The Microsurgical Anatomy of the Orbitofrontal Arteries

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■ OBJECTIVE: **The orbitofrontal (or frontobasal) arteries (OFAs) are the medial (MOFA) and lateral (LOFA) orbitofrontal artery, branches of the anterior and middle cerebral artery, respectively. They supply the orbitofrontal cortex. The purpose of this microscopic cadaveric study was the detailed and precise anatomic identification of the OFAs along their course.**

■ METHODS: **Twenty formalin-fixed, colored latex-injected cadaveric heads were studied with the aid of an operating microscope and microsurgical instrumentation. The anatomy of the OFAs was examined after removing the cerebrum from the cranial vault. Anatomic features of the MOFA and LOFA were investigated and assessed in relation to demographic and anthropometric variables.**

■ RESULTS: **The MOFA supplies approximately 15 branches and LOFA almost 16 branches. The MOFA provides 1 branch to the olfactory bulb and 4 branches to the olfactory tract, and there are approximately 2 MOFA-LOFA anastomoses per hemisphere (novel finding). The MOFA origin is located approximately 7.9 mm anterior to the anterior communicating artery and 4.7 cm posterior to the anterior limit of the gyrus rectus. The LOFA origin is located approximately 11.1 mm from the middle cerebral artery bifurcation. Younger, shorter, and lighter individuals have more MOFA-LOFA anastomoses. Finally, the number of MOFA branches for the olfactory bulb is positively correlated with the number of MOFA branches for the olfactory tract, as well as with the number of MOFA-LOFA anastomoses.**

■ CONCLUSIONS: **The present study provides a detailed description of the OFAs' microsurgical anatomy and can help neurosurgeons to easily identify, manipulate, and preserve these vessels during surgery.**

INTRODUCTION

The orbitofrontal (or frontobasal) arteries (OFAs) consist of the medial (MOFA) and lateral (LOFA) orbitofrontal arteries. The MOFA is usually the first branch of the A2 segment of the anterior cerebral artery (ACA) and is distributed to the gyrus rectus and medial orbital gyri. The LOFA most frequently branches off the superior (frontal) trunk of the middle cerebral artery (MCA) (M2 segment) and irrigates the lateral orbital gyri.[1,2]

Although the OFAs supply the orbital gyri giving rise to many perforators, the arterial vascularization pattern of the orbitofrontal cortex varies significantly. Hence, issues regarding the microsurgical anatomy of the OFAs arise in terms of their respective emerging pattern, distribution area, branching configuration, anastomoses, and the possible anatomic landmarks aiding in their intraoperative identification.

Key words
- Anterior cerebral artery
- Lateral orbitofrontal artery
- Medial orbitofrontal artery
- Middle cerebral artery
- Orbitofrontal cortex

Abbreviations and Acronyms
a: Branches of the medial orbitofrontal artery
ACA: Anterior cerebral artery
ACoA: Anterior communicating artery
b: Branches of the lateral orbitofrontal artery
c: Branches of the medial orbitofrontal artery for the olfactory bulb
d: Branches of the medial orbitofrontal artery for the olfactory tract
e: Anastomoses of the orbitofrontal arteries of the same hemisphere
f: Distance of the origin of the medial orbitofrontal artery from the anterior communicating artery
g: Distance of the origin of the medial orbitofrontal artery from the anterior limit of the gyrus rectus
h: Distance of the origin of the lateral orbitofrontal artery from the middle cerebral artery bifurcation
LOFA: Lateral orbitofrontal artery
MCA: Middle cerebral artery
MOFA: Medial orbitofrontal artery
OFA: Orbitofrontal artery
RAH: Recurrent artery of Heubner

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Therefore, the purpose of this microscopic cadaveric study was to address these topics and assess the relation of the OFAs to major neurovascular structures of the frontal base, namely the anterior communicating artery complex (ACoA), the olfactory tract and bulb, and the MCA bifurcation. Anatomic features (branching, length, and anastomoses) of the OFAs were assessed in relation to demographic and anthropometric variables.

METHODS

Materials

Twenty formalin-fixed, colored latex-injected human cadaveric heads (8 men and 12 women), preserved in a solution of ethyl alcohol (10%), were studied. Their average age was 71.50 ± 13.75 years (range, 38–95 years), height 166.49 ± 11.05 cm (range, 152.40–187.96 cm), weight 65.10 ± 19.77 kg (range, 37.19–115.67 kg), and body mass index 23.77 ± 5.73 kg/m^2 (range, 14.29–37.12 kg/m^2). Microsurgical instruments and the operating microscope (Carl Zeiss Meditec AG OPMI pico, Oberkochen, Germany) were used during the dissection process.

Methods

We performed a bifrontal craniotomy to expose the orbitofrontal cortex (frontal base), the OFAs and the A2 segment area and subsequently, a pterional approach to explore the M2 segment area. In addition, we removed the cerebrum from the cranial vault to meticulously investigate the branching pattern of the OFAs. We recorded the total number of MOFA (branches of the MOFA [a]) and LOFA (branches of the LOFA [b]) branches, the number of MOFA branches for the olfactory bulb (branches of the MOFA for the olfactory bulb [c]) and olfactory tract (branches of the MOFA for the olfactory tract [d]), as well as the anastomoses between the ipsilateral OFAs (anastomoses of the OFAs of the same hemisphere [e]). We also measured the distances between the MOFA origin and the ACoA complex (distance of the origin of the MOFA from the ACoA [f]), the MOFA origin and the anterior end of the gyrus rectus (distance of the origin of the MOFA from the anterior limit of the gyrus rectus [g]) and the LOFA origin and MCA bifurcation (distance of the origin of the LOFA from the MCA bifurcation [h]).

