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COMMUNICATIONS

THE OPHTHALMIC ARTERY

I. ORIGIN AND INTRA-CRANIAL AND INTRA-CANALICULAR COURSE*

BY

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EXTENSIVE accounts of the blood vessels of the orbit are to be found in various text-books of ophthalmology and anatomy, but there are few systematic descriptions of the anomalies. The various authors differ very little from one another in their descriptions, and deal almost exclusively with the so-called normal pattern of the ophthalmic artery. It was therefore considered desirable to study the origin, course, branches, and anastomoses of the ophthalmic artery in detail.

Material

The origin and intra-cranial and intra-canalicular course of the ophthalmic artery were studied in 106 human orbits obtained from 58 dissection-room cadavers. There were three specimens from male children aged 4, 11, and 12 years, and the rest were from adults mostly past middle-age. Both sides were examined in 48 individuals, and in the remaining ten only one.

Some features were studied in 170 specimens (this includes the 106 mentioned above).

Methods

The skull was opened and the brain removed leaving behind a long stem of the internal carotid arteries. The optic tracts were cut so that the optic chiasma and optic nerves were left intact within the skull, and investigations were carried out by two methods:

(*i*) In 56 specimens from 28 cadavers (22 adult males, 3 adult females, 3 children), the origin and intra-cranial and intra-canalicular course were studied under a low-power stereoscopic binocular dissection microscope with direct illumination from a lamp having a high-power and low-voltage filament. Distances were measured by a micrometer disc introduced into the eye-piece of the microscope.

(*ii*) The remaining fifty specimens (both sides in 20 individuals and only one side in 10) were examined with the naked eye.

All the findings in those examined by the first method were submitted to statistical analysis and all the measurements and statistical data given in the text pertain to the first 56 specimens examined. The findings in the second group were not usually analysed statistically because they were not sufficiently detailed, but wherever the data from the second group are mentioned, a note to that effect is given in the text.

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Observations

Before describing the origin and intra-cranial and intra-canalicular course of the ophthalmic artery, it is essential to describe the various aspects of the cranial opening of the optic canal in detail.

Cranial Opening of Optic Canal.—This is bounded above and below by the anterior and posterior roots respectively of the lesser wing of the sphenoid (Fig. 1).

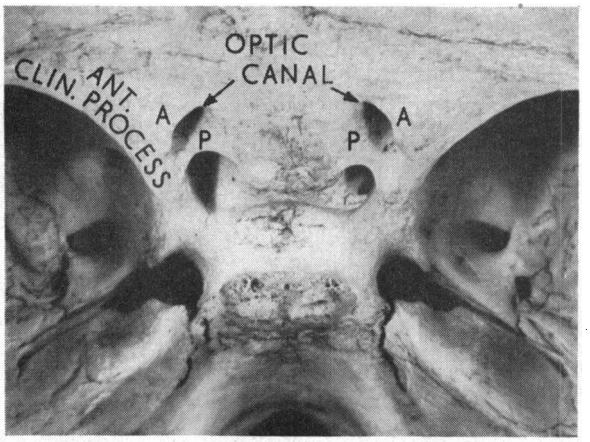


FIG. 1.—Cranial openings of optic canals and surrounding bony landmarks, as seen at the base of the skull.

The upper and lower margins of the opening are designated "A" and "P" respectively in the text. "A" was usually situated about 0·6 to 7·3 mm. anterior to "P", though in three specimens (two of them from one subject) "A" lay vertically above "P", and in seven specimens (six of them from three subjects) "P" lay 1·4 to 4·1 mm. anterior to "A". The distance between "A" and "P" was not equal on both sides of the same subject except in two cases.

A falciform fold of dura extended for some distance posterior to "A" in the cranial cavity (Figs 2, 5, 6, 15, 16). The posterior free margin of this dural fold was crescentic in shape and was continuous medially with the dura on the body of

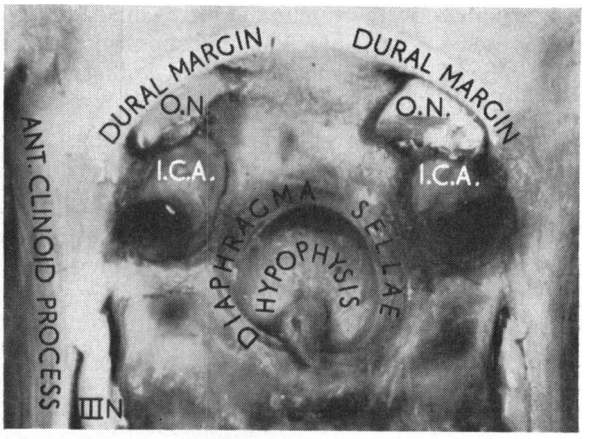


FIG. 2.—Cranial openings of the optic canals with dural margins intact, optic nerves, internal carotid arteries, hypophysis, and diaphragma sellae, as seen after removal of the brain.

O.N. = Optic nerve
I.C.A. = Internal carotid artery
III N = 3rd nerve

the sphenoid and laterally with the anterior clinoid process. This dural free margin is designated "D" in the text. This fold made the optic canal longer than the distance actually bounded by the bony part. The various terms pertaining to the optic canal in the text are used in relation to the length of canal extending from "D" up to the opening at the apex of the orbit, rather than to the usual length from "A" onwards.

The "A" and "D" margins were not necessarily parallel with each other, as at times there was a deep notch on the former and this notch had no relationship with the course of the ophthalmic artery. The distance between "A" and "D" was very variable with no constant pattern and relationship between them and the distance of the origin of the ophthalmic artery from "D" or "A". The distance between "D" and "A" varied from 0·5 to 6 mm., the commonest distance being 0·7 to 2·8 mm.

The relationship of "P" to "D" was also variable: in sixteen specimens "D" was 0·3 to 5·5 mm. posterior to "P", in 36 specimens "P" was 0·2 to 4·1 mm. posterior to "D", and in four "P" and "D" lay one above the other.

Intra-cranial Length of Optic Nerve (from "D" to Optic Chiasma).—This was found in fifty specimens to vary from 4·8 to 15·1 mm. In a child of 12 years it was 2·1 mm. on one side and 2·7 mm. on the other. In eleven subjects the lengths were equal, and in the remaining fourteen there was a difference of 0·6 to 2·7 mm., the commonest difference being 0·7 to 1·4 mm. The actual length of the optic nerve from "D" to the optic chiasma, as seen in fifty specimens, is given in Table I.

TABLE I

INTRA-CRANIAL LENGTH OF OPTIC NERVE IN FIFTY SPECIMENS

Intra-cranial Length Optic Nerve (mm.)	2·1	2·7	4·8	5·5	6·2	6·5	6·9	7·6	8·3	8·9	9·6	10·0	11·0	11·7	12·4	13·1	13·8	15·1	Total
No. of Specimens	1	1	1	3	2	1	4	3	5	4	13	2	5	1	1	1	1	1	50

Origin of the Ophthalmic Artery

Source.—This was studied in 170 specimens (Fig. 3, overleaf). In 164 (Fig. 3A) the ophthalmic artery arose from the internal carotid artery, but in four (Fig. 3 B, C, D, E), although it arose from the internal carotid artery as usual, the main contribution of blood came from the middle meningeal artery through a marked enlargement of the normal anastomosis between the orbital branch of the middle meningeal and the recurrent meningeal branch of the lacrimal artery. In these four specimens, the calibre of the ophthalmic artery between its origin from the internal carotid artery and the point of origin of the lacrimal artery was much reduced. In the remaining two specimens (Fig. 3 F, G), the arrangement was as above, except that the trunk of origin from the internal carotid artery was either obliterated (Fig. 3 G) or absent (Fig. 3 F) in its intra-cranial and intra-canalicular course, so that the middle meningeal artery was the only source of blood reaching the ophthalmic artery. The two trunks from the internal carotid and the middle meningeal arteries united on the lateral side of the optic nerve in three specimens (Fig. 3 B, C, G) and on the medial side in the rest (Fig. 3 D, E, F).

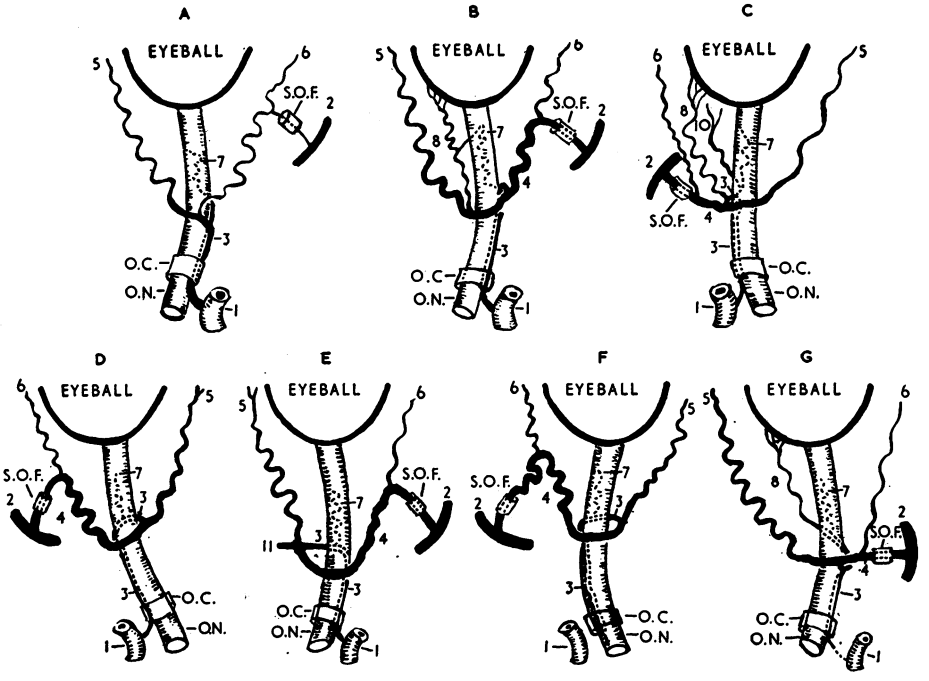


FIG. 3.—Variations in origin and intra-orbital course of the ophthalmic artery.
(A) Normal pattern.
(B, C, D, E) The ophthalmic artery arises from the internal carotid artery as usual, but the major contribution comes from the middle meningeal artery.
(F, G) The only source is the middle meningeal artery, as the connexion with the internal carotid artery is either absent (F) or obliterated (G).

