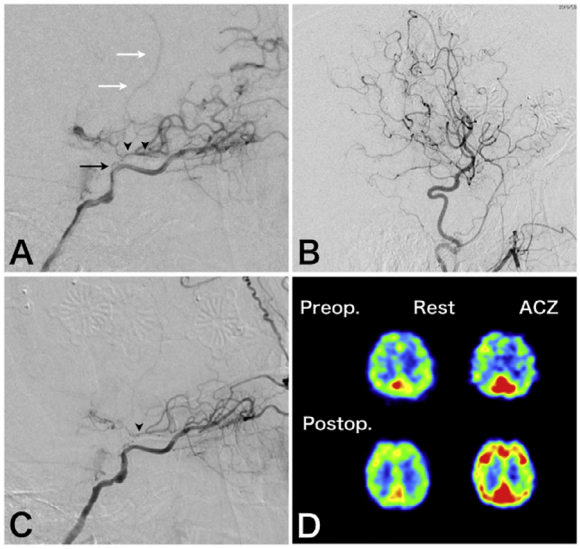

Figure 3. *Radiological findings in Case 3. (A) Lateral view of right internal carotid angiography reveals a complete occlusion of the internal carotid artery just after branching the ophthalmic artery (black arrow, Stage 5). The persistent POA is opacified through ethmoidal moyamoya (arrowheads) and connects the ophthalmic artery and ACA (white arrows). (B) Lateral view of right external carotid angiography 3 months after STA-MCA anastomosis and EDMAPS shows well-developed surgical collaterals to the operated hemisphere. (C) Lateral view of left internal carotid angiography 3 months after surgery reveals a marked diminishment of the persistent POA (arrowhead). Note almost no blood flow supply to the ACA through the persistent POA. (E) Pre- and postoperative CBF data before and after intravenous injection of acetazolamide (ACZ) demonstrate that cerebral hemodynamics markedly improves on the right hemisphere, including the ACA territory, after surgery. Abbreviations: ACA, anterior cerebral artery; EDMAPS, encephalo-duro-myo-arterio-pericranial synangiosis; POA, primitive olfactory artery; STA-MCA, superficial temporal artery to middle cerebral artery.*

surgery, including the right ACA territory (Fig 3D). He is free from any cerebrovascular events for these 31 months after surgery.

Case 4

A 44-year-old man had the episodes of transient hemiparesis after hyperventilation during his childhood, but was not referred to hospital. He developed pontine infarction because of hypertension and diabetes mellitus, and was incidentally diagnosed as moyamoya disease on magnetic resonance (MR) examinations. On cerebral angiography, disease stage was judged as Stage 5 and Stage 3 on the right and left side, respectively. Right internal carotid angiography demonstrated that the persistent POA was clearly visible through ethmoidal moyamoya and connected the ophthalmic artery and the A1 segment of the ACA. The persistent POA provided blood flow from the ophthalmic artery to the ACA (Fig 4A and B). Cerebral blood flow study demonstrated subnormal cerebral hemodynamics probably because of well-developed collateral circulations after long-standing ischemia (Fig 4C). He is conservatively followed up and is free from any cerebrovascular events for these 63 months after diagnosis.

Discussion

Collateral Channel via Persistent POA

As aforementioned, there are a variety of collateral routes to compensate persistent cerebral ischemia in moyamoya disease. Previously, Lin et al (2009) reported a case of persistent POA associated with moyamoya disease, but the persistent POA was just simple coincidence and did not function as a collateral route in this case.[10] To our knowledge, therefore, this is the first report showing that the persistent POA is an alternative, spontaneous collateral route to the ACA territory in moyamoya disease with advanced disease stage. In this case series, the collateral channel through the persistent POA was observed in about 5% of patients with moyamoya disease. Therefore,