Statistical Analysis

The anatomic variables of the OFAs were assessed for statistically significant differences between hemispheres, genders, age groups (<73 years vs. ≥73 years), height groups (<166 cm vs. >166 cm), weight groups (<65 kg vs. >65 kg), and body mass index groups (<23 kg/m^2 vs. >23 kg/m^2). Normally distributed variables were expressed as mean value ± standard deviation, whereas variables with skewed distribution were expressed as median value (interquartile range). If the normality assumption was satisfied for the comparison of means between 2 groups, Student's *t*-test was used. Mann-Whitney test was used for the comparison of continuous variables between 2 groups when the distribution was not normal. Pearson's correlation coefficient was used to explore the association of 2 continuous variables. Correlation coefficient 0.1–0.3 was considered low, 0.31–0.5 moderate, and those >0.5 were considered high. All reported P values were 2-tailed and statistical significance was set at $P < 0.05$. Analysis was carried out using SigmaStat Statistical Analysis Software (Systat Software, Inc., San Jose, California).

RESULTS

Microsurgical Study

During microsurgical dissection, we observed that the MOFA origin (A2 segment) is usually found medially to the gyrus rectus (particularly at its proximal part). Consequently, its access necessitates dissection of the interhemispheric fissure toward the ACoA complex. Slight manipulation of the olfactory tract aids in exposing the MOFA, especially when it lies between the olfactory tact and the orbitofrontal cortex.

During Sylvian fissure dissection to expose the LOFA origin (emerging from M1 or M2 segment) early on we encountered MCA branches intervening. Actually, the origin site of the LOFA may be difficult to identify, particularly in cases where its proximal part has a short course within the posteroinferior frontal lobe.

Microanatomic Study

The microanatomic study aimed at clarifying the detailed anatomy of the OFAs. Table 1 demonstrates the mean values ± standard deviations of the measured parameters: MOFA branches (a) = 15.41 ± 7.05 branches (range, 2–28 branches), LOFA branches (b) = 15.78 ± 10.44 branches (range, 2–40 branches), MOFA branches for the olfactory bulb (c) = 1.45 ± 1.32 branches (range, 0–5 branches), MOFA branches for the olfactory tract (d) = 3.74 ± 3.44 branches (range, 0–16 branches), MOFA-LOFA anastomoses (e) = 2.40 ± 1.32 anastomoses (range, 1–5 anastomoses), MOFA origin distance from the ACoA (f) = 7.89 ± 4.79 mm (range, 2–30 mm), MOFA origin distance from the anterior end of the gyrus rectus (g) = 4.67 ± 0.59 cm (range, 2.9–5.8 cm), LOFA origin distance from the MCA bifurcation (h) = 9.36 ± 9.28 mm (range, 1–26 mm). Therefore, on average, MOFA and LOFA has 15 and 16 branches, respectively, to the orbitofrontal cortex, MOFA gives off 1 branch to the olfactory bulb and 4 branches to the olfactory tract (Figure 1) and there are 2 ipsilateral anastomoses between MOFA and LOFA (Figure 2). In addition, the MOFA emerges approximately 7.9 mm anterior to the ACoA (Figure 3) and 4.7 cm posterior to the anterior limit of the gyrus rectus (Figure 4), whereas the LOFA emerges 9.4 mm distal to the MCA bifurcation (Figure 5).

Observations on the Medial Orbitofrontal Artery

The MOFA arises approximately 1 cm anterior to the posterior end of the gyrus rectus. Despite commonly emerging from the A2 segment, a single case where the MOFA arose from the A1 segment of the ACA was recorded. The MOFA usually courses within the interhemispheric fissure for a short distance until it deviates to run oblique to the olfactory tract, above its proximal part, dividing into branches that enter the olfactory sulcus (Figure 4). The MOFA was the main feeder (and usually the only feeder) of the olfactory bulb and tract (Figures 1 and 2). The branches to the olfactory bulb pierce its pia matter, whereas the rami for the olfactory tract follows its course, attached to its inferior surface, and occasionally form a plexus around the olfactory bulb.

Table 1. Results of the Studied Anatomic Parameters Regarding the OFAs and Relative Morphometric Data

Hemisphere Number	Morphometric Data						Studied Parameters							
	Sex	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Side	a (branches)	b (branches)	c (branches)	d (branches)	e*	f (mm)	g (cm)	h (mm)
1	M	84	175.26	65.77	21.41	R	2	2	1	-†	1	12	3.8	−1.5
2						L	8	9	-	-	1	8	5	4
3	M	90	185.42	115.67	33.64	R	8	6	0	1	-	7	5.7	5
4						L	7	5	0	3	-	7	5.8	20
5	F	65	152.40	54.53	23.44	R	13	9	1	1	4	30	2.9	7
6						L	20	6	1	2	3	4	4.5	20
7	F	71	160.00	56.00	21.88	R	7	4	0	0	-	9	4.6	4
8						L	15	25	2	5	4	6	4.6	3
9	F	63	167.64	104.33	37.12	R	15	10	1	2	1	12	4.6	−15
10						L	25	15	1	1	1	9	4.3	20
11	F	73	170.18	48.99	16.92	R	16	-	-	-	-	5	4.6	-
12						L	9	18	-	-	-	10	4.2	12
13	F	65	152.40	46.72	20.12	R	-	12	-	-	-	-	-	6
14						L	-	11	-	-	-	-	-	7
15	F	95	152.40	45.36	19.53	R	12	-	-	-	-	8	4.5	14
16						L	8	14	0	1	1	20	3.6	9
17	M	38	175.26	72.57	23.63	R	13	7	-	2	1	5	4.7	-
18						L	12	7	2	3	2	6	5.1	5
19	M	70	172.72	72.57	24.33	R	15	15	-	4	3	8	4.5	5
20						L	22	10	-	-	5	7	5.4	10
21	F	80	162.56	49.90	18.88	R	15	17	1	7	2	4	4.6	12
22						L	23	4	5	16	4	6	3.9	15
23	M	79	170.18	79.38	27.41	R	23	40	1	3	1	5	5.6	11
24						L	12	23	1	4	2	6	4.4	15
25	M	73	172.72	42.64	14.29	R	28	31	2	-	1	2	5.3	9
26						L	27	29	1	3	3	8	5.2	2
27	F	77	167.64	81.65	29.05	R	-	11	-	-	2	9	4.9	8
28						L	-	-	-	-	1	7	4.6	20
29	F	76	152.40	37.19	16.01	R	-	-	-	-	-	7	4.8	−14
30						L	-	-	-	-	-	6	5	26
31	F	47	160.02	58.97	23.03	R	-	-	-	3	-	7	4.5	-
32						L	18	33	3	3	3	3	4.4	3
33	M	88	180.30	70.31	21.63	R	6	30	4	10	3	6	5.2	26
34						L	-	28	-	-	-	-	-	3
35	F	67	154.94	56.70	23.62	R	23	13	-	4	3	7	4.5	8
36						L	23	8	-	5	5	9	4.5	22

