Ventral and Dorsal Persistent Primitive Ophthalmic Arteries

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BACKGROUND: Before the development of the adult ophthalmic artery (OA), the primitive maxillary artery (MA), the primitive dorsal OA, and the primitive ventral OA contribute to the vascularization of early ocular structures, whereas the primitive olfactory artery (OlfA) forms in the vicinity of the optic vesicle. These vessels are involved in several OA origin variants.

OBJECTIVE: To clarify the developmental history of the OA, emphasizing in particular the criteria used to define persistent primitive OAs.

METHODS: Eight rare variants relevant to the discussion of aberrant OA origins are presented.

RESULTS: Five abnormal anatomic configurations are described including (1) OAs branching from the cavernous internal carotid artery (ICA) involving a persistent primitive MA, (2) OAs originating from the distal supraclinoid ICA involving persistent primitive ventral or dorsal OAs, (3) an OA originating from the anterior cerebral artery (ACA) involving a persistent primitive OlfA, (4) a persistent primitive OlfA, and (5) infraoptic ACAs involving the persistent primitive MA, OlfA, and OA.

CONCLUSION: Discrepancies regarding the identification of persistent primitive OAs appear to result from a misinterpretation of the literature. Notably, an OA arising from the cavernous segment of the ICA derives from a primitive MA, whereas an OA arising from the ACA represents the partial persistence of a primitive OlfA; neither corresponds to a persistent primitive OA. Two new observations of this latter variant, which is exceptional, are presented.

KEY WORDS: Anomalous ophthalmic artery, Dorcas Padget, Dorsal ophthalmic artery, Cavernous ophthalmic artery, Infraoptic anterior cerebral artery, Olfactory artery, Ventral ophthalmic artery

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The ophthalmic artery (OA) normally originates from the anterior aspect of the supraclinoid segment of the internal carotid artery (ICA), as the latter emerges from the laterosellar compartment to enter the subarachnoid space. The OA then crosses the optic canal to supply the orbital content.

The embryology of aberrant OA origins has been discussed extensively, the focus being mainly placed on 2 precursors of the adult OA, the primitive dorsal and ventral OAs. The primitive olfactory artery (OlfA) and the primitive maxillary artery (MA) also supply the developing eye.[1] We present 8 observations involving these primitive vessels, which illustrate 5 types of variations pertinent to the discussion of aberrant OA origins. The relevant literature is reviewed, with emphasis placed on the discrepancy between our observations and previously published cases of OAs originating from the cavernous segment of the ICA or the anterior cerebral artery (ACA) and incorrectly labeled as persistent dorsal or ventral OAs.

ABBREVIATIONS: ACA, anterior cerebral artery; **DSA,** digital subtraction angiography; **ICA,** internal carotid artery; **ILT,** inferolateral trunk; **MA,** maxillary artery; **MMA,** middle meningeal artery; **MRA,** magnetic resonance angiography; **OA,** ophthalmic artery; **OlfA,** olfactory artery; **PComA,** posterior communicating artery; **SOF,** superior orbital fissure

METHODS

Seven observations relevant to the formation of the OA were selected from an institutional review board-approved clinical database, and 1 case with a related variant added from another institution. Additional permission was granted for publication. The cases involved 7 women and 1 man (average age, 47 years; range, 29-65 years). The OA variant was identified angiographically in 5 cases, by magnetic resonance angiography (MRA) in 2 cases and by direct surgical observation in 1. All the reported findings were incidental discoveries documented between January 9, 2001 and January 28, 2015.

RESULTS

Clinical Presentation

Case 1

A 53-year-old woman investigated for intracranial aneurysms by cerebral digital subtraction angiography (DSA). Incidentally, the left OA originated from the cavernous segment of the left ICA and entered the orbit through the superior orbital fissure (SOF), but showed an otherwise normal course (Figure 1).

Case 2

A 34-year-old man was evaluated for intracranial aneurysms by cerebral DSA. Two OAs were incidentally noted that originated from the supraclinoid and cavernous segments of the ICA and entered the orbit through the optic canal and the SOF, respectively. The cavernous stem had a small infundibulum at its origin, accounting for a suspected aneurysm by magnetic resonance imaging (MRI)/MRA (Figure 2).

Case 3

A 43-year-old woman investigated for intracranial aneurysms by cerebral DSA. Incidentally, the right OA arose from the terminal portion of the supraclinoid ICA. It was otherwise unremarkable, entering the orbit through the optic canal with an otherwise normal course (Figure 3).

Case 4

A 65-year-old woman was evaluated for subarachnoid hemorrhage by cerebral DSA. Incidentally, the right OA originated from the superior aspect of the supraclinoid ICA, a few millimeters distally to the posterior communicating artery (PComA), and entered the orbit through the optic canal with an otherwise normal course (Figure 4).

Case 5

A 58-year-old woman was treated for a PComA aneurysm. During surgery, the OA was incidentally noted to arise from the anterior aspect of the A1 segment of the left ACA. The origin of the OA and its entrance into the optic canal were documented during surgery (Figure 5).

Case 6

A 53-year-old woman investigated for a transient ischemic attack by MRA. Incidentally, a persistent primitive OlfA was seen stemming from a normal left A1 segment that also provided the main supply to the distal right ACA through the anterior communicating artery. The persistent OlfA followed a typical anterior course, curving back sharply to continue as the A2 segment of the left ACA. The right A1 segment was hypoplastic. The origin and course of the OAs were unremarkable (Figure 6).

Case 7

A 29-year-old woman was investigated for a cerebellar stroke. Incidentally, MRA disclosed an infraoptic A1 segment of the left ACA branching from the medial aspect of the left supraclinoid ICA. A true left A1 segment of normal caliber was also observed, whereas the right A1 segment was hypoplastic. The origin and course of the OAs could not be determined with certainty (Figure 7).