(1) Internal carotid artery.
(2) Middle meningeal artery.
(3) Ophthalmic artery trunk from internal carotid artery.
(4) Ophthalmic artery trunk from middle meningeal artery.
(5) Terminal part of ophthalmic artery.
(6) Lacrimal artery.
(7) Central retinal artery.
(8) Medial posterior ciliary artery in B and G; lateral posterior ciliary artery in C.
(10) Muscular artery.
(11) Anterior and posterior ethmoidal artery.

ON = Optic nerve.
OC = Optic canal.
SOF = Superior orbital fissure.

Where the middle meningeal artery supplied all or most of the blood to the orbit (Fig. 3B to G), the condition was bilateral in two subjects (E and F of one and B and D of another), and unilateral in two (C and G). All these four subjects were past middle age.

No other abnormal source of origin was seen in the present series.

Distance of Origin from Dural Margin ("D").—The site of origin of the ophthalmic artery from the internal carotid artery was situated at a point varying from 3 mm. anterior to "D" to 4·8 mm. posterior to "D". In four specimens the origin was anterior to "D", in three it was below "D", and in the remaining 49 it was posterior to "D" (Figs 6, 11, 16). The distances in 52 specimens are given in Table II (opposite).

TABLE II

DISTANCE BETWEEN ORIGIN OF OPHTHALMIC ARTERY AND DURAL MARGIN IN 52 SPECIMENS

Distance (mm.)	Nil	0·4	0·7	1·0	1·4	1·6	1·8	1·9	2·1	2·4	2·5	2·6	2·7	3·0	3·4	3·6	4·1	4·5	4·8	Total
No. of Specimens	3	1	2	2	3	2	2	3	1	3	3	1	5	4	5	1	8	2	1	52

Where the origin was intra-canalicular (*i.e.* anterior to "D"), the condition was bilateral. In six subjects the distance was the same on both sides, and in the remaining 22 it varied. This difference was marked in seven subjects (1 to 2·7 mm.), but in the remaining fifteen it ranged from 0·2 to 0·9 mm. The distance was not related to age or sex.

Distance of Origin from "A".—The origin was usually situated posterior to "A" (Fig. 6, 11, 16), but in one specimen it was 1·6 mm. anterior. The distance was the same on both sides in six specimens, in two of which the distance from "D" was also the same on both sides. In the 55 specimens in which the origin was posterior to "A", the distance varied from 0·7 to 9·4 mm. (Table III).

TABLE III

DISTANCE BETWEEN ORIGIN OF OPHTHALMIC ARTERY AND "A" IN 55 SPECIMENS

Distance (mm.)	0·7	1·1	1·4	1·8	2·0	2·4	2·6	2·7	3·0	3·2	3·4	4·1	4·4	4·5	4·8	5·1	5·2	5·4	5·5	6·5	6·9	7·8	8·9	9·4	Total
No. of Specimens	2	2	2	1	3	1	1	1	2	1	1	4	2	1	8	1	1	2	11	2	3	1	1	1	55

Distance of Origin from "P".—The origin was usually situated posterior to and slightly above "P" at a distance of 0 to 6·8 mm., but in two specimens it was 1·3 and 3·7 mm. anterior. In these two the origin was extra-dural, as the internal carotid artery lay in the cavernous sinus (Fig. 15). In eight subjects the distance was the same on both sides. The initial part of the ophthalmic artery was over-riding "P".

The distances between the origin of the ophthalmic artery and "D", "A", and "P" had absolutely no relationship with each other and varied widely.

Relationship of Site of Origin with Optic Nerve.—The relationship of the site of origin of the ophthalmic artery with the optic nerve in the 56 specimens studied in detail is shown in Table IV.

TABLE IV

RELATIVE POSITIONS OF SITE OF ORIGIN OF OPHTHALMIC ARTERY AND OPTIC NERVE IN 56 SPECIMENS

Relationship with Optic Nerve	Medial to Nerve	Under Medial Border	Inferior and Medial to Nerve	Under Centre of Nerve	Inferior and Lateral to Nerve	Lateral to Nerve	Total
No. of Specimens	1	1	23	21	9	1	56

In the remaining fifty specimens this relationship was found to be similar; the most frequent site was under the medial part of the nerve and the next most frequent under the centre of the nerve, other sites being very few indeed.

The origin was usually intimately related to the inferior surface of the optic nerve, but in rare cases it lay at a lower level, so that the nerve and the artery were not necessarily closely related with each other.

Site of Origin from Internal Carotid Artery.—The ophthalmic artery arose from the bend made by the internal carotid artery as it pierced the dura to emerge from the cavernous sinus on the medial side of the anterior clinoid process (Figs 4 to 12, 16 to 20). Usually the point of origin was situated in the sub-dural space just after the internal carotid had pierced the dura, but in seven specimens it occurred a short distance (less than 1 mm.) distal to that site.

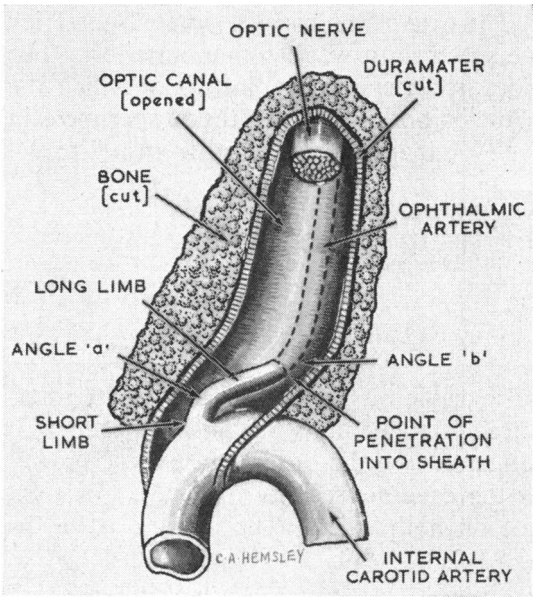
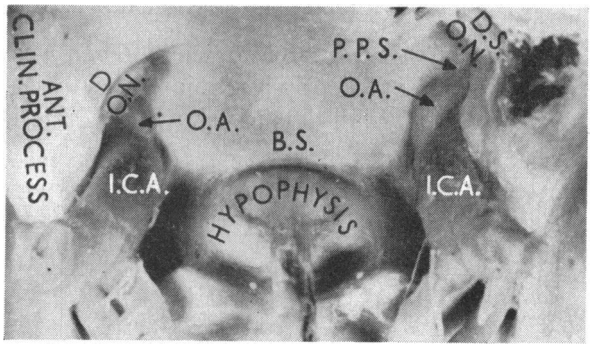


FIG. 4.—Origin and intra-cranial and intra-canalicular course of ophthalmic artery and its sub-divisions as seen on opening the optic canal.

FIGS 5–10.—From a child aged 11 years.

FIG. 5.—Ophthalmic and internal carotid arteries on both sides, with a partially-opened optic canal on right side and an intact canal on left.



In this and the subsequent figures, the following abbreviations are used:

B.S. = Body of sphenoid
D.S. = Dural sheath
I.C.A. = Internal carotid artery
O.A. = Ophthalmic artery
O.N. = Optic nerve
P.P.S. = Point of penetration of dural sheath
A., D., and P. as in text

In 95 of the 106 specimens studied, the origin was situated in the sub-dural space, in eight specimens it was proximal to the point where the internal