Continues

Table 1. Continued

	Morphometric Data						Studied Parameters							
Hemisphere Number	Sex	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Side	a (branches)	b (branches)	c (branches)	d (branches)	e*	f (mm)	g (cm)	h (mm)
37	M	55	187.96	68.04	19.26	R	-	-	-	-	-	6	5.3	—1
38						L	22	35	2	3	3	6	5.1	20
39	F	74	157.48	74.82	30.17	R	-	-	-	-	-	8	4.4	13
40						L	-	18	-	-	-	7	4.1	14
MV		71.50	166.49	65.10	23.77		15.41	15.78	1.45	3.74	2.40	7.89	4.67	9.36
SD		13.75	11.05	19.77	5.73		7.05	10.44	1.32	3.44	1.32	4.79	0.59	9.28

a, branches of the medial orbitofrontal artery; b, branches of the lateral orbitofrontal artery; BMI, body mass index; c, branches of the medial orbitofrontal artery for the olfactory bulb; d, branches of the medial orbitofrontal artery for the olfactory tract; e, anastomoses of the orbitofrontal arteries of the same hemisphere; F, female; f, distance of the origin of the medial orbitofrontal artery from the anterior communicating artery; g, distance of the origin of the medial orbitofrontal artery from the anterior limit of the gyrus rectus; h, distance of the origin of the lateral orbitofrontal artery from the middle cerebral artery bifurcation; L, left; LOFA, lateral orbitofrontal artery; M, male; MOFA, medial orbitofrontal artery; MV, mean value; OFAs, orbitofrontal arteries; R, right; SD, standard deviation.

*Anastomoses.

†Not identifiable parameter (usually due to specimens' limitations).

Occasionally, the suppliers of the olfactory tract arose from a MOFA branch within the olfactory sulcus and coursed along this tract. A few branches of the olfactory tract and bulb arose rarely (1 case) from an independent artery (posterior OFA), emerging from the ACA just proximal to the MOFA (Figure 2). In most cases the posterior OFA was a MOFA branch. In 8% of cases the recurrent artery of Heubner (RAH) was also supplying a few (usually 2) branches to the proximal part of the olfactory tract and in 1 of these cases it supplied the olfactory bulb as well.

In the case of the MOFA originating from the A1 segment, this artery coursed along the olfactory sulcus and clearly supplied more than half of the orbitofrontal cortex. In another case the MOFA extended to the anterolateral border of the frontal lobe. We further observed an interesting rare case where the left MOFA anastomosed (15 mm far from its origin) with the contralateral (right) A2 segment, as well as a case of an ACA branch (duplicated MOFA) that supplied the anterior orbitofrontal cortex and anastomosed with the LOFA. Regarding the MOFA distribution, it supplied, with multiple branches, variable parts of the medial orbitofrontal cortex.

Observations on the Lateral Orbitofrontal Artery

The initial LOFA part was often helical in shape, demonstrating an intraparenchymal course into the middle part of the posterior orbitofrontal cortex (Figure 5), whereas the LOFA origin was completely intraparenchymal in 1 case. The LOFA origin proximal to the MCA bifurcation was observed in 18% and distal to the MCA bifurcation in 77% of cases. In the remaining 5% of cases the LOFA had a duplicated origin with 2 stems arising 1 proximal and 1 distal to the MCA bifurcation. When the LOFA arose after the MCA bifurcation, it always emerged from the superior (frontal) MCA trunk (Figure 5).

The LOFA supplies variable parts of the lateral orbitofrontal cortex (Figure 6). We found a case of LOFA anastomosis with the superior MCA trunk (~10 mm distal to the origin of the LOFA), as well as a case of duplicated LOFA, where the first arose 7 mm before the MCA bifurcation and the second, 13 mm after this bifurcation (from the superior MCA trunk). This second artery distributed at the lateral part of the orbitofrontal cortex and was larger in diameter compared with the first one. In 6% of cases the LOFA gave off a branch to the Sylvian fissure just after its origin. In addition, LOFA branches were occasionally emerging as multiple converging small stems. Finally, a couple of anastomoses with the MOFA were the rule in our series and all cases (100%) presented with at least 1 MOFA-LOFA anastomosis. In cases with a single MOFA-LOFA anastomosis (36% in our series), this was usually located at the frontal pole area.

Anatomic Parameters of the Orbitofrontal Arteries in Relation to Gender, Age, Side, Height, Weight, and Body Mass Index

As shown in Table 2, we found statistically significant differences for the following parameters: e between younger (2.9 ± 1.4 anastomoses) and older (1.8 ± 1.0 anastomoses) individuals ($P = 0.037$), taller (1.9 ± 1.2 anastomoses) and shorter (3.2 ± 1.2 anastomoses) individuals ($P = 0.016$), and between heavier (1.9 ± 1.2 anastomoses) and lighter (3.0 ± 1.3 anastomoses) individuals ($P = 0.042$), as well as g between men (5.1 ± 0.5 cm) and women (4.4 ± 0.5 cm) ($P < 0.001$), taller (4.9 ± 0.5 cm) and shorter (4.3 ± 0.5 cm) individuals ($P = 0.002$) and between heavier (4.9 ± 0.6 cm) and lighter (4.5 ± 0.6 cm) individuals ($P = 0.031$). Thus, younger, shorter, and lighter individuals have more MOFA-LOFA anastomoses and the distance between the MOFA origin and the anterior limit of the gyrus rectus (Figure 4) is more in male, taller, and heavier individuals.