Case 8

A 43-year-old woman evaluated for vasculitis by cerebral DSA. Bilateral infraoptic A1 segments branching from the cavernous ICAs were incidentally noted. Both infraoptic A1 segments were dominant, but true hypoplastic A1 segments were also observed

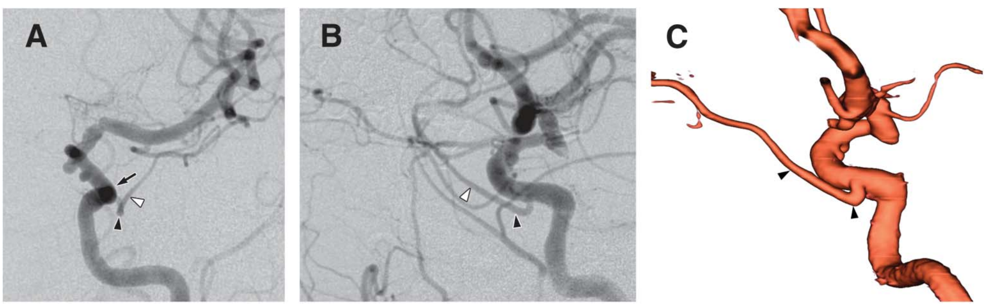

FIGURE 1. *A 53-year-old woman with left internal carotid artery (ICA) aneurysms.* **A**, *digital subtraction angiography (DSA), left ICA injection, right anterior oblique projection, showing the ophthalmic artery (***black arrowhead***) originating from the cavernous segment of the left ICA (***arrow***) and passing through the superior orbital fissure (***white arrowhead***).* **B**, *DSA, left ICA injection, lateral projection, showing the OA (***black arrowhead***) originating from the cavernous segment of the left ICA and passing through the SOF (***white arrowhead***).* **C**, *3D-DSA, left ICA injection, left lateral view, showing the OA (***black arrowheads***) originating from the cavernous segment of the left ICA. Color version available online only.*

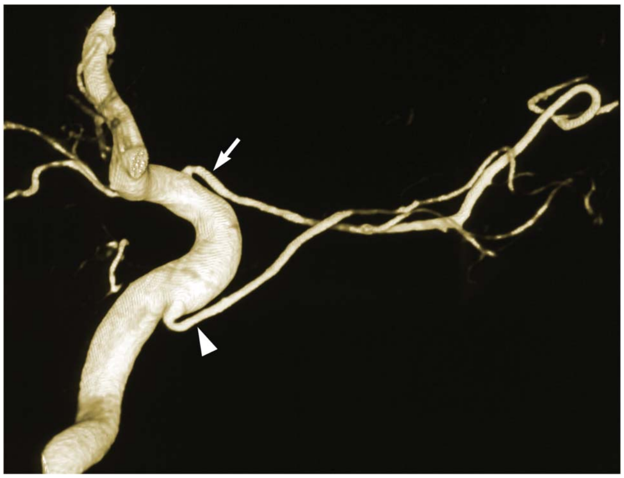

FIGURE 2. *A 34-year-old man evaluated for intracranial aneurysms. Three-dimensional digital subtraction angiography, right internal carotid artery (ICA) injection, right lateral view; the 2 ophthalmic arteries originate from the supraclinoid (**arrow**) and cavernous (**arrowhead**) segments of the ICA and respectively enter the orbit through the optic canal and the superior orbital fissure. Color version available online only.*

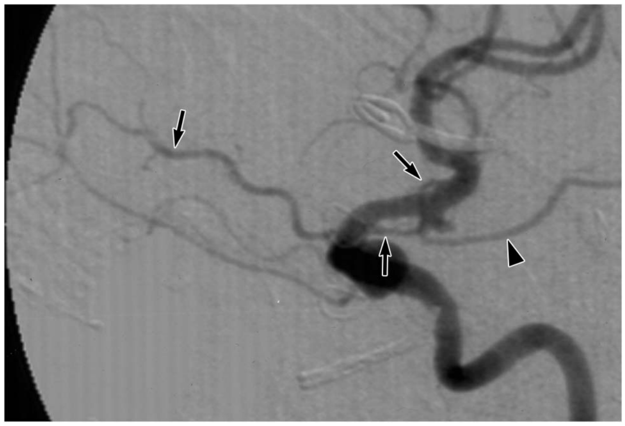

FIGURE 4. *A 65-year-old woman with multiple intracranial aneurysms. Digital subtraction angiography, right internal carotid artery (ICA) injection, lateral projection, showing the ophthalmic artery (**arrows**) originating from the superior aspect of the supraclinoid ICA, a few millimeters distally to the takeoff of the posterior communicating artery (PComA) (**arrowhead**). Note the presence of a small saccular aneurysm at the point of origin of the PComA.*

bilaterally. The origin and course of the OAs could not be determined with certainty (Figure 8).

DISCUSSION

Aberrant Ophthalmic Artery Origins

The Table summarizes the literature related to aberrant OA origins, with the exception of its most common form, ie, an OA arising from the middle meningeal artery (MMA).[2] In the latter instance, the MMA either provides some OA branches[3-13] or the entire vessel, without ICA contribution.[5,8-10,13-34] The MMA can also contribute to the collateral supply of the OA or ICA territories through secondary enlargement of small anastomoses established with the meningolacrimal or sphenoidal artery, for example, in cases of ICA occlusion.[2,3,7,10,31,35-38]

The OA can originate partially[20,33,39-44] or completely[8,9,20,24,29,45-48] from the cavernous segment of the ICA. In most cases, the origin lies a few millimeters proximal to the dural ring.[8,9,20,21] This common configuration (excluded from the Table) was noted in 7.5% of the orbits examined by Hayreh and Dass.[20] A second type of cavernous OA originates from the inferolateral trunk (ILT); this variant (case 1 and partially case 2) is often inappropriately labeled as a persistent dorsal OA.[24,45] Finally, 1 observation of an OA deriving from the meningohypophyseal trunk and coursing along the lateral aspect of the ICA to enter the orbit via the SOF has been reported.[43]

OAs arising from the distal supraclinoid ICA are exceedingly rare, with only 2 cases reported. Hamada et al[49] described a case of bilateral OAs branching from the ICA bifurcation, whereas N'da et al[50] observed an OA arising superiorly and laterally to its normal origin. Parlato et al[51] (excluded from the Table) reported an OA originating at the level of the anterior choroidal artery; although apparently confirmed during surgical exploration, angiography suggests, in fact, a duplicated middle cerebral artery overlapping an OA of normal origin. Cases 3 and 4 offer 2 new observations of distal supraclinoid OA origin, which represent true persistent primitive OAs.