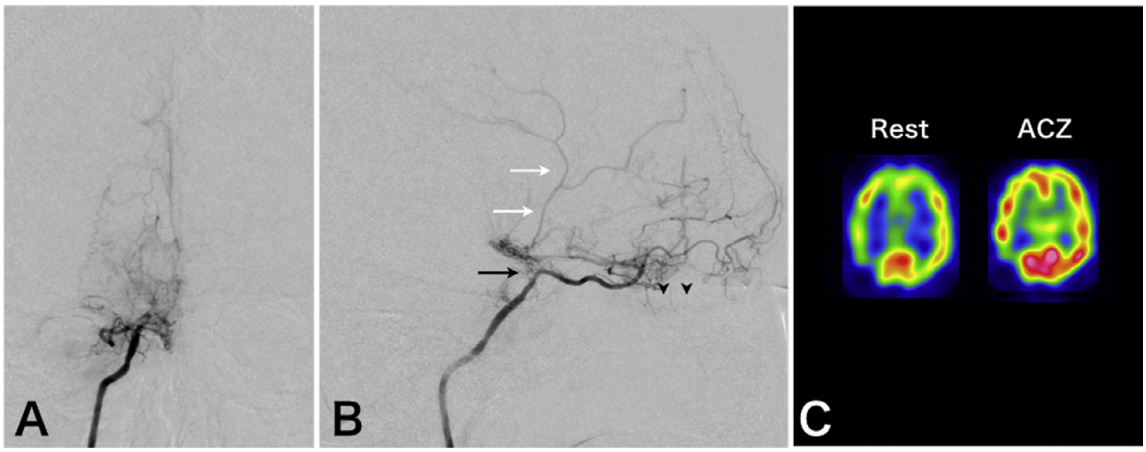

Figure 4. *Radiological findings in Case 4. Towne's (A) and lateral (B) views of right internal carotid angiography reveal a complete occlusion of the internal carotid artery just after branching the ophthalmic artery (black arrow, Stage 5). The persistent POA is opacified through ethmoidal moyamoya (arrowheads) and connects the ophthalmic artery and ACA (white arrows). (C) On admission, CBF data before and after intravenous injection of acetazolamide (ACZ) demonstrate that cerebral hemodynamics is kept within normal ranges on both sides. Abbreviations: ACA, anterior cerebral artery; POA, primitive olfactory artery.*

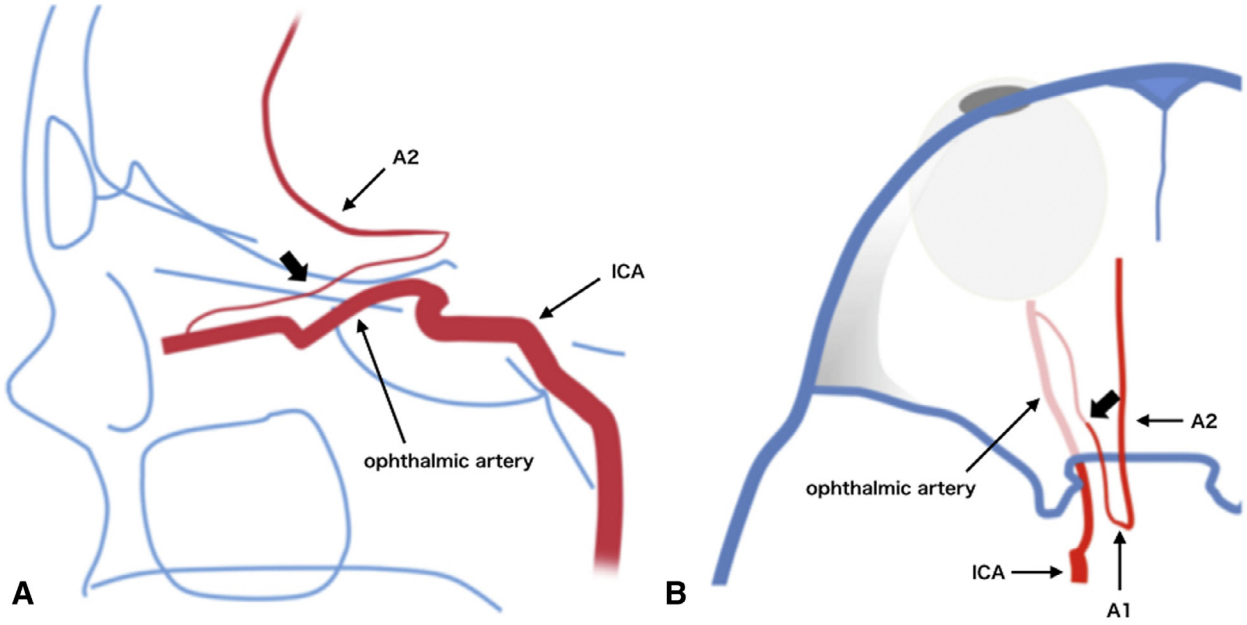

Figure 5. *Diagrams to demonstrate the anatomical structure of the persistent POA (arrows) in moyamoya disease with advanced disease stage. Abbreviation: POA, primitive olfactory artery.*

it should be recognized that its prevalence is not so low. In all four cases, the internal carotid artery was completely occluded just after branching the ophthalmic artery (so-called Stage 5 on Suzuki's angiographical grade) and the rich development of ethmoidal moyamoya was observed. The persistent POA was visible through ethmoidal moyamoya that penetrated the cribriform plate and run to the A1 segment, supplying collateral blood flow to the ACA territory. The persistent POA supplied no blood flow to the MCA territory because the bifurcation of internal carotid artery was occluded in all four patients.