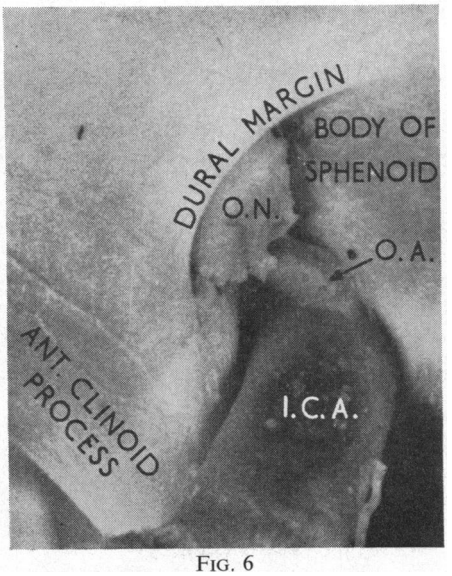


FIG. 6

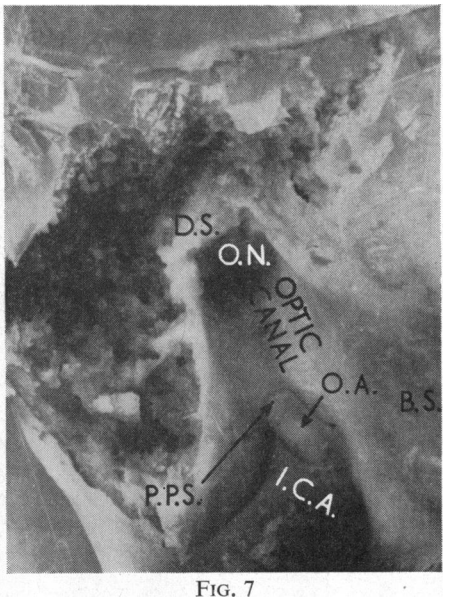


FIG. 7

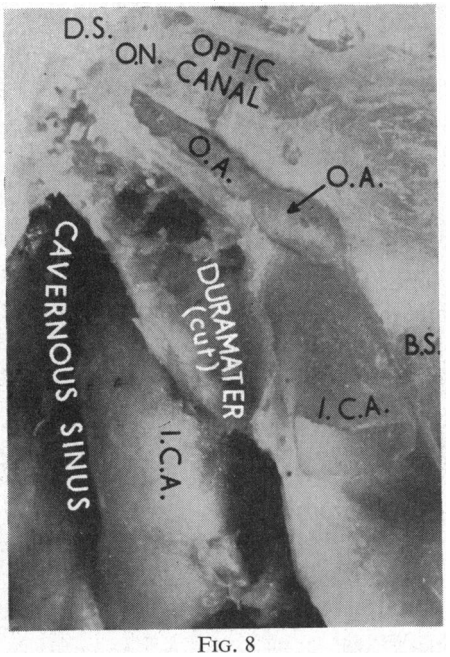


FIG. 8

FIGS 6, 7, 8.—Three stages in exposure of left ophthalmic artery.

Fig. 6 shows structures as seen intra-cranially, with optic canal intact.

In Fig. 7 the optic canal is opened and that part of the optic nerve has been cut. The ophthalmic artery is seen penetrating the dural sheath of the optic nerve.

Fig. 8 shows the intra-cranial and intra-canalicular course of the artery with cavernous and cerebral portions of the internal carotid artery.

carotid artery pierced the dura (Figs 13, 15), and in one the connexion between the ophthalmic and internal carotid arteries had disappeared (Fig. 3F). In the other two specimens, the artery arose just as the internal carotid artery was piercing the dura: in one the origin lay partly in the sub-dural space and partly within the dura; in the other the ophthalmic artery carried a thin prolongation of dura over its sub-dural course. When the

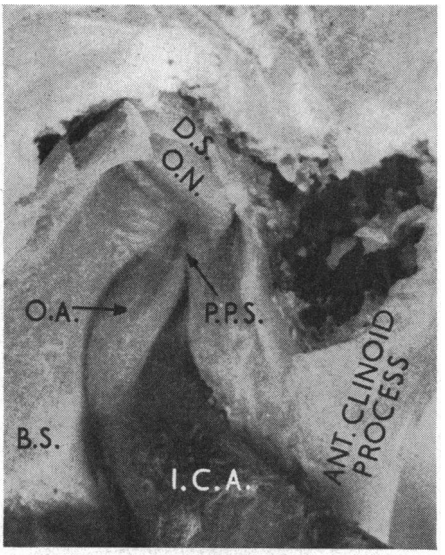


FIG. 9.—Right optic canal partially opened; the ophthalmic artery is seen penetrating into the dural sheath of the optic nerve.

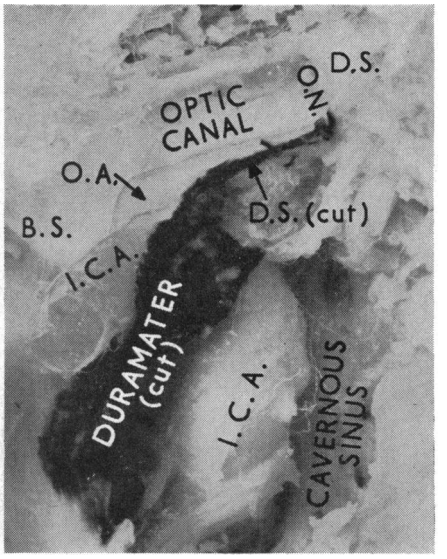


FIG. 10.—Right intra-cranial and intra-canalicular course of the ophthalmic artery with cavernous and cerebral portions of the internal carotid artery.

ophthalmic artery arose from the internal carotid artery outside the sub-dural space, the condition was right-sided in six specimens and left-sided in two.

When the origin was extra-dural, it was usually close to the point where the internal carotid artery pierced the inner layer of dura from the cavernous sinus (Figs 13, 14), but in one specimen it was very deep down in the cavernous sinus. In these specimens no evidence of the ophthalmic artery was seen intra-cranially on removing the optic nerve, except for an occasional small bulge, until the overlying dura was removed. When the origin was sub-dural, however, the ophthalmic artery was always clearly seen on lifting up the optic nerve from the internal carotid artery.

The ophthalmic artery arose from the supero-medial aspect (21 specimens), antero-medial aspect (30 specimens), antero-superior aspect (1 specimen), or medial aspect (4 specimens) of the bend of the internal carotid artery.

Sometimes the origin and/or initial part of the ophthalmic artery was closely related to the body of the sphenoid (Figs 5, 6, 9, 17, 19, 20). The internal carotid artery was very intimately related to "P", and the ophthalmic artery usually arose at a point after the internal carotid had emerged from beneath "P", so that its initial course was intimately related to the proximal part of the internal carotid artery, to which it frequently adhered for some distance and then over-rode "P".

Narrowing of the Internal Carotid Artery beyond the Site of Origin of the Ophthalmic Artery.—The calibre of the internal carotid artery usually became smaller about 0·5 cm. beyond the point where the ophthalmic artery branched

FIGS 11–14.—All from one specimen.

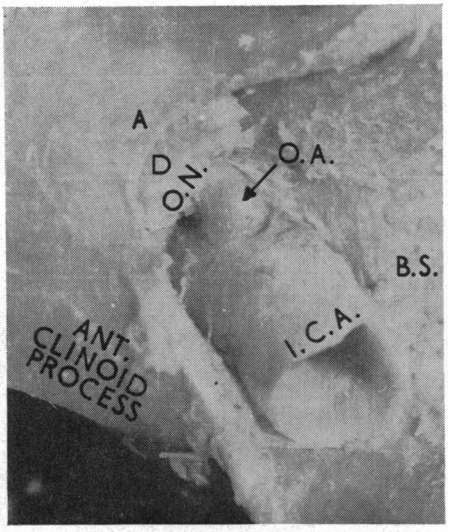


FIG. 11.—Origin and intra-cranial part of left ophthalmic artery.

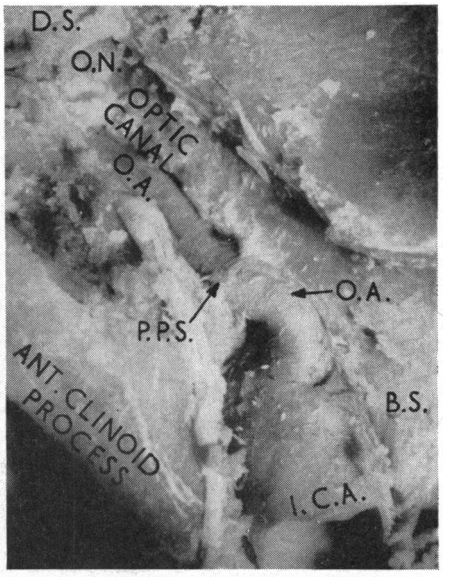


FIG. 12.—Origin and intra-cranial and intra-canalicular course of left ophthalmic artery as seen after opening the optic canal and removing the covering dural sheath.

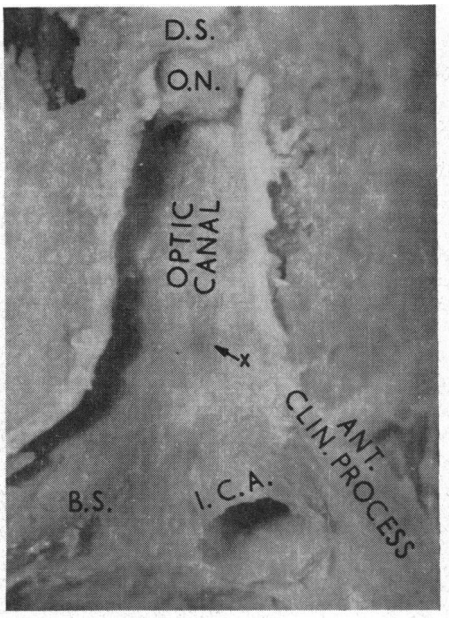


FIG. 13.—The origin of the right ophthalmic artery was extra-dural, so that no ophthalmic artery could be seen, even on opening the optic canal; a thinning of the dural sheath was seen at X, indicating the position of the artery.

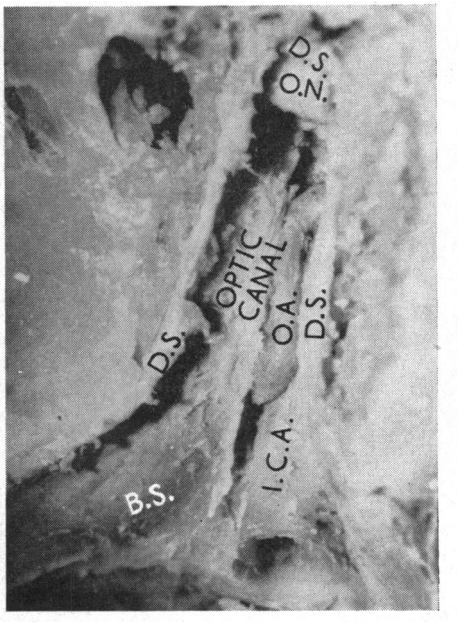


FIG. 14.—Right ophthalmic artery as seen after removing the covering dural sheath.