Eight cases of OAs partially[42] or completely[29,46,52-55] originating from an ACA have been published (case 5). Additional

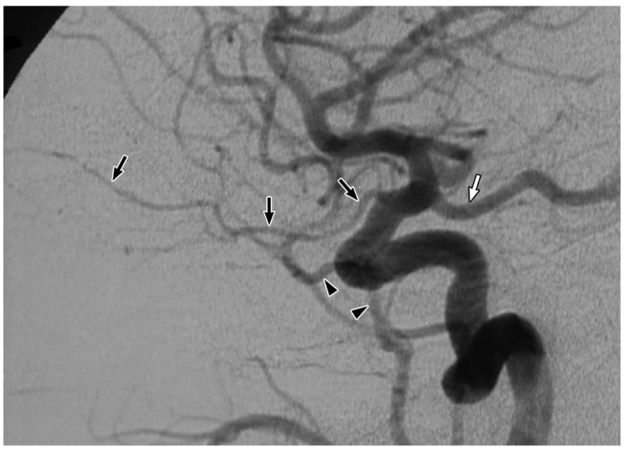

FIGURE 3. *A 43-year-old woman investigated for intracranial aneurysms. Digital subtraction angiography, right internal carotid artery (ICA) injection, lateral projection, documenting an ophthalmic artery (**black arrows**) originating from the terminal segment of the supraclinoid ICA, close to the level of origin of the posterior communicating artery (**white arrow**). The superficial temporal artery (**arrowheads**) overlaps the cavernous segment of the ICA in this view.*

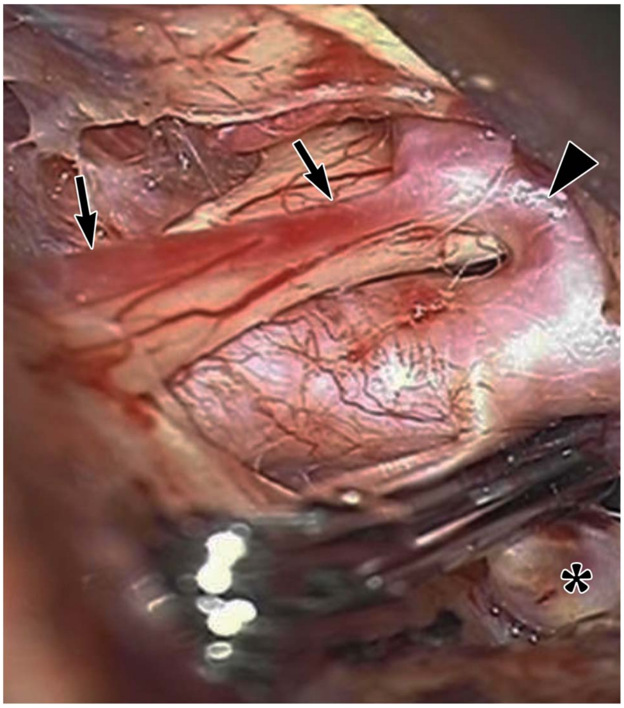

FIGURE 5. *A 58-year-old woman with a posterior communicating artery (PComA) aneurysm. Intraoperative view showing the ophthalmic artery (***arrows***) branching from the anterior aspect of the A1 segment of the left anterior cerebral artery (***black arrowhead***) and entering the optic canal (the point of entrance, observed during the surgery, is not visible on the image); the PComA aneurysm (***asterisk***) has been clipped. Color version available online only.*

reports include 3 cases of aberrant OAs arising from the basilar artery,[56-58] 2 cases from the PComA[16,60] (both associated with congenitally absent ICAs), and 2 equivocal cases from the middle cerebral artery.[61,62]

The frequency of OA origin variants is low. Dilenge and Ascherl[8] reported 7 cases (0.2%) of complete OA origin from the cavernous segment of the ICA and 3 cases (0.09%) of complete origin from the MMA in 3500 patients studied by angiography.

Development of the Optic and Orbital Arteries

Before the formation of the adult OA, the vascularization of the developing eye is provided by the primitive MA, dorsal OA, and ventral OA, whereas the stapedial artery supplies the remaining of the orbital content. The primitive OlfA also appears in the vicinity of the optic vesicle.[1] Figure 9 summarizes Padget's embryological observations[1] and incorporates subsequent clarifications made by Moffat.[63,64]

The ocular vascular supply in 4- to 5-mm embryos (Figure 9A) derives from the cranial division of the ICA that surrounds the caudal aspect of the optic vesicle and ends in the olfactory region. The primitive MA originates from the future cavernous ICA and provides a lateral branch that transiently supplies the optic vesicle and a medial branch that aims toward Rathke's pouch (the future hypophysis). The lateral branch, well visible in 4-mm embryos, starts regressing at the 5- to 6-mm stage. Its remnant will form the ILT and its branches, including the deep recurrent OA,[1,65] which enters the orbit through the medial aspect of the SOF.[9] The medial branch will become the inferior hypophyseal artery, a component of the meningohypophyseal trunk.[1]

A small vessel sprouting from the ICA at the level of origin of the PComA (or caudal division of the ICA) represents the future primitive dorsal OA.[1] In 5- to 6-mm embryos (Figure 9B), it courses over the dorsal margin of the optic vesicle to reach the site of the future lens.[1] Both the primitive OlfA and the primitive dorsal OA arise from the ICA distally to the origin of the primitive MA.

In rats, the primitive OlfA provides a branch that connects to the regressing primitive MA and contributes to a capillary network surrounding the optic stalk; from this branch derive the small chiasmatic rami of the adult ACA. Moffat[63,64] named this vessel the recurrent primitive OlfA and speculated that it may also be present in humans. This periocular capillary network is visible in 6- to 9-mm rat embryos,[66] 12-somite embryos in chickens,[67] and 4- to 9-mm human embryos.[1,68] Although Padget did not indicate a direct connection between the periocular plexus and the primitive OlfA, she mentioned that several small branches from the cranial division of the ICA supply the cranial part of the optic vesicle before the appearance of the primitive ventral OA. She also noted that the arteries surrounding the optic vesicle near the primitive OlfA had a plexiform configuration until embryos reach a length of 12 to 14 mm. Through these small branches (Figures 3A and 3B in Padget[1]), the primitive OlfA connects with the other primitive arteries supplying the periocular plexus. These connections are involved in the formation of variants such as an anomalous OA origin from the ACA or an infraoptic ACA.