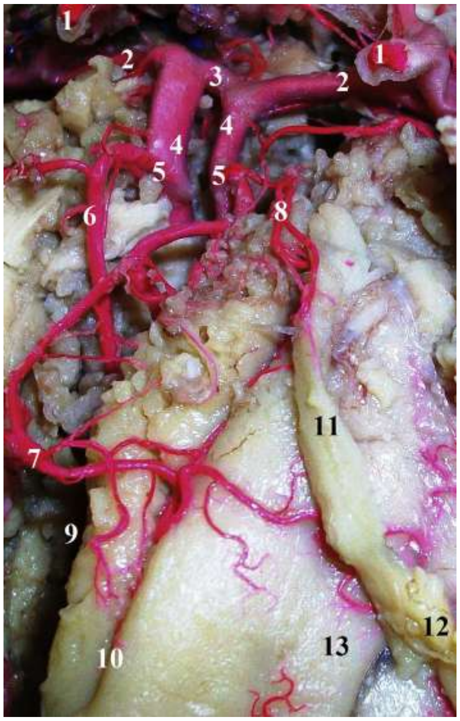

Figure 1. The origin and distribution of MOFA. Human brain, posterior frontal lobe, inferior surface. *1*, ICA; *2*, ACA (A1 segment); *3*, ACoA; *4*, ACA (A2 segment); *5*, MOFA origin; *6*, left MOFA; *7*, right MOFA (retracted medially); *8*, MOFA branches to the olfactory system (tract and bulb); *9*, interhemispheric fissure; *10*, olfactory sulcus; *11*, olfactory tract (retracted laterally); *12*, olfactory bulb; *13*, orbitofrontal cortex; *ACA*, anterior cerebral artery; *ACoA*, anterior communicating artery; *ICA*, internal carotid artery; *MOFA*, medial orbitofrontal artery.

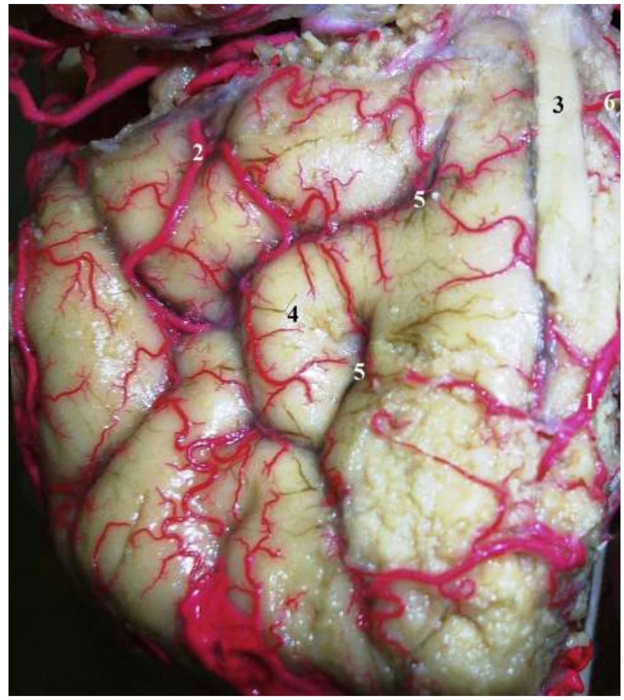

Figure 2. Anastomoses between the OFAs. Human brain, left hemisphere, frontal lobe, inferior surface. *1*, MOFA; *2*, LOFA; *3*, olfactory tract; *4*, orbitofrontal cortex; *5*, arterial anastomoses; *6*, posterior OFA; *LOFA*, lateral orbitofrontal artery; *MOFA*, medial orbitofrontal artery; *OFAs*, orbitofrontal arteries.

Correlations Between Anatomic Parameters of the Orbitofrontal Arteries

As shown in Table 3, we found statistically significant correlations between the following parameters: a and b ($P = 0.037$), c and d ($P < 0.001$), c and e ($P = 0.028$), and f and g ($P < 0.001$). Thus the number of MOFA branches is positively correlated with the number of LOFA branches. The number of MOFA branches for the olfactory bulb is positively correlated with the number of MOFA branches for the olfactory tract, as well as with the number of MOFA-LOFA anastomoses. Finally, the distance between the MOFA origin and the ACoA (Figure 3) is negatively correlated with the distance between the MOFA origin and the anterior limit of the gyrus rectus.

DISCUSSION

Neuroanatomy

MOFA: Origin. Our results demonstrate a remarkable variability in the origin of the MOFA, usually located 8 mm anterior to the ACoA complex and almost 5 cm posterior to the anterior limit of the gyrus rectus. Rarely (3% of cases) it was found along the A1 segment of the ACA. The fact that the distance between the MOFA origin and the anterior limit of the gyrus rectus is greater in male, taller, and heavier individuals, is expected as bigger individuals tend to have larger brains.

The MOFA is the first cortical branch of the distal (post-ACoA) ACA[3,4] and 1 of the 3 ACA branches arising near the ACoA complex (the remaining are the RAH and frontopolar artery).[5] In most cases (52%–100%)[3-11] (97% in our study) MOFA arises from the A2 segment. In addition, the MOFA can originate from the A1 segment (0%–38%),[7,8,10] 3% in our study, in the vicinity of the ACoA,[4,12] the RAH (4%),[13] the ACoA complex (A1-A2 junction),[8] the frontopolar artery,[11] the internal frontal artery,[11] and the callosomarginal artery.[11] The MOFA can arise as a common trunk with the frontopolar artery[3,4] or even with the RAH (4%).[8,13] An accessory ACA (atypical branch of the internal carotid artery) may rarely be the MOFA origin.[14] The MOFA originates 0–15 mm anterior to the ACoA,[3,5,6,8,15] with a mean of either 5–6 mm[3,5] or 7.7 ± 3.9 mm.[15] Our results (7.9 ± 4.8 mm) agree with those of Stefani et al[15] and reveal a greater (actually double) range (2–30 mm) for the location of the MOFA origin in relation to the ACoA than previously described.