According to the recent review, the POA is the rostral division of the primitive internal carotid artery. The POA branches off the medial olfactory artery, which physiologically becomes the ACA, and then the lateral olfactory artery, which becomes the Heubner's recurrent artery, anterior choroidal artery, and MCA later. Finally, the POA terminates in the nasal fossa. In case that the terminal portion of POA does not regress, it is called as the persistent POA.[4]. The persistent POA is anatomically classified into three types, although it still remains to be debated. Type-1 persistent POA originates from the internal carotid artery, runs along the olfactory tract, and make a hairpin bend to supply the territory of the distal ACA. Type-2 persistent POA originates from the horizontal portion of ACA and passes through the cribriform plate to supply the nasal cavity as the ethmoid artery. Type-3 persistent POA is the transitional type between types 1 and 2.[4,5,11] Therefore, the persistent POA observed in the present cases can be categorized into Type 2, but the direction of blood flow is completely opposite in them. Namely, the persistent POA provides the blood flow from the ophthalmic artery to the ACA through the ethmoidal moyamoya in all four patients (Fig 5).

Ethmoidal moyamoya is often observed at the roof of the orbit in about 30% of patients with moyamoya disease. The origin of ethmoidal moyamoya is known as anterior and posterior ethmoidal arteries mainly arising from the ophthalmic arteries. Under physiological condition, their small branches are considered to pass through the open pore-like structure in the cribriform plate and form a vascular connection between intra-orbital and intracranial vessels. In response to long-lasting cerebral ischemia, ethmoidal moyamoya may start to form a dilated vascular network between them and supply collateral blood flow to the base of frontal lobe, especially to the ACA.[3,12] Therefore, ethmoidal moyamoya would be essential to develop the collateral channel through the persistent POA. In fact, to a greater or lesser extent, the ethmoidal moyamoya was clearly observed in all four patients with the persistent POA. In this case series, 3D CT angiography was not performed. However, 3D CT angiography would be valuable for anatomical understanding of the persistent POA in moyamoya disease.

Angiographical finding in Case 1 was quite interesting. Thus, the persistent POA was not observed on the first and second cerebral angiography, but started to dilate and functioned as collateral channel when the occlusive lesion in the internal carotid artery progressed from Stage 2 to Stage 5. Therefore, the POA may exist even if it is not opacified on cerebral angiography and be ready to dilate in order to function as collateral channels when necessary.

Effect of STA-MCA and EDMAPS on Persistent POA

In this report, three of four patients safely underwent STA-MCA anastomosis and EDMAPS onto the hemispheres with the collaterals through the persistent POA. Follow-up cerebral angiography performed 3 to 4 months after surgery revealed complete disappearance (Case 1) or marked regression of the persistent POA (Case 2 and 3). The finding strongly suggests that STA-MCA anastomosis and EDMAPS significantly improve cerebral hemodynamics in the territory of not only the MCA but also the ACA, because the persistent POA supplied collateral blood flow to only the ACA.

Surgical procedures can be classified into three categories: direct bypass, indirect bypass, and combined bypass. Direct bypass such as STA-MCA anastomosis is useful to improve cerebral hemodynamics and to resolve ischemic attacks immediately after surgery. Surgical procedures for indirect bypass are simple and specific for moyamoya disease. Previously, the STA, dura mater, temporal muscle, and galeal tissue were used as the pediculate donor tissues. Combined procedures, which include direct and indirect, have the advantage of both.[2] However, the majority of previously reported procedures aimed to improve cerebral hemodynamics in the MCA territory. Therefore, we have developed a novel indirect bypass procedure, EDMAPS, in order to simultaneously improve cerebral hemodynamics in the territory of both MCA and ACA, because persistent cerebral ischemia in the ACA territory is known to induce the attacks of bilateral low-extremity motor weakness and intellectual impairment.[9] For this purpose, the medial frontal lobe was widely covered by the pediculate flap of frontal pericranium in addition to STA-MCA anastomosis and traditional indirect bypass with the STA, dura mater, and temporal muscle. A pericranial flap has been widely used to reconstruct the anterior cranial fossa. Likewise, the pericranial flap is large enough to cover the medial frontal lobe. After surgery, the annual risk of cerebrovascular events was very low: 0% in pediatric patients and 0.4% in adults over a mean follow-up period of 67 months. Single photon emission tomography study demonstrated that cerebral blood flow and its reactivity to acetazolamide markedly improved in both the MCA and ACA territories. The present study strongly supports it by showing that the collaterals to the ACA territory through the persistent POA disappeared or markedly diminished after STA-MCA anastomosis and EDMAPS.[9]

Conclusion

The persistent POA can potentially provide collateral blood flow to the ACA in a certain subgroup (approximately 5%) of patients with moyamoya disease, and should be recognized as the first-ever collateral channel in moyamoya disease. The collateral channel through the persistent POA may be useful to evaluate therapeutic effects of surgical revascularization on the ACA territory, because the persistent POA supplies blood flow to only the ACA territory (Table 1).

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