In 7- to 12-mm embryos (Figure 9C), the primitive ventral OA emerges from the ICA at the level of the anterior choroidal artery and courses to the cranioventral portion of the optic cup, supplementing the primitive dorsal OA supply. The primitive OlfA also provides a new medial twig that will become the ACA, while the optic (lateral) branch of the primitive MA regresses.[1]

In 12- to 14-mm embryos, the primitive dorsal OA provides the temporociliary and hyaloid arteries, whereas the primitive ventral OA provides the future common nasal ciliary artery. By the time the embryo reaches 14 mm, the midline fusion of the ACAs arising from the primitive OlfA forms the anterior communicating artery. The stapedial artery, a branch of the hyoid artery, is also visible; the stapedial artery will annex the distal branches of the ventral pharyngeal artery, which will become the maxillomandibular division of the external carotid artery.[1]

It is only near the end of the 16- to 18-mm stage (Figure 9D) that the adult OA origin can be detected, proximally to the regressing primitive ventral and dorsal OAs and distally to the remnants of the primitive MA. The stem of the adult OA annexes the branches of the primitive ventral and dorsal OAs through an anastomotic process that is not fully elucidated. The stalks of the 2 primitive OAs soon involute while the OlfA begins to regress. The dorsal

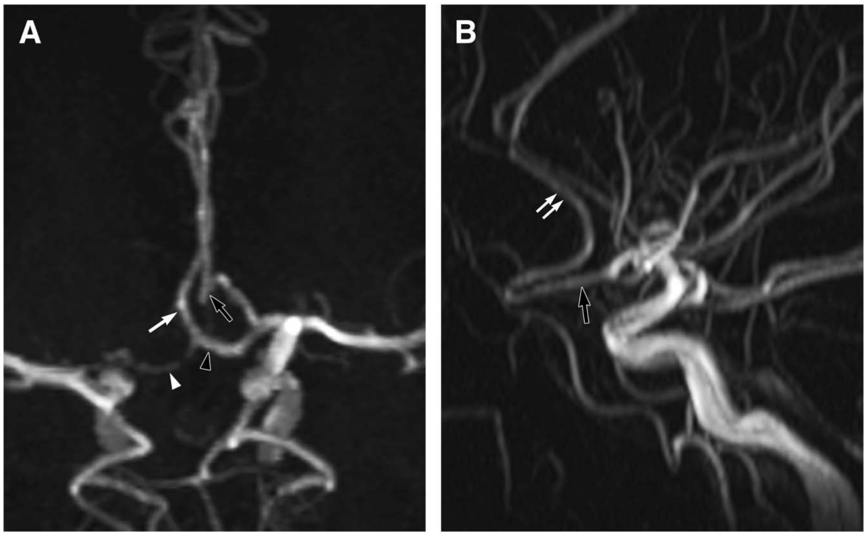

FIGURE 6. *A 53-year-old woman evaluated for an episode of a transient ischemic attack.* **A**, *magnetic resonance angiography (MRA), maximum intensity projection, anteroposterior view; a persistent primitive olfactory artery (OlfA) (***black arrow***) originates from a normal left A1 segment that also provides the main supply to the distal right anterior cerebral artery (ACA) (***white arrow***) through the anterior communicating artery (***black arrowhead***). The right A1 segment is hypoplastic (***white arrowhead***).* **B**, *MRA, maximum intensity projection, lateral view; the persistent OlfA (***black arrow***) follows a typical anterior trajectory along the orbital roof before sharply reversing its course to continue as the A2 segment of the left ACA (***white double arrow***). Images courtesy of Francesco Causin, MD, Division of Neuroradiology, Padua University Hospital.*

(orbital branch) and ventral (maxillary and mandibular branches) divisions of the stapedial artery are clearly discernible; the dorsal division supplies the orbital component of the future OA through the primitive orbital artery.[1]

In 20- to 24-mm embryos (Figure 9E), the medial branch of the primitive MA has developed into the inferior hypophyseal artery, and the primitive OlfA has regressed into a small ACA branch. The MA (embryologically distinct from the primitive MA) connects with the ventral division of the stapedial artery; the latter then separates completely from the hyoid artery to become a branch of the MA, thus forming the adult external carotid artery. The primitive orbital artery, stemming from the stapedial artery, establishes an intraorbital anastomosis with the OA, thus forming a complete arterial loop around the optic nerve.[1]

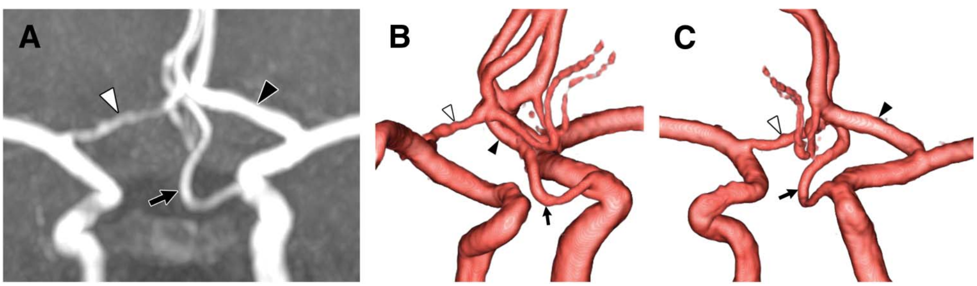

FIGURE 7. *A 29-year-old woman investigated for cerebellar stroke.* **A**, *magnetic resonance angiography (MRA), maximum intensity projection, anterior view; an infraoptic A1 segment (***arrow***) originates from the medial aspect of the left supraclinoid internal carotid artery. The true left A1 segment (***black arrowhead***) has a normal caliber, whereas the right A1 segment (***white arrowhead***) is hypoplastic. The origin and course of the ophthalmic arteries could not be determined with certainty.* **B**, *MRA, 3D reconstruction, right anterior-oblique view, further clarifies the course of the infraoptic A1 segment (***arrow***), true left A1 segment (***black arrowhead***), and hypoplastic right A1 segment (***white arrowhead***).* **C**, *MRA, 3D reconstruction, left anterior-oblique view, showing the infraoptic A1 segment (***arrow***), true left A1 segment (***black arrowhead***), and hypoplastic right A1 segment (***white arrowhead***). Color version available online only.*