The MOFA is the smallest cortical ACA branch,[5,8,11] the mean diameter at its origin being nearly 1 mm (range, 0.2–2 mm).[3,5,11] The MOFA is one of the most consistent cortical ACA branches[8] and can be identified in 90%–100% of hemispheres[3,5,9-11] (100%

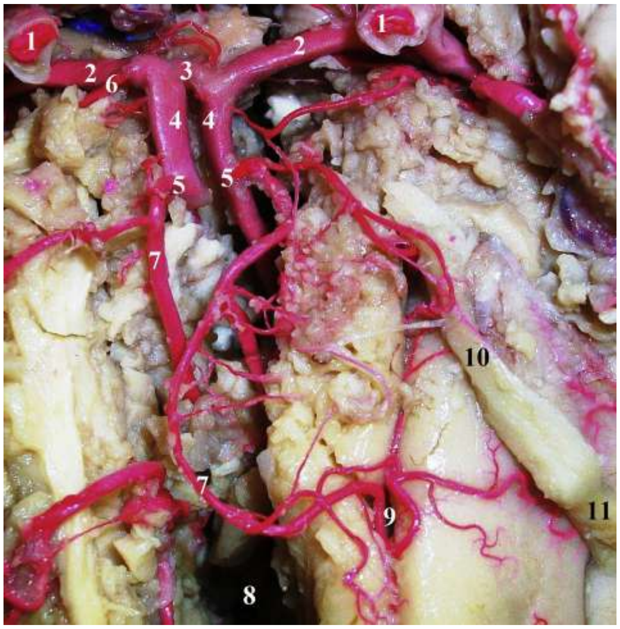

Figure 3. The relation of the MOFA origin to the ACoA. Human brain, posterior frontal lobe, inferior surface, zoom in on the MOFA origin. *1*, ICA; *2*, ACA (A1 segment); *3*, ACoA; *4*, ACA (A2 segment); *5*, MOFA origin; *6*, left RAH; *7*, MOFA (right MOFA retracted medially); *8*, interhemispheric fissure; *9*, olfactory sulcus; *10*, olfactory tract (retracted laterally); *11*, olfactory bulb; *ACA*, anterior cerebral artery; *ACoA*, anterior communicating artery; *ICA*, internal carotid artery; *MOFA*, medial orbitofrontal artery; *RAH*, recurrent artery of Heubner.

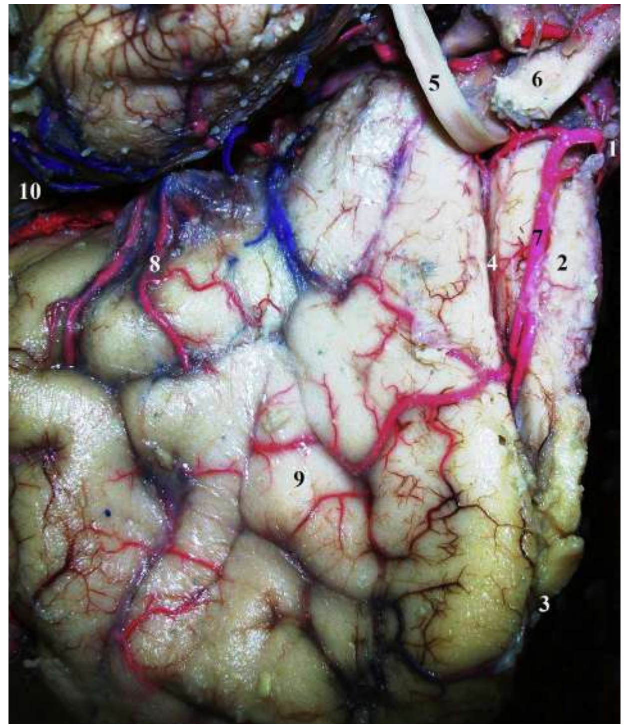

Figure 4. The relation of the MOFA origin to the anterior limit of the gyrus rectus. Human brain, left hemisphere, frontal lobe, inferior surface. *1*, MOFA origin; *2*, gyrus rectus; *3*, anterior limit of the gyrus rectus; *4*, olfactory sulcus; *5*, olfactory tract (retracted posteriorly); *6*, optic nerve; *7*, MOFA; *8*, LOFA; *9*, orbitofrontal cortex; *10*, Sylvian fissure; *LOFA*, lateral orbitofrontal artery; *MOFA*, medial orbitofrontal artery.

in our study). In 15%–62% of cases a MOFA multiplication may be observed.[3,11] In the study of Ugur et al[11] 42%, 16%, and 4% of hemispheres had 2, 3, or even 4 MOFAs. However, Avci et al[5] reported that MOFA always arose (from the A2 segment) as a single trunk. Our results are in agreement with those of Avci et al,[5] with only a single case of a MOFA duplication being recorded.

MOFA: Course and Branches. The MOFA arises distal to the ACoA[16] and passes down and forward toward the floor of the anterior cranial fossa to reach the level of the planum sphenoidale.[3,4,9] It passes around the gyrus rectus, perpendicularly or diagonally to the olfactory tract and bulb,[5,6,16] often penetrating the olfactory cistern, but finally terminating at the orbitofrontal cortex.[16] Its area of perfusion includes the orbital gyri, the medial part of the orbital surface, and the inferomedial portion of the frontal lobe (Brodmann areas 11 and 25).[3,4,6,7,9,16] In our study, the MOFA branched off 4 rami (0–16 rami) to the olfactory tract and 1 (0–5 rami) to the olfactory bulb, being their main feeder (96%), with secondary rami arising from the RAH (8%) and posterior OFA (3%). The MOFA often sends a small branch along the olfactory sulcus to the tip of the frontal pole.[3] In addition, we revealed that the MOFA can rarely be the site of interhemispheric arterial anastomosis (right A2–left A2).