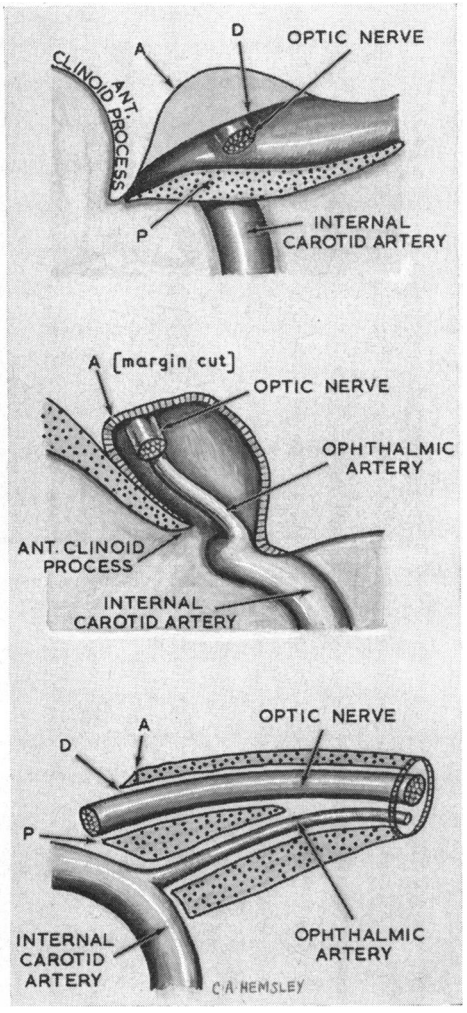


FIG. 15.—The origin of the ophthalmic artery was extra-dural and the artery travelled through a special bony canal.

(*a*) No evidence of the ophthalmic artery even on removal of the dura from "P".

(*b*) Ophthalmic artery as seen after removing the bony lamina, separating the artery from the optic nerve.

(*c*) Schematic representation of the specimen.

FIGS 16–19.—All from one specimen.

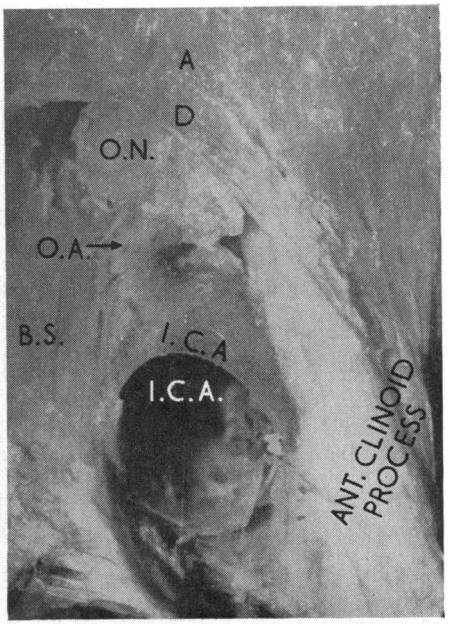


FIG. 16.—Origin and intra-cranial part of right ophthalmic artery, with optic canal intact.

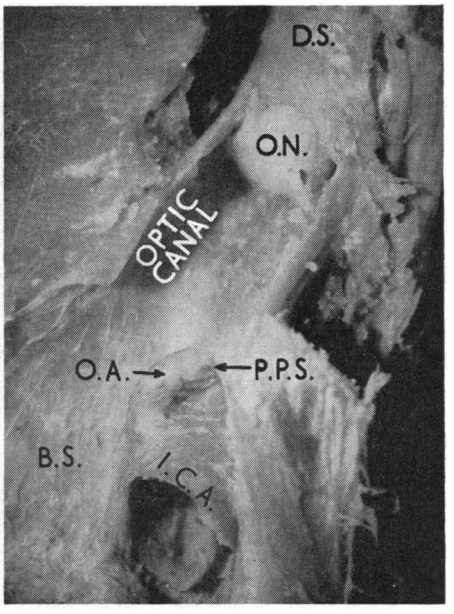


FIG. 17.—On opening the optic canal, in addition to the above, the penetration of the right ophthalmic artery into the dural sheath is seen.

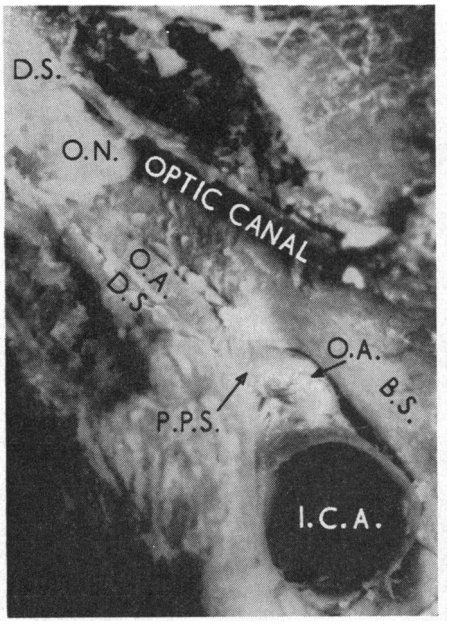


FIG. 18.—Origin and intra-cranial and intra-canalicular course of the right ophthalmic artery as seen on opening the optic canal and removing the covering dural sheath.

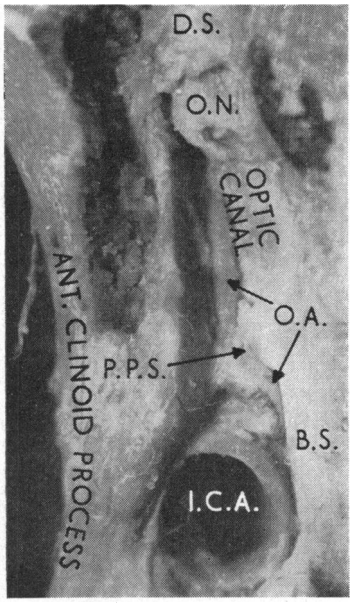


FIG. 19.—Origin and intra-cranial and intra-canalicular course of left ophthalmic artery as seen on opening the optic canal and removing the covering dural sheath.

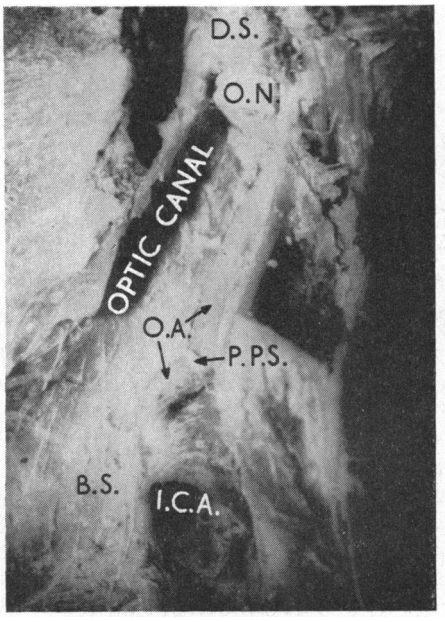


FIG. 20.—Origin and intra-cranial and intra-canalicular course of ophthalmic artery as seen on opening the optic canal and removing the covering dural sheath

off. Before the site of origin the calibre varied from 3·3 to 5·4 mm., and beyond it from 2·4 to 4·1 mm., the difference varying from nil to 1·3 mm. (Tables V and VI).

TABLE V

CALIBRE OF INTERNAL CAROTID ARTERY BEFORE AND AFTER ORIGIN OF OPHTHALMIC ARTERY IN 56 SPECIMENS

Diameter (mm.)		2·4	2·6	2·9	3·0	3·1	3·2	3·3	3·4	3·5	3·6	3·7	3·8	4·0	4·1	4·3	4·4	4·5	4·7	4·8	4·9	5·1	5·2	5·4	Total
No. of Specimens	Before Origin	—	—	—	—	—	—	2	6	—	—	1	6	4	13	4	5	3	2	6	1	1	1	1	56
	After Origin	1	1	2	2	2	3	5	10	3	5	6	5	2	9	—	—	—	—	—	—	—	—	—	56

TABLE VI

DIFFERENCE IN CALIBRE OF INTERNAL CAROTID ARTERY BEFORE AND AFTER ORIGIN OF OPHTHALMIC ARTERY IN 56 SPECIMENS

Difference (mm.)	Nil	0·1	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0	1·1	1·2	1·3	Total
No. of Specimens	5	1	5	5	4	4	12	5	2	6	4	2	1	56

In two specimens, this narrowing was only 0·5 and 0·7 mm. at a point 0·5 cm. from the site of origin, but further on it was more marked, giving the internal carotid artery a somewhat ampoule-like appearance. In one of these specimens, there was a hard cast in the lumen of the internal carotid artery just proximal to the narrowing and in the other there was an oval area of very thin, more or less transparent, wall distal to the origin of the ophthalmic artery. In another specimen, a similar thinning of the medial wall was seen below the origin of the ophthalmic artery; this area was ballooned out so that the lumen of the origin of the ophthalmic artery could be seen through it and this thinning was closely related to the body of the sphenoid. In yet another specimen, the ophthalmic artery arose at the summit of a small dilatation of the internal carotid artery, and the wall of the latter lateral to the site of origin showed a similar very thin circular area. Sclerotic changes, as described above, were not uncommon, particularly in specimens from the older age group.

In one subject the internal carotid artery was very small on both sides, but the ophthalmic arteries given off were of normal size.