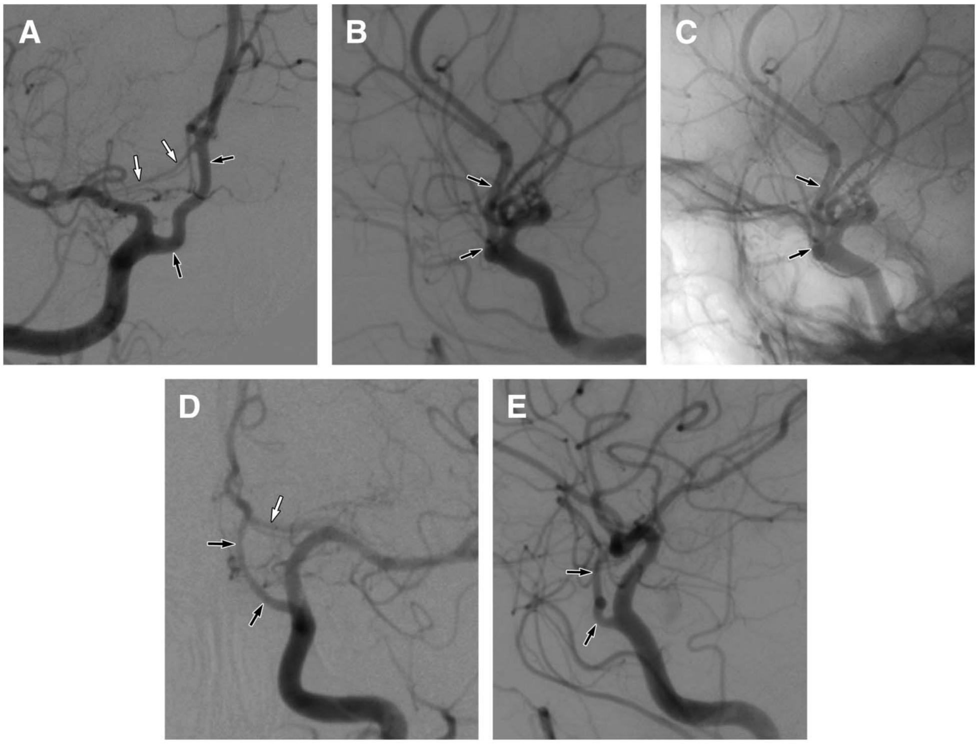

FIGURE 8. *A 43-year-old woman with bilateral infraoptic A1 segments.* **A**, *digital subtraction angiography (DSA), right internal carotid artery (ICA) injection, posteroanterior projection, showing a right infraoptic A1 segment (***black arrows***) arising from the cavernous segments of the ICA, and a hypoplastic true A1 segment (***white arrows***).* **B**, *DSA, right ICA injection, lateral projection, confirming the cavernous origin of the infraoptic A1 segment (***black arrows***).* **C**, *Native image, right ICA injection, lateral projection, documenting surrounding osseous landmarks and the cavernous origin of the infraoptic A1 segment (***black arrows***).* **D**, *DSA, left ICA injection, posteroanterior projection, demonstrating a left infraoptic A1 segment (***black arrows***) of cavernous origin as well as a hypoplastic true A1 segment (***white arrow***).* **E**, *DSA, left ICA injection, lateral projection, showing the cavernous origin of the infraoptic A1 (***black arrows***).*

In the 40-mm embryo (Figure 9F), the OA has taken over the primitive orbital artery and its supply to nonneural orbital structures. The supraorbital division of the stapedial artery distal to its anastomosis with the MA is now the adult MMA.[1] The cranioventral segment of the arterial ring surrounding the optic nerve regresses, leaving the typical optic loop of the OA.[1] With the exception of the hyaloid artery, which involutes during the fetal period, the OA has reached its adult configuration.

Persistent Lateral Branch of the Primitive Maxillary Artery (or Cavernous Origin of the OA)

Padget[1] showed that the origin of the adult OA was proximal to that of the primitive dorsal and ventral OAs. She suggested that the proximal migration of the OA origin was a hemodynamic solution to the growth of the cerebral hemispheres, which moves the origin of the 2 primitive OAs away from the developing eye. The adult origin provides a more direct, hence more efficient, supply to the eye. Padget never mentioned a cavernous origin of the primitive dorsal OA, as is often erroneously quoted in the literature. Descriptions of so-called persistent dorsal OAs originating from the cavernous segment of the ICA (via the ILT)[45,69-73] derive from a misinterpretation of Padget's work, ie, the incorrect assumption that the ILT and its deep recurrent OA are adult remnants of the primitive dorsal OA.[69-71] The ILT and the deep recurrent OA artery are, in fact, developmentally linked to the lateral branch of the primitive MA. An abnormal OA originating from the cavernous ICA and entering the orbit through the SOF rather than the optic canal can, therefore, not represent a persistent dorsal OA.

The canine maxillocarotid anastomotic artery (*arteria anastomotica*), which connects the cavernous ICA to the base of the external OA, a branch of the orbital artery in dogs[65,74] (Figure 10), has been used to support the concept of a persistent primitive dorsal OA of cavernous origin in humans.[75-78] However, De La Torre and Netsky[65] have convincingly shown

TABLE. Published Reports of Partial or Complete Aberrant Origin of the Ophthalmic Artery[a]

Series	Side	OA Branches	No. of Variants	Identification
Cavernous segment origin				
Hayreh and Dass, 1962	—	Partial	2	Dissection
	—	Complete	1	Dissection
Dilenge and Ascherl, 1965	—	—	1	Angiography
Renn and Rhoton, 1975	—	—	4	Dissection
Picard et al, 1975	—	—	7	Angiography
Harris and Rhoton, 1976	—	—	4	Dissection
Dilenge and Ascherl, 1980	—	Complete	7	Angiography
Fiore et al, 1981	R	Complete	1	Angiography
Gibo et al, 1981	—	—	1	Dissection
Nakagawa et al, 1982	R	Partial	1	Angiography
Lasjaunias, 1983	R	Complete	1	Angiography
	—	Complete	1	Angiography
Tran-Dinh, 1987	—	—	5	Dissection
Willinsky et al, 1987	—	Partial	1	Angiography
Ogawa et al, 1990	R	Partial	1	Angiography
Aldrich, 1991	L	Complete	1	Angiography
Pretterklieber et al, 1994	L	Complete	1	Dissection
Kam et al, 2003	R	Partial	1	Angiography
Gailloud et al, 2009	R	Complete	1	Angiography
	L	Partial	1	Angiography
Agarwal et al, 2012	R	Partial	1	Angiography
Uchino et al, 2013[13]	R	Partial	1	Angiography
Uchino et al, 2013[43]	—	—	7	MRA
Namba and Nemoto, 2013	R	Partial	1	Angiography
Indo et al, 2013	—	—	3	Angiography
			Total = 56	
Supraclinoid and internal carotid artery bifurcation origin				
Hamada et al, 1991	R	Complete	1	Angiography/surgery
	L	Complete	1	Angiography/surgery
N'da et al, 2014	L	Complete	1	Angiography/surgery
			Total = 3	
Anterior cerebral artery origin				
Picard et al, 1975	L	—	1	Angiography
Hassler et al, 1989	R	—	1	Surgery
Islak et al, 1994	R	Complete	1	Angiography
Honma et al, 1997	R	—	1	Surgery
Li et al, 2011	L	Complete	1	Angiography/surgery
Agarwal et al, 2012	R	Partial	1	Angiography
Indo et al, 2013	—	—	2	Angiography
			Total = 8	
Basilar artery origin				
Schumacher et al, 1994	R	Complete	1	Angiography
Sade et al, 2004	L	Complete	1	Angiography
Rivera et al, 2014	L	Complete	1	Angiography
			Total = 3	
Posterior communicating artery origin				
Fisher, 1913	R	Complete	1	Dissection
Naeini et al, 2005	R	Complete	1	Angiography
			Total = 2	
Middle cerebral artery origin				
Flemming, 1895	L	—	1	Dissection
Lowrey, 1918	R	Complete	1	Dissection
			Total = 2	

[a]OA, ophthalmic artery; —, not specified; R, right; L, left; MRA, magnetic resonance angiography. The most common variant, an OA arising from the middle meningeal artery, was not included in the table.