Ciołkowski et al[17] reported that the vascularization of the olfactory tract is provided by 3 discrete vessels: the artery to the posterior orbitofrontal surface, the MOFA, and the distal medial striate artery. According to their study, in 25% of the cases the olfactory tract was supplied by branches of the posterior OFA, which was originally a branch of the MOFA. Only in 18% of hemispheres, the MOFA was found to directly supply the superior surface of the tract.[17] In our study, we also documented 3 arterial feeders of the olfactory tract, 1 major (the MOFA) and 2 minor (the RAH and posterior OFA), but these did not include the distal medial striate artery. A possible explanation could be that the study by Ciołkowski et al[17] focused on the proximal part of the olfactory tract. It should be further noted that a rare RAH origin from the MOFA has been previously reported.[9,11]

Finally, according to Ciołkowski et al,[17] branches to the olfactory tract are encountered mostly in its proximal part, where the posterior OFA courses below the gyrus rectus and enters the olfactory sulcus (**Figure 2**) and the RAH courses toward the anterior perforated substance. Rarely, the distally located branches to the olfactory tract originate either from the MOFA or from the vessel running along the olfactory tract, which branches off the posterior OFA or the RAH.[17] Our findings confirm these observations, the only exception being that the artery running along the olfactory tract usually was a MOFA branch.

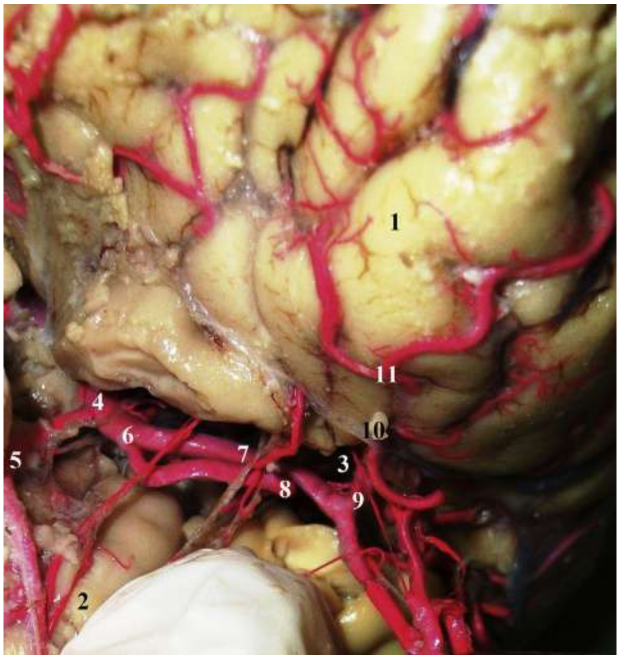

Figure 5. The relation of the LOFA origin to the MCA bifurcation. Human brain, left hemisphere, Sylvian fissure, anterior view. *1*, frontal lobe (orbitofrontal cortex); *2*, temporal lobe (superior surface); *3*, Sylvian fissure; *4*, MCA; *5*, early MCA branch; *6*, MCA bifurcation; *7*, superior (frontal) MCA branch; *8*, inferior (temporal) MCA branch; *9*, LOFA origin; *10*, intraparenchymal LOFA part; *11*, LOFA; *LOFA*, lateral orbitofrontal artery; *MCA*, middle cerebral artery.

Figure 6. Distribution of the LOFA. Human brain, left hemisphere, frontal lobe, inferior surface. *1*, LOFA; *2*, MOFA; *3*, orbitofrontal cortex; *4*, arterial anastomoses; *5*, frontal pole; *LOFA*, lateral orbitofrontal artery; *MOFA*, medial orbitofrontal artery.

LOFA: Origin. Our results demonstrate remarkable variability in the origin of the LOFA, which was found to be, on average, 9.4 mm distal to the MCA bifurcation. We have documented 3 main patterns regarding the origin of the LOFA (i.e., distal [77%] to the MCA bifurcation, proximal [18%] to the MCA bifurcation, and a duplication with 2 stems arising proximal and distal the MCA bifurcation [5%]). Remarkably, when the origin of the LOFA was distal to the MCA bifurcation, it always branched off the superior MCA trunk. This origin could rarely be completely intraparenchymal. The LOFA is usually the first cortical branch of the superior trunk of the MCA bifurcation[4,18,19] (72% of cases[18]) or trifurcation (12% of cases).[18] Other possible origins of the LOFA include the MCA, where the LOFA may constitute either the main early (proximal to the MCA bifurcation or trifurcation) frontal MCA branch[18,20] (6% of cases) or a branch of the MCA main trunk (10% of cases),[18] the early frontal branches of the MCA,[16,20] and rarely the accessory MCA (ACA branch).[13,21] In addition, the LOFA may arise as a common trunk with the prefrontal artery[20] or even with the prefrontal and lateral striate arteries.[19] Gibo et al[18] reported a LOFA diameter of 0.8 mm (range, 0.4–1.5 mm).

LOFA: Course and Branches. According to our results the initial LOFA part may be intraparenchymal (penetrating the middle part of the posterior orbitofrontal cortex) and helical in shape. This vessel passes between the posteroinferior frontal lobe and anterosuperior temporal lobe to the surface of the posterolateral orbitofrontal cortex and distributes primarily to the lateral orbitofrontal cortex. A remarkable variability in the number of its branches was noted (2–40 branches), displaying 16 branches on average that supplied variable parts of the lateral orbitofrontal cortex. We further observed LOFA anastomoses with the superior MCA trunk and LOFA duplication as rare variations and the Sylvian fissure (frontal operculum) as an occasional (6% of cases) LOFA branch receiver.