The ophthalmic and internal carotid arteries showed no variation in calibre with age, but in the 4-year-old child the internal carotid arteries were smaller than in the adults (measuring 2·7 and 2·5 mm. proximal to the site of origin of the ophthalmic artery, and 2·5 and 2·1 mm. distal to it on the right and left sides respectively). The lumina of the ophthalmic arteries, however, were almost the same as in the adults (0·9 and 1·0 mm.).

The lumina of the internal carotid arteries were the same on both sides in about 25 per cent. of the specimens, and in the remainder it varied.

Calibre of the Ophthalmic Artery

This varied in different subjects from 0·7 to 1·4 mm. (Table VII).

TABLE VII

CALIBRE OF OPHTHALMIC ARTERY IN 56 SPECIMENS

Diameter (mm.)	0·7	0·8	1·0	1·1	1·2	1·3	1·4	Total
No. of Specimens	4	10	11	11	14	1	5	56

In about 40 per cent. of subjects, the calibre was the same on both sides. The difference in the calibre of the internal carotid artery before and after the origin of the ophthalmic artery was not usually proportional to the calibre of the ophthalmic artery. In only five specimens were the two measurements equal; the narrowing of the internal carotid was greater in eight specimens and less in the remaining 43.

Course of the Ophthalmic Artery

The intra-cranial and intra-canalicular course of the artery is divided into the following parts for descriptive purposes: short limb, angle "a", long limb, angle "b", and the distal part up to the apex of the orbit (Figs 4, 12, 15, 18, 19, 20).

Short Limb.—This was very clearly seen in 52 out of the 56 specimens studied in detail (Figs 4, 6, 9, 11, 12, 16, 17, 18, 19, 20), and varied from 0·7 to 2·7 mm. in length, the average being about 1·4 mm. (Table VIII).

TABLE VIII

LENGTH OF SHORT LIMB IN 52 SPECIMENS

Length (mm.)	0·7	1·1	1·2	1·4	1·5	1·6	1·8	1·9	2·1	2·5	2·7	Total
No. of Specimens	2	4	1	22	2	3	5	4	6	1	2	52

In twelve subjects the distances were equal or nearly equal on both sides and in the rest they varied widely.

The short limb took many different directions (Table IX, overleaf). In the three children studied, the direction was forwards and horizontally in five arteries and upwards with a slight forwards and lateral inclination in the sixth. In most subjects the direction was not the same on both sides.

TABLE IX
DIRECTION OF SHORT LIMB IN 52 SPECIMENS

Direction	Number of Specimens
Forward and horizontally, parallel with inferior surface of optic nerve	17
Forward, with slight upward inclination	16
Forward and medially	2
Forward, medially, and slightly upward	1
Forward, downward, and slightly laterally	1
Forward and laterally	3
Forward, laterally, and upward	2
Upward, and slightly forward and laterally	3
Upward and forward	4
Upward, forward, and medially	2
Undetermined	1
Total	52

In one specimen the direction could not be determined because the short limb was swollen and ballooned out just distal to the site of origin of the ophthalmic artery, and the superior aspect showed a very much thinned area, through which the opening of the ophthalmic artery into the internal carotid artery could be clearly seen.

The short limb usually formed part of the intra-cranial section of the ophthalmic artery (Figs 5, 6, 11, 16). In five specimens, however, it was intra-canalicular and in two it was partly intra-cranial and partly intra-canalicular.

Angle "a".—This is the point where the short limb bends to form the long limb (Figs 4, 6, 12, 16, 17, 18, 19, 20). It varied in different specimens and was ill-defined in five of the 52 specimens in which the short limb was clearly seen. In fourteen subjects it was equal on both sides. The approximate size is shown in Table X. The fact that, in all the three children of the series, the angle was about 135° suggests that this angle may have some relationship with age, but no definite conclusion is possible because of the small number of children examined.

TABLE X
SIZE OF ANGLE "a" IN 52 SPECIMENS

Angle "a"	Ill-defined	90°	110°	120°	135°	150°	Total
No. of Specimens	5	21	3	7	14*	2	52

* Including all the three children.

The relative positions of angle "a" and the inferior surface of the optic nerve are shown in Table XI (opposite).

There was no definite relationship between the position of angle "a" with regard to the optic nerve and the distance between the point of origin of the

ophthalmic artery and the optic canal, but the angle tended in some cases to shift towards the lateral side of the nerve as the point of origin drew nearer to the optic canal.

TABLE XI

RELATIVE POSITIONS OF ANGLE "a" AND INFERIOR SURFACE OF OPTIC NERVE IN 52 SPECIMENS

Relationship of Angle "a" with Optic Nerve	No. of Specimens
Projecting medial to nerve	2
Under medial border of nerve	13
Under medial part of nerve	23
Under centre of nerve	10
Under lateral part of nerve	2
Under lateral border of nerve	2
Total	52

Long Limb.—This was nearly always present, starting at angle "a" and being marked off from the distal part of the ophthalmic artery by angle "b" (Figs 4, 12, 18, 19, 20). In eleven (six of them from three subjects) out of the specimens studied in detail, no angle "b" was seen and the long limb was directly continuous with the distal part.

When the ophthalmic artery arose in the sub-dural space, the short and long limbs usually ran in the sub-dural space throughout their length (Figs 4, 7, 9, 12, 17, 18, 19, 20), but very rarely the long limb ran partly in the sub-dural space and partly within the dural sheath. Its length varied from 1·4 to 5·2 mm. and it was the same on both sides in only one subject. The lengths in 45 specimens are given in Table XII.

TABLE XII

LENGTH OF LONG LIMB IN 45 SPECIMENS

Length (mm.)	1·4	1·5	1·6	1·8	2·0	2·1	2·5	2·7	2·9	3·0	3·3	3·4	3·6	3·8	4·1	4·4	5·2	Total
No. of Specimens	6	1	1	2	1	7	2	10	1	2	1	3	2	1	3	1	1	45

The long limb was directed forwards and laterally in 41 of the 45 specimens; the lateral inclination sometimes corresponded with that of the optic nerve, so that the two ran parallel, but it was usually slightly more marked than in the optic nerve.

In thirteen of the 41 specimens, the lateral deviation was more pronounced than the forward direction.

In two other specimens, the limb ran laterally, in one it ran laterally and upwards, and in yet another directly forwards.

It usually ran horizontally, parallel with the inferior surface of the optic nerve, but at times it was inclined slightly downwards. These findings were confirmed in the fifty additional specimens observed with the naked eye.

Angle "b".—This comes between the long limb and the distal part of the ophthalmic artery (Figs 4, 12, 18, 19, 20). It was usually situated at the point where the ophthalmic artery penetrated the dural sheath of the optic nerve (30 specimens), sometimes a little posterior to this point (10), and rarely anterior to it (1). In four specimens the ophthalmic artery arose and ran extra-durally, and in eleven angle "b" was absent. It lay below "D" in eleven specimens, posterior to "D" in six, and intra-canalicularly in 28. Thus, in seventeen specimens, both the short and long limbs were intra-cranial, while in the rest they were partly intra-cranial and partly intra-canalicular.

Angle "b" varied in size from 90° to 210° (Table XIII).

TABLE XIII
SIZE OF ANGLE "b" IN 56 SPECIMENS

Angle "b"	90°	120°	135°	150°	170°	210°	Absent	Total
No. of Specimens	2	1	15	14	12	1	11	56

In nine subjects angle "b" was the same on both sides.

Angle "b" lay under the lateral part of the optic nerve in 29 specimens, under the centre of the nerve in nine, and under the lateral border in six; it projected lateral to the nerve in one. There was no definite relationship between the sites of angles "a" and "b" in the same artery; it was usually seen that, if angle "a" was situated more medially, angle "b" also moved medially; *e.g.* when angle "b" was under the centre of the optic nerve, angle "a" was usually under the medial border.

Point of Penetration of Dural Sheath of Optic Nerve by Ophthalmic Artery

When the artery arose in the sub-dural space, it always pierced the dural sheath of the optic nerve on its inferior aspect (Figs 4, 7, 9, 12, 17, 18, 19, 20). This penetration, as seen in fifty specimens with sub-dural origin, occurred under the lateral aspect of the nerve in 36 specimens and under the centre in fourteen specimens. It occurred in the optic canal in 34 specimens, under the dural margin in ten, and intra-cranially in six. When the penetration was intra-canalicular, it was posterior to "A" in thirteen specimens, inferior to "A" in seven, and anterior to "A" in fourteen (the distance varying from 0·7 to 2·7 mm.). In two of these specimens the artery, although covered by a thin extension of the dural sheath right from its origin, finally entered the dural sheath distally.

In the specimens in which the ophthalmic artery was extra-dural, it had no chance of entering the sub-dural space (Figs 13, 15).

The ophthalmic artery ran within the substance of the dural sheath until it emerged at the apex of the orbit, which it usually entered at the infero-lateral aspect of the optic nerve.

Intra-cranial Course of the Ophthalmic Artery

This section extends from the point of origin to "D". In seven specimens the intra-cranial section was absent, and in three of these the ophthalmic artery was extra-dural. The length of the intra-cranial section was very variable (Table II). In four specimens, only the short limb was intra-cranial and in the rest the whole of the short limb and a part or the whole of the long limb was intra-cranial (in five of these even a part of the ophthalmic artery distal to the long limb was intra-cranial).

The sub-dural part of the ophthalmic artery was always attached to the under surface of the optic nerve by a loose meshwork of vascular connective tissue. In about 85 per cent. of the specimens, the whole of the intra-cranial course lay in the sub-dural space, in about 10 per cent. it lay partly in the sub-dural space and partly within the substance of the dural sheath, and in 5 per cent. it was extra-dural.