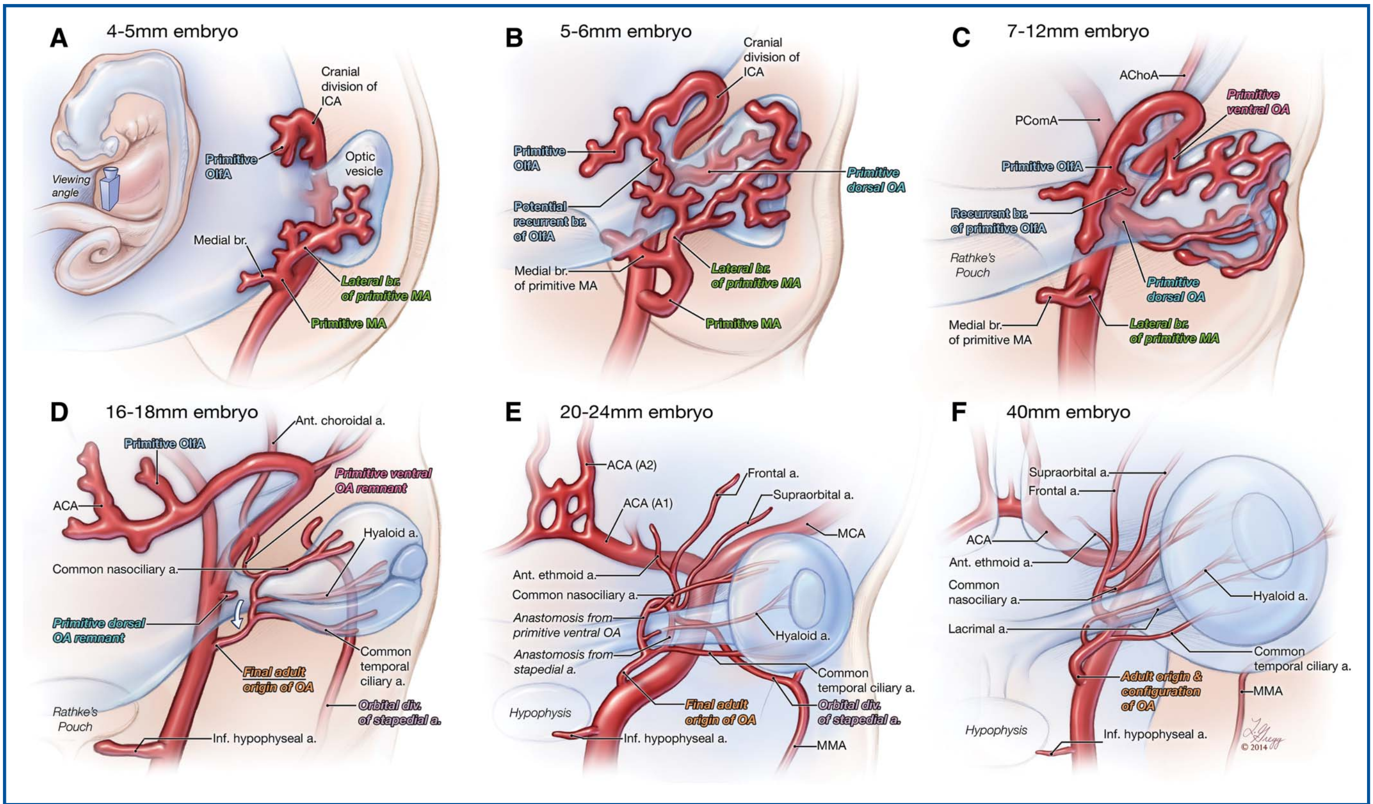

FIGURE 9. *Summary of the development of the ophthalmic artery (OA) (ventral view) based on Padget's embryological observations*[1] *and Moffat's subsequent clarifications.*[63,64] **A**, *4- to 5-mm stage: the primitive maxillary artery (MA) is the first artery to arise from the future cavernous segment of the internal carotid artery (ICA). It provides a lateral branch to the optic vesicle and a medial branch to the base of Rathke's pouch.*[1] *The cranial division of the ICA terminates in the olfactory region.*[1] **B**, *5- to 6-mm stage: the primitive olfactory artery (OlfA) and the primitive dorsal OA arise from the ICA distal to the origin of the primitive MA. The primitive dorsal OA originates at the level of origin of the posterior communicating artery and courses over the optic vesicle to the site of the future lens.*[1] *Recurrent branches from the primitive OlfA form connections with the capillary network surrounding the developing eye.*[64] **C**, *7- to 12-mm stage: the primitive dorsal OA supplies the caudal and dorsal portions of the optic cup, whereas the primitive ventral OA emerges from the ICA (at the level of the developing anterior choroidal artery) to supply its cranial and ventral portions. The primitive OlfA branches off a small twig that will later become the adult anterior cerebral artery (ACA). The optic branch of the primitive MA has regressed; its medial branch reaches the base of Rathke's pouch.*[1] **D**, *16- to 18-mm stage: the adult OA origin can now be seen; its origin lies proximal to both the primitive ventral and dorsal OAs and distal to the remnants of the primitive MA, essentially represented at this stage by the inferior hypophyseal artery. The stem of the adult OA annexes the temporociliary artery and the hyaloid branch from the primitive dorsal OA and the common nasal ciliary artery from the primitive ventral OA. The ACA has become the dominant continuation of the ICA, the primitive OlfA now appearing as an ACA side branch. The AComA is visible. The orbital component of the future adult OA is supplied by the dorsal division of the stapedial artery.*[1] **E**, *20- to 24-mm stage: the medial branch of the primitive MA has become the inferior hypophyseal artery. The primitive OlfA regresses further, whereas the primitive orbital artery (continuation of the stapedial artery) establishes an intraorbital anastomosis with the OA. This connection creates an arterial loop around the optic nerve, formed in part by the previous acquisitions of the primitive dorsal OA and primitive ventral OA.*[1] **F**, *40-mm embryo: the OA annexes the primitive orbital artery from the stapedial artery. The supraorbital division of the stapedial artery distal to the anastomosis with the MA is now the adult middle meningeal artery. With the exception of the hyaloid artery, the branches of the OA are in their adult configuration after the cranioventral segment of the arterial ring disconnects to form the turn of the OA around the optic nerve.*[1] *Color version available online only.*