Gibo et al[18] found a mean of 1.2 LOFAs (range, 1–3 LOFAs) per hemisphere and found this artery to be the smallest cortical MCA branch (only 27% were $\geq$1 mm in diameter) and having the shortest cortical segment. They specifically found LOFA length on the cortical surface to be 13.1 mm (range, 0–40 mm).[18] The LOFA irrigates the lateral orbitofrontal cortex[16,20] (including the inferior portion of the pars orbitalis and the orbital portion of the middle and inferior frontal gyri)[20] and may also supply the anterosuperior part of the insula (transverse and accessory insular gyri and adjacent anterior limiting sulcus).[20] Rarely, the LOFA may give rise to lenticulostriate arteries[20] and the central artery.[22]

Anastomoses Between the Orbitofrontal Arteries (MOFA–LOFA). We recorded approximately 2 MOFA–LOFA anastomoses (1–5 anastomoses) per hemisphere, most frequently located near the frontal pole area. The statistical inference that younger, shorter, and

Table 2. Anatomic Parameters of the Orbitofrontal Arteries in Relation to Gender, Age, Side, Height, Weight, and BMI

	a*	b*	c*	d*	e†	f (mm)	g (cm)	h (mm)
Gender								
F	16.1 ± 5.8	13.4 ± 7.4	1.5 ± 1.5	3.8 ± 4.2	2.6 ± 1.4	8.8 ± 5.9	4.4 ± 0.5	12.4 ± 6.4
M	14.6 ± 8.4	18.5 ± 12.8	1.4 ± 1.2	3.6 ± 2.4	2.2 ± 1.3	6.6 ± 2.1	5.1 ± 0.5	9.2 ± 7.8
P value	0.579	0.176	0.870	0.870	0.408	0.179	<0.001	0.182
Side								
L	16.7 ± 6.9	16.6 ± 10.1	1.6 ± 1.4	4.1 ± 4	2.7 ± 1.4	7.5 ± 3.6	4.7 ± 0.6	12.5 ± 7.7
R	14 ± 7.1	14.8 ± 11.2	1.2 ± 1.2	3.4 ± 2.9	2.0 ± 1.1	8.3 ± 5.8	4.7 ± 0.6	9.4 ± 6.1
P value	0.306	0.642	0.499	0.628	0.186	0.635	0.863	0.186
Age (years)								
<73	17.4 ± 5.3	13.8 ± 9.3	1.4 ± 0.9	2.7 ± 1.5	2.9 ± 1.4	8.4 ± 6.2	4.6 ± 0.6	9.8 ± 7.2
≥73	13.6 ± 8.1	17.8 ± 11.4	1.5 ± 1.6	5.3 ± 4.9	1.8 ± 1.0	7.5 ± 3.5	4.7 ± 0.6	12.1 ± 7.0
P value	0.155	0.278	0.987	0.074	0.037	0.600	0.513	0.331
Height (cm)								
<166	16.1 ± 5.8	13.4 ± 8.4	1.6 ± 1.7	4.3 ± 4.4	3.2 ± 1.2	8.8 ± 6.8	4.3 ± 0.5	11.6 ± 6.7
>166	15 ± 7.8	17.4 ± 11.6	1.3 ± 1.1	3.3 ± 2.3	1.9 ± 1.2	7.2 ± 2.4	4.9 ± 0.5	10.6 ± 7.6
P value	0.694	0.290	0.640	0.489	0.016	0.315	0.002	0.686
Weight (kg)								
<65	17.1 ± 6.7	15.6 ± 9.7	1.6 ± 1.5	4.2 ± 4.2	3.0 ± 1.3	8.4 ± 6.6	4.5 ± 0.6	10.7 ± 6.8
>65	13.6 ± 7.2	15.9 ± 11.3	1.3 ± 1.2	3.3 ± 2.5	1.9 ± 1.2	7.4 ± 2.0	4.9 ± 0.6	11.4 ± 7.5
P value	0.179	0.928	0.624	0.546	0.042	0.547	0.031	0.778
BMI (kg/m^2)								
<23	14.1 ± 8.2	17.9 ± 11	1.8 ± 1.6	5.6 ± 5.3	2.3 ± 1.3	7.6 ± 3.9	4.7 ± 0.5	9.9 ± 7.8
>23	16.6 ± 5.8	13.9 ± 9.8	1.1 ± 0.9	2.7 ± 1.2	2.5 ± 1.4	8.2 ± 5.5	4.7 ± 0.6	12.3 ± 6.3
P value	0.358	0.281	0.245	0.052	0.765	0.728	0.979	0.319

P values used Student's *t*-test.

a, branches of the medial orbitofrontal artery; b, branches of the lateral orbitofrontal artery; BMI, body mass index; c, branches of the medial orbitofrontal artery for the olfactory bulb; d, branches of the medial orbitofrontal artery for the olfactory tract; e, anastomoses of the orbitofrontal arteries of the same hemisphere; F, female; f, distance of the origin of the medial orbitofrontal artery from the anterior communicating artery; g, distance of the origin of the medial orbitofrontal artery from the anterior limit of the gyrus rectus; h, distance of the origin of the lateral orbitofrontal artery from the middle cerebral artery bifurcation; L, left; M, male; R, right.

*Branches.

†Anastomoses.

Table 3. Correlations Between the Studied Anatomic Parameters of the Orbitofrontal Arteries

Parameter	b*	c*	d*	e†	f (mm)	g (cm)	h (mm)
a*							
r	0.40	0.29	0.16	0.29	−0.30	0.14	0.15
P value	0.037	0.218	0.464	0.180	0.117	0.454	0.441
b*							
r	1.00	0.28	0.06	−0.06	−0.31	0.26	0.05
P value		0.236	0.792	0.764	0.107	0.165	0.805
c*							
r		1.00	0.83	0.53	−0.31	−0.08	0.23
P value			<0.001	0.028	0.177	0.728	0.326
d*							
r			1.00	0.42	−0.30	−0.05	0.31
P value				0.073	0.161	0.824	0.178
e†							
R				1.00	0.07	−0.09	0.08
P value					0.756	0.679	0.724
f (mm)							
r					1.00	−0.64	−0.15
P value						<0.001	0.408
g (cm)							
r						1.00	0.07
P value							0.711

a, branches of the medial orbitofrontal artery; b, branches of the lateral orbitofrontal artery; c, branches of the medial orbitofrontal artery for the olfactory bulb; d, branches of the medial orbitofrontal artery for the olfactory tract; e, anastomoses of the orbitofrontal arteries of the same hemisphere; f, distance of the origin of the medial orbitofrontal artery from the anterior communicating artery; g, distance of the origin of the medial orbitofrontal artery from the anterior limit of the gyrus rectus; h, distance of the origin of the lateral orbitofrontal artery from the middle cerebral artery bifurcation; r, Pearson's correlation coefficient.