Intra-canalicular Course of the Ophthalmic Artery (Table XIV).

This section lies in the optic canal, extending from "D" to the orbital opening. It ran forwards with a varying degree of lateral inclination; in some specimens it was parallel with the axis of the optic nerve and in others the lateral deviation was slightly more marked. Very rarely it ran forwards only or forwards and medially. The intra-canalicular section usually lay partly in the sub-dural space (0·3–4·8 mm.) and partly within the substance of the dura, or less commonly wholly within the dural sheath with no sub-dural course.

TABLE XIV

RELATIONSHIP OF INTRA-CANALICULAR COURSE OF OPHTHALMIC ARTERY WITH OPTIC NERVE IN 56 SPECIMENS

At Cranial End of Optic Canal	At Orbital End of Optic Canal	No. of Specimens
Inferior and lateral	Inferior and lateral	36
Inferior and medial	Inferior and lateral	2
Inferior and lateral	Inferior and medial	4*
Inferior to centre	Inferior and medial	1
Inferior to centre	Inferior and lateral	6
Inferior and lateral	Inferior to centre	3
Inferior to lateral part of nerve and then to centre of nerve in middle of optic canal	Inferior and lateral	4
Total		56

* In one of these specimens the ophthalmic artery arose extra-durally and ran in a separate bony canal.

This section of the ophthalmic artery was usually related to the inferior and lateral aspect of the optic nerve (Figs 4, 8, 10, 12, 14, 18, 19, 20), but its position sometimes varied at the beginning and end of the optic canal.

In four out of five specimens in which the ophthalmic artery entered the orbit at the inferior and medial aspect of the optic nerve, the artery crossed under the optic nerve during its intra-orbital course.

In three specimens in which the ophthalmic artery arose extra-durally (two of them from one subject), it entered the orbit from the cranial cavity in a separate bony canal enclosed in a dural covering (Fig. 15C). This canal was separated from the optic canal by a thin bony lamina, and the dural covering of the artery joined the dural sheath of the optic nerve on its infero-lateral aspect near the orbital end of the canal.

In one specimen the right ophthalmic artery entered the orbit through the most medial part of the superior orbital fissure medial to the oculomotor nerve; it then lay against the infero-lateral aspect of the nerve and thereafter ran the usual intra-orbital course.

Very rarely an angle "c" was seen in addition to angles "a" and "b", so that a third limb appeared in addition to the usual short and long limbs.

Discussion

An exhaustive study of the literature reveals many lacunae and controversies regarding the origin and intra-cranial and intra-canalicular course of the ophthalmic artery. Classical investigations in this field include those of Meyer (1887), Whitnall (1932), Sudakevitch (1947), Böck and Schwarz-Karsten (1953, 1955), and Linc, Puzanova, and Puzanov (1955).

Cranial Opening of Optic Canal.—Whitnall (1932) and Wolff (1954) have described the margin "A" lying anterior to "P". Sudakevitch (1947) found "A" lying anterior to "P" in 90 per cent., and "A" and "P" in one vertical line in the remaining 10 per cent. of 103 cases examined. In the present series, "A" was 0·6 to 7·3 mm. anterior to "P" in 82·1 per cent., "A" and "P" in one vertical line in 5·4 per cent., and "P" 1·4 to 4·1 mm. anterior to "A" in 12·5 per cent.

The prolongation of a fold of dura behind "A", called the "falciform fold" (Figs 2 and 6), has been described by Whitnall (1932) and Wolff (1954). Whitnall (1932) found the fold extending backwards for a few millimetres, and Wolff (1954) thought that it filled up the distance between "A" and "P". This margin ("D") was always seen to extend 0·5 to 6 mm. posterior to "A". The extension backwards of "D" was unrelated to the distance between "A" and "P"; in 64.3 per cent. "D" was anterior to "P", in 28·6 per cent. "D" was posterior to "P", and in 7·1 per cent. "D" and "P" lay in the same vertical plane.

Intra-cranial Part of Optic Nerve.—The length of this section from "A" to the optic chiasma is usually given as 10 mm. (Whitnall, 1932; Duke-Elder, 1932; Wolff, 1954), Whitnall (1932) adding that it varied from 3 to 16 mm. In the present series this measurement varied from 6·2 to 16·5 mm. in adults, and in a child aged 12 years it was 2·7 mm. on one side and 3·5 mm. on the other. In the present investigation, the optic canal has been taken as extending forwards not from "A", as by other authors, but from "D". Thus, by our calculations, the intra-cranial length of the nerve from "D" to the optic chiasma varied from 2·1 mm. to 15·1 mm. (Table I). No definite relationship was seen between the length of the intra-cranial part of the optic nerve and the distance between the origin of the ophthalmic artery and the optic canal, but there was a tendency for the ophthalmic artery to arise more and more posteriorly where the intra-cranial optic nerves were longer. This, however, was by no means universal and there was no regular proportion between the two.

This part of the optic nerve was flattened from above downwards. Adhesions of the nerve to the dural sheath in the optic canal have been described by Schwalbe (1887), Pfister (1890), Whitnall (1932), and Wolff (1954). Schwalbe (1887) and Whitnall (1932) described these adhesions on the superior part of the nerve and Pfister (1890) stated that they might occur anywhere in the circumference of the nerve, but most commonly in the region where the ophthalmic artery was embedded in the dural sheath, *i.e.* on the infero-lateral aspect. In the present series well-marked adhesions were usually seen; these were situated all round the nerve and were usually most marked on the inferior aspect.

Ophthalmic Artery.—Haller (1781) gave a comprehensive description of the history of the ophthalmic artery, and Arnold (1847) a masterly description of its origin and course:

> The arteria ophthalmica arises from the convexity of the fourth arch of the internal carotis, immediately after the penetration of the same through the hard skin. It runs through the foramen, first on the lower and then on the outer side of the optic nerve into the orbit...At the beginning it is between the optic nerve and its sheath, then perforates the latter, comes to lie between the origin of the lateral rectus ocular muscle and the lateral side of the optic nerve.

Origin of the Ophthalmic Artery.—All the authors who have described the ophthalmic artery have said that it arises from the internal carotid artery between the anterior clinoid process and the body of the sphenoid, after the internal carotid has pierced the dura of the cavernous sinus. Duke-Elder (1932) and Whitnall (1932) stated that it might arise from the internal carotid before it had pierced the dura.

Whitnall (1932) stated that the artery arose from the medial side of the fourth part of the internal carotid, being the last branch from it before it

terminated in the anterior and middle cerebral arteries. According to Wolff (1954), the ophthalmic artery arose as a vertical branch from the medial side of the convexity of the fifth bend of the internal carotid, just after the latter had penetrated the dura of the cavernous sinus, and was situated medial to the anterior clinoid process and below the middle of the optic nerve. Böck and Schwarz-Karsten (1953, 1955) found that the ophthalmic artery arose from the antero-medial aspect of the internal carotid artery immediately after it had penetrated the dura. Streiff and Monnier (1946) stated that it arose from the convexity of the first arch of the carotid siphon. Linc and others (1955) said that it arose in the region of the dorsal end of the first arch of the siphon. On the other hand, Lyle (1956, 1958) found (in some thirty autopsies) that the ophthalmic artery arose from the internal carotid artery extradurally in a "goodly number", and that it then passed forwards to the optic foramen without entering the sub-dural space; he thus excluded the possibility of any supply to the intra-cranial part of the optic nerve and optic chiasma from the ophthalmic artery.

In the present series, the ophthalmic artery was found to arise as the first major branch of the internal carotid artery in 168 out of 170 specimens (Fig. 3A–E). In the remaining two specimens it did not arise from the internal carotid and the only source of blood supply to the orbit was the middle meningeal artery (Fig. 3F, G). Usually (in the 106 specimens of the series), the ophthalmic artery arose from the internal carotid when the latter had just emerged from the cavernous sinus by penetrating the dura and was lying in the sub-dural space (Figs 4, 5, 6, 7, 8, 9, 10, 11, 12, 16, 17, 18, 19, 20). In 6·6 per cent. it arose distal to this site but less than 1 mm. away from it, and in 7·5 per cent. it arose closely proximal to it (Figs 13, 14, 15). In 1·9 per cent. it arose just as the internal carotid artery was penetrating the dura, so that it was partly extra-dural and partly sub-dural, the extra-dural origin being three times more common on the right side than on the left.

The ophthalmic artery arose from the antero-medial surface of the internal carotid in 53·6 per cent. of specimens, from the supero-medial aspect in 37·5 per cent., from the medial surface in 7·1 per cent., and from the antero-superior surface in 1·8 per cent. The initial part of the ophthalmic artery was seen to be intimately related to the proximal part of the internal carotid artery (Figs 4, 7, 8, 9, 10, 17, 18, 19), to which it was at times adherent, before riding over the "P" margin.