that this artery is, in fact, related to the primitive MA, in agreement with Padget,[1] who located the trunk of the primitive MA at the expected location of the ILT, just lateral to the inferior hypophyseal artery (the adult derivative of the medial branch of the primitive MA). The hypothesis that the lateral branch of the primitive MA becomes the deep recurrent OA is further supported by 6 observations of persistent primitive MA reported by De La Torre and Netsky,[65] described as lateral branches of the cavernous ICA supplying the adjacent dura mater, orbital structures, and semilunar ganglion. An OA originating from the cavernous ICA and entering the orbit via the medial aspect of the SOF is embryologically and anatomically consistent with a dominant anastomosis between the ILT and the OA via the deep recurrent OA, therefore corresponding to the persistence of the lateral branch of the primitive MA. The SOF is an important anatomic landmark in distinguishing true

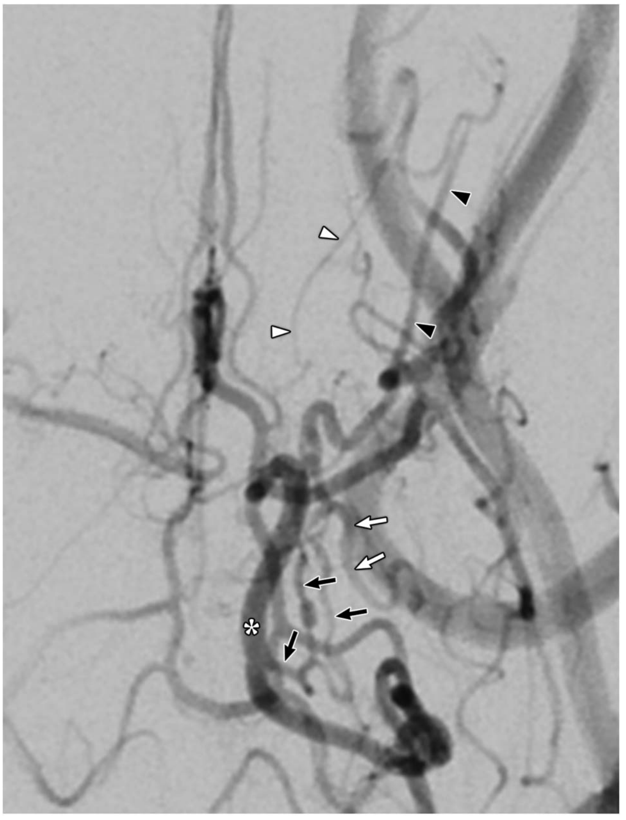

FIGURE 10. *Cerebral digital subtraction angiography (DSA) of the arterial phase in a dog. DSA, common carotid artery injection, ventral projection; the maxillocarotid anastomotic artery (**black arrows**) connects the cavernous ICA (**asterisk**) to the base of the external ophthalmic artery (OA) (**black arrowheads**).[65,74] The internal OA (**white arrowheads**) branches from the anterior cerebral artery into the orbit to anastomose with the external OA. An anastomotic branch from the middle meningeal artery is also visible (**white arrows**). In this case, the maxillocarotid anastomotic artery is duplicated as seen in Figure 5F of Jewell's 1952 publication.[74] De La Torre and Netsky[65] interpreted the maxillocarotid anastomotic artery as a derivation of the primitive maxillary artery proximally and a derivative of the vidian and stapedial systems distally.*

persistent primitive OAs, which enter the orbit via the optic canal, from OA variants involving the primitive MA and coursing through the SOF.

Persistent Ventral and Dorsal Ophthalmic Arteries

According to Padget's observations,[1] a persistent primitive ventral or dorsal OA must stem from the ICA between the PComA and the ACA. Persistent ventral or dorsal primitive OAs cannot be distinguished with certainty given the close proximity of their sites of origin and their similar courses. Published reports of so-called persistent primitive ventral OAs, after the initial observation by Picard et al[29] in 1975, generally describe a vessel taking off from the ACA,[52,53,55] which is in fact related to the persistence of a primitive OlfA,[1,64,66] a variant discussed in the next section. Our 2 observations (cases 3 and 4) appear to represent the third and fourth cases of persistent primitive OAs, after the reports by Hamada et al[49] and N'da et al.[50] Both of our cases document an OA branching from the supraclinoid ICA at or distal to the level of the PComA and entering the orbit via the optic canal.

Persistence of Primitive OlfA Branches

The complete persistence of a primitive OlfA (case 6) has been described as an aberrant ACA, with a course following the olfactory tract anteriorly before making an abrupt turn to continue as a normal ACA.[63,79,80] Through its close relationship with the periocular capillary plexus, the primitive OlfA can also be involved in OA origin variants.[64] Bosma[81] recognized the role of the primitive OlfA in the formation of an infraoptic ACA (cases 7 and 8), when its connection with the primitive MA established through the early periocular plexus persists at the adult stage. In this case, the infraoptic ACA originates from the cavernous ICA and resumes a normal ACA course proximal to the anterior communicating artery (case 7) (Figure 11K). Besides this well-described configuration, our findings suggest that an infraoptic ACA can also develop through the persistence of an anastomosis between the primitive OlfA and a primitive dorsal or ventral OA, the infraoptic ACA branching in this instance from the supraclinoid segment of the ICA (case 8) (Figure 11L). Hence, 2 alternate embryonic pathways may explain how infraoptic ACAs can originate from the ICA, either proximally or distally to the expected site of origin of the OA.

Similarly, an OA originating from an ACA (case 4) can result from the persistence of the primitive connection between the periocular capillary plexus and the recurrent branch of the OlfA, allowing the latter to annex the distal branches of the OA, in agreement with the observations made by Padget[1] and Moffat.[64] Figure 11 offers a graphic summary of the primitive arteries involved in the supply of the developing eye and associated anatomic variants.