*Branches.

†Anastomoses.

lighter individuals have more MOFA—LOFA anastomoses is quite interesting and hard to explain. It seems plausible that microvasculopathy, which is a common finding in the elderly, contributes to the degeneration of microscopic branches of the OFAs, including their anastomosing branches. Similarly, heavier individuals are usually more vulnerable to atheromatosis, the main cause of microvasculopathy. In addition, our finding of a positive correlation between the number of MOFA branches for the olfactory bulb and the number of MOFA—LOFA anastomoses could be explained that an increased number of MOFA branches near the frontal pole (the usual place of anastomoses) may increase the probability of anastomoses with LOFA branches.

Conversely, Izci et al[16] studied 10 brains and found no MOFA—LOFA anastomosis on the surface of the orbitofrontal cortex. A proper explanation could be that studying the orbitofrontal cortex in relation to the RAH, Izci et al[16] did not focus on the frontal pole area, the most common place of MOFA—LOFA anastomoses. However, the lack of demographic and anthropometric data in the study of Izci et al[16] hinders a direct comparison with the present findings.

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MOFA. The ACoA complex, gyrus rectus, olfactory sulcus, tract, and bulb serve as important landmarks for the intraoperative identification of the MOFA and its branches. It is important to distinguish the RAH from MOFA (e.g., during ACoA aneurysm surgery)[16] by dissecting the vessel for definite confirmation before potential sacrifice.[6] Although these vessels have similar diameters, they can be differentiated from their course and distribution.[5] The MOFA runs almost perpendicular to the gyrus rectus and across the olfactory tract, whereas the RAH crosses the posterior end of the gyrus rectus following the course of the A1 segment.[16] Interestingly, on computed tomography angiograms, a MOFA infundibulum may be misinterpreted as an ACoA aneurysm.[23]

MOFA aneurysms are rare and have been associated with vascular malformations[6,24] and multiple aneurysms.[6] In the study of Lehecka et al[25] 2 of 108 distal ACA aneurysms were located at the orbitofrontal branches (frontobasal aneurysms), both near the midline. The frontobasal and the A2 segment aneurysms have the tendency to be smaller than more distally located aneurysms.[25] Acute angulation of the distal MOFA along with a recurrent configuration of the anterior ethmoidal arteries have been postulated as causes of hemodynamic stress in MOFA aneurysms.[24] In addition, distal MOFA aneurysms are very rare and may be angiographically misdiagnosed as proximal ACA aneurysms, especially when partially thrombosed.[6] These aneurysms may be difficult to dissect and reconstruct, mainly because of the limited space of the interhemispheric fissure.[24]

The MOFA can be also used for end-to-end and end-to-side anastomoses with the A1 segment during microvascular reconstruction procedures in the anterobasal part of the interhemispheric space, where cerebral aneurysms frequently develop.[26] Furthermore, tumors of the anterior cranial fossa may be supplied by the OFAs, especially those located at olfactory grooves (e.g., meningiomas).[27]

It can be easily deducted that intraoperative injury of the MOFA branches can cause (ipsilateral) anosmia.[17]

LOFA. Meticulous dissection of the Sylvian fissure is necessary to access the LOFA's origin (M1 or M2 segment), which can be difficult to identify, mainly due to the frequent intraparenchymal course of its proximal segment. During revascularization procedures using superficial temporal artery to MCA anastomosis (combined with encephalo-duro-arterio-myo-synangiosis), the LOFA participates actively in the development of a collateral circulation.[28] An interesting observation regarding the LOFA is that it rarely suffers stenotic changes compared with other MCA branches.[29]

Orbitofrontal Cortex. One of the most interesting findings of this study is the presence of MOFA—LOFA anastomoses, usually located near the frontal pole.

The orbitofrontal cortex contains the secondary taste area, as well as the secondary and tertiary olfactory cortical areas.[16] In addition to olfactory sensation,[30] it is involved in high order functions related to emotion, cognition, reward, punishment, personality, learning association, and reversing stimulus-reinforcement association.[16] The medial orbitofrontal cortex has a specific role in cognitive inhibition[16] and is involved in lower-order processes such as response inhibition and stimulus-based switching of attention.[16,31]

Lesions of the orbitofrontal cortex can result in the orbitofrontal syndrome (characterized by behavioral disturbances),[32] the ACoA complex syndrome (profound amnestic syndrome with personality changes),[33] the squalor syndrome (a behavioral disorder characterized by extreme self-neglect and domestic squalor), inappropriate decision-making, abnormal impulsivity,[34] and spontaneous confabulations (posterior orbitofrontal cortex).[35,36] In addition, damage to the orbitofrontal cortex impairs the learning and reversal of stimulus-reinforcement associations and can also impair the identification of face expression.[17] Finally, a functional imbalance between the right and left orbitofrontal cortex is considered important in mania.[37]

CONCLUSIONS

The MOFA origin is typically located 8 mm anterior to the ACoA and almost 5 cm posterior to the anterior limit of the gyrus rectus. It is the principal supplier of the olfactory tract and bulb and can rarely be the site of interhemispheric arterial anastomosis. The ACoA complex, gyrus rectus, and olfactory sulcus, tract, and bulb are important landmarks for the intraoperative identification of the MOFA and its branches, and for distinguishing it from RAH.

The LOFA origin is found 9.4 mm distal to the MCA bifurcation, with 3 emerging patterns. It usually arises distal to the MCA bifurcation from the superior MCA trunk. Meticulous dissection of the Sylvian fissure is necessary to access the LOFA origin, which is hard to identify due to the often intraparenchymal course of its initial segment.

Our findings offer to neurosurgeons the necessary anatomic knowledge for precise identification of the location of the MOFA and LOFA origin during surgery, as well as additional novel and crucial information for surgical dissection of these arteries (i.e., the existence of MOFA—LOFA anastomoses). These anastomoses are affected by microvasculopathy, which is a hypothesis that warrants further investigation.

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