The narrowing of the calibre of the internal carotid artery beyond the point of origin of the ophthalmic artery has been described by many authors. In ten specimens, Whitnall (1932) found that the diameter of the internal carotid was 5·4 mm. when it entered the cavernous sinus and 3·8 mm. at a distance of 0·5 cm. distal to the origin of the ophthalmic artery, the diameter of which was 1·5 mm. Duke-Elder (1932) gave similar dimensions for the internal carotid and ophthalmic arteries, and remarked that the narrowing of the

internal carotid was proportional to the cross-section of the ophthalmic artery. Sudakevitch (1947) found that the difference in calibre of the internal carotid artery before and after the origin of the ophthalmic artery was usually 2 to 3 mm. and not more than 4 mm., though it was 5 to 8 mm. in five out of his 103 specimens. In the present series, the lumen of the internal carotid artery before and after the origin of the ophthalmic artery was 3·3 to 5·4 mm. and 2·4 to 4·1 mm. respectively; the difference in calibre ranging from nil to 1·3 mm. The lumen of the ophthalmic artery was 0·7 to 1·4 mm. in diameter and no correlation between the narrowing of the internal carotid and the diameter of the ophthalmic artery was seen. Whitnall (1932) suggested two explanations for the diminution in calibre of the internal carotid. He thought that, because the ophthalmic artery branched off from the internal carotid at right-angles and at once turned to lie almost parallel with the latter, the main stream of the internal carotid would tend to suck blood out of the ophthalmic artery rather than to force blood into it. The narrowing of the internal carotid, however, would tend to dam up the main blood stream and force the blood back into the ophthalmic artery; another advantage of this reduction in calibre might be that it reduced the direct impulse of the arterial pulsation on the brain. Duke-Elder (1932) gave the same reasons for the narrowing of the internal carotid artery, and stated that it would help to ensure an adequately high arterial pressure in the eye.

Böck and Schwarz-Karsten (1953, 1955) also pointed out that the ophthalmic artery, because of its acute angle with the internal carotid at its origin, ran against the direction of the blood flow in the internal carotid. They described certain peculiarities in the arterial wall at the site of origin based on a study of serial sections of eleven subjects of various ages. They demonstrated the presence of spiral "cushions" composed of smooth muscle and elastic tissue which were produced by a thickening of the intima:

(*i*) A "spiral cushion" like the spiral ridge of a screw at the angle of origin;

(*ii*) An "ophthalmic cushion" running almost vertically in the proximal part of the ophthalmic artery;

(*iii*) A "cushion" seen within the internal carotid itself.

They were unable to ascribe a definite functional significance to these cushions in the haemodynamics of the artery.

The syntopical relation of the origin of the ophthalmic artery with the optic nerve has been variously described by various workers. Janošík (1900), Testut (1911), Spaltenholz (1920), Whitnall (1932), Woerdeman (1948), Wood Jones (1949), Ivanov (1949), Schaeffer (1953), Borovanský (1953), Grant (1958), Johnston, Davies, and Davies (1958), and many others have shown the site of origin as lateral to the optic nerve in their schematic diagrams. Tandler (1926) and Benninghoff (1942) described it as medial to the nerve. Zuckerkandl (1904), Rouvière (1924), and Sudakevitch (1947) described it as

inferior to the nerve. Hollinshead (1954) said that it lay under the nerve and might be medial to it. Fawcett (1895), Kershner (1943), and Wolff (1954) described it as inferior to the middle of the nerve. Linc and others (1955) found it under the nerve in 60 per cent., medial to it in 26·7 per cent., and lateral to it in 13·3 per cent. of cases. The appearances in the present series are shown in Table IV.

Abnormal Origins of the Ophthalmic Artery.—These depend upon the anastomoses established by the ophthalmic artery with adjacent vessels. Krause (see Henle, 1868) stated that "the varieties originate through abnormal development of normal anastomoses". Meyer (1887) confirmed this principle by observations and tried to explain the various abnormalities of the ophthalmic artery on this basis. If the initial part of the artery does not develop normally or having developed normally is subsequently destroyed (as described by Sudakevitch, 1947: p. 93 below), then one of the anastomoses with adjoining vessels becomes more prominent and conveys blood to the bed of the ophthalmic artery. These cases will naturally show an abnormal origin and even an abnormal course depending upon the artery with which the anastomosis is established.

To understand these variations it is necessary to consider the various anastomoses of the ophthalmic artery (described very well by Meyer, 1887; Quain, 1892; Tichomiroff, 1900):

(*i*) Between the middle meningeal artery and the lacrimal artery;

(*ii*) Between the angular branch of the facial artery and the dorsal nasal branch of the ophthalmic artery;

(*iii*) Between the infra-orbital branch of the maxillary artery and branches of the ophthalmic artery (particularly the muscular branches);

(*iv*) Between the anterior deep temporal artery and the lacrimal and muscular branches of the ophthalmic artery;

(*v*) Between fine branches from the internal carotid artery going to the superior orbital fissure and similar branches from the ophthalmic.

Thus the ophthalmic artery may arise abnormally through the development of any of these anastomoses. The literature contains evidence of some of these modes of origin, but others remain hypothetical.

(*i*) *Abnormal Origin from the Middle Meningeal Artery.*—This is due to the strong development of the normal anastomosis between the recurrent meningeal branch of the lacrimal artery and the orbital branch of the middle meningeal artery passing through the superior orbital fissure or through a foramen in the greater wing of the sphenoid (as mentioned by Rau, *cited by* Haller, 1781). This anastomosis is normally present during foetal life. The embryonic anastomosis is between the supra-orbital branch of the stapedial artery and the ophthalmic artery. Meyer (1887) found this anastomosis to

be present in all his twenty cases. It becomes stronger when the ophthalmic artery or its parent trunk is weakly developed or completely degenerated.

This abnormality is frequently mentioned in the literature. The blood supply to the orbit may come partially or totally from the middle meningeal artery (Tiedemann, 1824; Blandin, 1834; Dubrueil, 1847; Luschka, 1867; Cruveilhier, 1871; Curnow, 1874; Henle, 1876; Meyer, 1887; Quain, 1892; Musgrove, 1893; Adachi, 1928; Whitnall, 1932; Chanmugam, 1936; Harvey and Howard, 1945; Hollinshead, 1954; Priman and Christie, 1959). Tiedemann (1824) gave an illustration showing that the greater part of the region of the ophthalmic artery was supplied from the middle meningeal artery. Dubrueil (1847) cited two cases in which the middle meningeal artery supplied the ophthalmic artery, and pointed out that the ophthalmic artery might pass through a special foramen or through the superior orbital fissure. Cruveilhier (1871) also mentioned this variation in the origin of the ophthalmic artery from the middle meningeal and quoted one of Dubrueil's cases as an example.

Blandin (1834) mentioned that the ophthalmic artery sometimes divided into two branches which enclosed the optic nerve and then reunited. One of these two branches came in the ordinary way from the internal carotid and the other came from the middle meningeal artery after passing through the superior orbital fissure. Luschka (1867) described a "rare variation" in which on both sides the ophthalmic artery originated as two branches of unequal size, the smaller arising from the internal carotid and the larger from the middle meningeal, and the latter entering the orbit through a special foramen. A similar case was described by Adachi (1928). Priman and Christie (1959) described a case showing a marked enlargement of the orbital branch of the middle meningeal with a greatly diminished diameter of the internal carotid; the normal ophthalmic channel was also present but it was small. Chanmugam (1936) reported a case in which the two trunks supplying the orbit (*i.e.* from the middle meningeal and internal carotid) did not anastomose with one another; the former took the normal course of the ophthalmic artery while the latter supplied only the central retinal artery and the ciliary arteries.

It is very rare for the entire orbit, including the central retinal artery, to be supplied from the middle meningeal artery. The central artery of the retina usually preserves its connexion with the cerebral circulation by arising from the internal carotid even though other branches in the orbit may arise from other sources such as the middle meningeal (Curnow, 1874; Harvey and Howard, 1945). The whole literature has yielded only ten instances. Dubrueil (1847) recorded two cases. Musgrove (1893) reported a case in which all the branches in both orbits, including the central retinal artery, arose from a trunk arising from the middle meningeal artery. A similar bilateral case was seen in a Negro subject by Harvey and Howard (1945).

Whitnall (1932) saw the ophthalmic artery arising from the middle meningeal artery with no trunk from the internal carotid on both sides of a specimen from the Oxford anatomical museum. Hollinshead (1954), in a dissection, saw the ophthalmic artery arising from the middle meningeal artery only. Another doubtful case is that reported by Adachi (1928), who gave no clear description of the origin of the central retinal artery. In all these cases in which the ophthalmic artery was reported as arising from the middle meningeal artery totally or partially, the only abnormality of the internal carotid artery was that reported by Priman and Christie (1959).

Occasionally the lacrimal artery alone may arise from the middle meningeal artery (Haller, 1781; Murray, 1794; Velpeau, 1833; Blandin, 1834; Arnold, 1847; Barkow, 1866; Cruveilhier, 1871; Merkel, 1874; Meyer, 1887; Quain, 1892; Adachi, 1928; Whitnall, 1932; Duke-Elder, 1932; Schaeffer, 1953; Hollinshead, 1954; Johnston and others, 1958). This condition was seen in some of the specimens of the present series also, where on the ophthalmic trunk the site of the missing lacrimal artery was usually represented by one of the usual branches of the latter, *e.g.* the branch to the lateral rectus.

Another anomaly closely related to these variations is the abnormal origin of the middle meningeal artery from the ophthalmic artery instead of from the maxillary artery. Zuckerkandl (1876) described four such cases, and Quain (1892) and Whitnall (1932) described similar conditions. None was seen in the present series.

In all of the 59 specimens in the present series in which the ophthalmic artery was injected with Latex and its branches were studied, the anastomosis with the middle meningeal artery was present (Fig. 3A). The very rare instances in which this was not seen were probably due to lack of proper injection or to breaking the branch rather than to its absence. Latex injected into the ophthalmic artery usually filled the middle meningeal artery and at times the external carotid and even the aorta as well. In four specimens (Fig. 3B, C, D, E), the *main* blood supply to the orbit came from the middle meningeal artery, and the ophthalmic artery had two trunks like those described by Blandin (1834), Luschka (1867), and Adachi (1928). In two specimens (Fig. 3F, G), the *only* source of blood supply to the orbit was the middle meningeal artery and the connexion of the normal ophthalmic trunk with the internal carotid had disappeared; in one of these specimens the intra-cranial and intra-canalicular part was completely missing, and in the other this part was represented by a fibrous cord.