CONCLUSION

Persistent ventral and dorsal OAs have been misrepresented in the literature as abnormal OAs respectively originating from the ACA and the cavernous ICA. The available information regarding the embryology of the ocular blood supply firmly establishes that OAs originating from the ACA are linked to the partial persistence of a primitive OlfA, whereas OAs arising from the cavernous ICA derive from the lateral branch of the primitive MA.

In the embryo, the primitive ventral and dorsal OAs originate from the ICA at the levels of the anterior choroidal artery and the PComA, respectively, and must therefore be sought for distally to the origin of the adult OA. Because of the proximity of their origins and their similar courses, persistent primitive

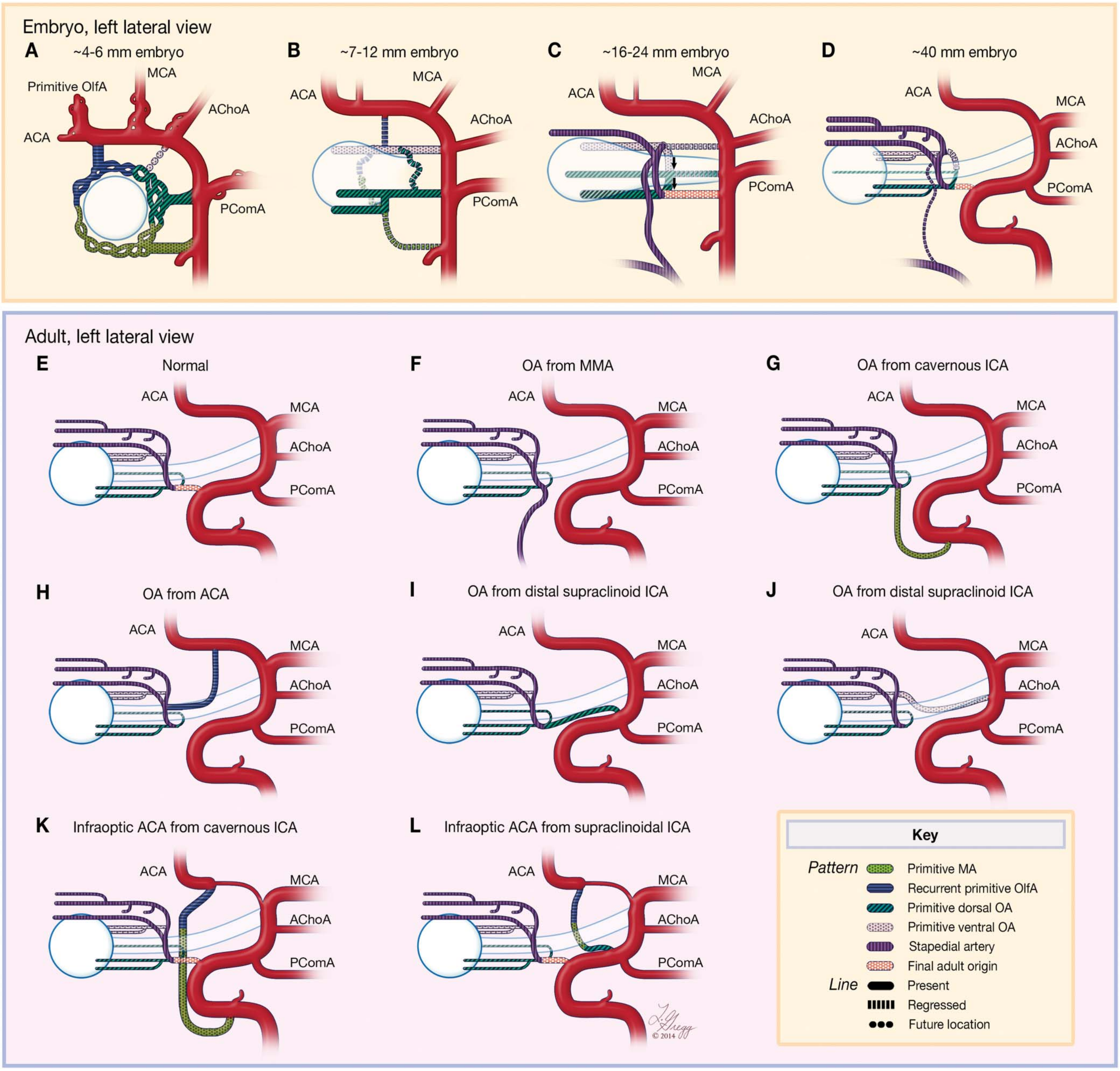

FIGURE 11. *Diagrammatic summary of the involvement of primitive arteries (primitive maxillary artery, recurrent primitive OlfA, primitive dorsal OA, primitive ventral OA, and stapedial artery) in the development of the normal adult OA from a lateral view, left side.* A-D *depict normal development, whereas* E-L *depict adult anomalies that each primitive artery may contribute to through variations in development. ACA, anterior cerebral artery; AChoA, anterior choroidal artery; ICA, internal carotid artery; MCA, middle cerebral artery; MMA, middle meningeal artery; OA, ophthalmic artery; OlfA, olfactory artery; PComA, posterior communicating artery. Color version available online only.*

ventral and dorsal OAs cannot be distinguished at the adult stage. The passage of persistent primitive OAs through the optic canal rather than the SOF differentiates them from OAs of cavernous origin.

Finally, our report also shows that infraoptic ACAs may result from a persistent primitive OlfA retaining a connection either to one of the primitive OAs or the primitive MA. In the latter instance, the infraoptic ACA originates from the supraclinoid segment of the ICA rather than from its cavernous segment.

Disclosure

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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COMMENTS

Ophthalmic artery (OA) anatomy is relevant to surgical and endovascular procedures performed on or in close proximity to the OA. The authors have presented a comprehensive review of the embryology of OA development and a thorough analysis of the literature describing aberrant OAs clarifying common misperceptions.

The authors describe 5 anatomic configurations, which they depict with 8 examples of these uncommon anomalies. Although it remains unclear how these anatomic variants might affect treatment, this paper and its illustrations will be a useful guide for those seeking to better understand OA development.

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This is a very well-presented series of patients with rare and interesting variants of an important part of the anterior circulation. It helps greatly to understand the embryology of this vascular region and to assess potential dangers arising from these findings. I very much enjoyed reading this paper, which will undoubtedly broaden everybody's comprehension of the relevant functional anatomy.

Wilhelm Kuker
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