(*ii*) *Abnormal Origin from the Facial Artery.*—There is surprisingly no reference available to an abnormal origin of the ophthalmic artery from the facial artery through an enlargement of the normal anastomosis between the angular branch of the facial artery and the dorsal nasal branch of the ophthalmic artery. This anastomosis is usually strongly developed like that

with the middle meningeal artery. Meyer (1887) said that the conditions for the use of this anastomosis were unfavourable because it would mean reversing the direction of the blood stream in the vessel. Though this anastomosis was invariably present, the ophthalmic artery was never seen to arise from the facial artery in the present series.

(*iii*) *Abnormal Origin from the Infra-orbital Artery.*—There is an anastomosis between the orbital branches of the infra-orbital branch of the maxillary artery, passing through the inferior orbital fissure or infra-orbital groove, and various branches of the ophthalmic artery, particularly the muscular branches, but no instance of the ophthalmic artery arising from the infra-orbital artery can be found in the literature. Winslow (1732), however, wrote as follows:

> The same external carotid, by means of the branch called internal maxillary artery, sends into the orbit through the fissure orbitalis inferior or the spheno-maxillaris, a notable branch, which is distributed in the periorbit, the muscles of the eyeball, in the proper retractor of the upper eyelid, in the fat, in the lacrimal gland, in the conjunctival membranes of the eyeball and the eyelids, in the caruncle, etc. It communicates with the internal carotid.

Haller (1781) commented on this as follows:

> Surely the utterances of Winslow, who had written rather too loosely, that the artery from the spheno-maxillari, which to us is infra-orbital, is sent to the muscles and ball of the eye have been misleading to clinical men.

There is no other mention of the ophthalmic artery arising as a branch of the infra-orbital artery. Meyer (1887) suggested that Winslow probably based his description on one exceptional case. No such mode of origin was seen in the present series, though the anastomosis was very frequently present.

(*iv*) *Abnormal Origin from the Anterior Deep Temporal Artery.*—The anastomosis between the ophthalmic artery and the anterior deep temporal artery through small canals in the zygomatic bone is not usually well developed, and no example is known of the ophthalmic artery arising from this source, although there are a few references in the literature to an abnormal origin of the lacrimal artery from the anterior deep temporal artery (Arnold, 1847; Merkel, 1874). No such case was seen in the present series.

(*v*) *Ophthalmic Artery arising from the Internal Carotid Artery but entering the Orbit through the Superior Orbital Fissure.*—Meyer (1887) described one case in which the ophthalmic artery developed from anastomoses between fine branches from the internal carotid on one side and the ophthalmic on the other side and then passed through the most medial part of the superior orbital fissure close to the posterior root of the lesser wing of the sphenoid. This was merely an anomalous course, because the ophthalmic artery still arose from the internal carotid. Quain (1892) and Wolff (1954) also mentioned that the artery might enter the orbit through the superior orbital fissure.

One such specimen was seen in the present investigation; the ophthalmic artery arose from the internal carotid and entered the orbit through the most medial part of the superior orbital fissure. In another specimen a branch from the lacrimal artery passed out into the cranial cavity through the superior orbital fissure and clearly anastomosed in the lateral wall of the cavernous sinus with a branch from the internal carotid which had arisen after the latter had just entered the sinus (Fig. 21). A similar branch was also seen in another specimen.

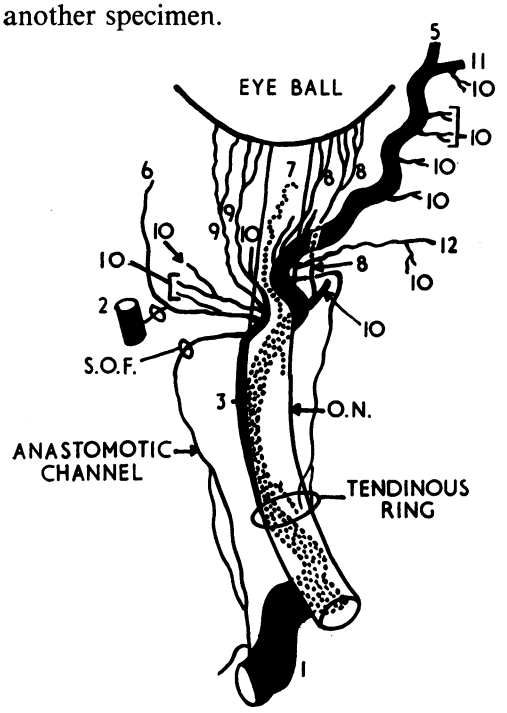


FIG. 21.—Origin, course, and branches of ophthalmic artery. Anastomosis in lateral wall of cavernous sinus between the proximal part of the cavernous portion of the internal carotid artery and a branch from the lacrimal artery passing through the superior orbital fissure.
(8) Medial posterior ciliary artery.
(9) Lateral posterior ciliary artery.
(12) Posterior ethmoid artery.
Other abbreviations as in Fig. 3.

(vi) Other Abnormal Modes of Origin

Middle Cerebral.—Flemming (1895) and Lowrey (1916) reported that the ophthalmic artery might arise from the middle cerebral artery when the ipsilateral internal carotid was absent. In the case cited by Lowrey (1916), the right internal carotid was absent, but the left vertebral artery was larger and so also was the right terminal division of the basilar which supplied the middle cerebral artery in addition to the usual distribution.

Posterior Communicating.—Fisher (1913) found a case in which the ophthalmic artery arose from the posterior communicating artery.

External Carotid.—This may be explained by studying the comparative anatomy of the orbital vessels (Parsons, 1903; Whitnall, 1932; Duke-Elder, 1932, 1958). In the lower animals the ophthalmic artery is derived from the external carotid, but as we ascend the ladder of the animal kingdom the ophthalmic artery tends to arise from the internal carotid instead of the external carotid. In intermediate species, such as the dog, the internal and external ophthalmic arteries arise

from the internal and external carotids respectively, the former supplying the eyeball and the latter the orbit; an anastomotic branch between the two can maintain the intra-ocular circulation from either source (Ellenberger and Baum, 1891; Henderson, 1903; Parsons, 1903). In rabbits the internal ophthalmic artery is smaller than the external (Krause, 1868; Henderson, 1903), and the same is the case in the horse and goat (Zietzschmann, 1912). The anastomosis between the two systems leads to individual variations in origin. The ophthalmic arteries were studied by us in two monkeys; though the pattern was similar to that in man the communication between the lacrimal and middle meningeal arteries was much more prominent. According to Sudakevitch (1947), the ophthalmic artery in pigs and cows terminates in two powerful posterior ciliary arteries behind the eyeball.

Intra-cranial Course of the Ophthalmic Artery

Very little attention has been paid to the details of the intra-cranial and intra-canalicular course of the ophthalmic artery, except by Sudakevitch (1947), Böck and Schwarz-Karsten (1953, 1955), and Wolff (1954).

Tandler (1926), in an illustration, showed the ophthalmic artery directed forwards and horizontally for a short distance from the origin (*cf.* short limb), then running forwards and laterally for a little longer distance (*cf.* long limb) with two bends (*cf.* angles "a" and "b"), and finally running along the infero-lateral aspect of the optic nerve in the optic canal.

Wolff (1954) described first a very short upwards course, then a right-angled bend to run directly forwards for a few millimetres under the medial part of the optic nerve to appear under the medial border, and thereafter a lateral bend (Fawcett, 1895). Böck and Schwarz-Karsten (1953, 1955) said that the artery bends sharply downwards and laterally from the point of origin, with a sharp angle on the lateral side and a flat angle on the medial side. This last observation was confirmed in the present series (Figs 6, 9, 17, 18, 20).

Sudakevitch (1947) stressed what he called "the normal osseo-vascular relationship between the initial part of the ophthalmic artery and the bony canal", with the internal carotid artery, the initial part of the ophthalmic artery, the optic nerve, and the edges of the intra-cranial opening of the optic canal meeting medial to the anterior clinoid process. He visualized this meeting as an equilateral triangle with its base to the front. The upper side was formed by the optic nerve, and the lower side by the upper part of the bend of the internal carotid, and the base was a surface lying at a tangent to the bony edges of the intra-cranial opening of the optic canal (Fig. 22). The origin of the ophthalmic artery lies in this triangle near the base. The relationship of these structures changes with age; the arc of the internal carotid gradually straightens upwards and partly forwards so that the sides of the triangle come closer together and the space occupied by the initial part of the ophthalmic artery is reduced. In these older specimens the internal carotid artery forms an angle rather than an arc and the initial part of the ophthalmic artery moves 2 to 3 mm. backwards from the vertical line which formed a tangent to the anterior edge of this arc. Sudakevitch

divided the initial part of the ophthalmic artery into a short knee and a long knee (*cf.* short and long limbs), the short knee being 2 mm. long and perpendicular to the optic nerve and the long knee forming a tangent to the lower surface of the nerve. This relationship is possible only when the bony edge "A" of the intra-cranial opening of the optic canal is anterior to the bony edge "P". The ophthalmic artery arose from the internal carotid artery 3·6 mm. posterior to "A" in nine out of every ten of his 103 cases, but in every tenth case he found that the two edges "A" and "P" were in one vertical line, and in these the ophthalmic artery branched off from the internal carotid below "A" and "A" formed a bony roof over it (Fig. 22). The

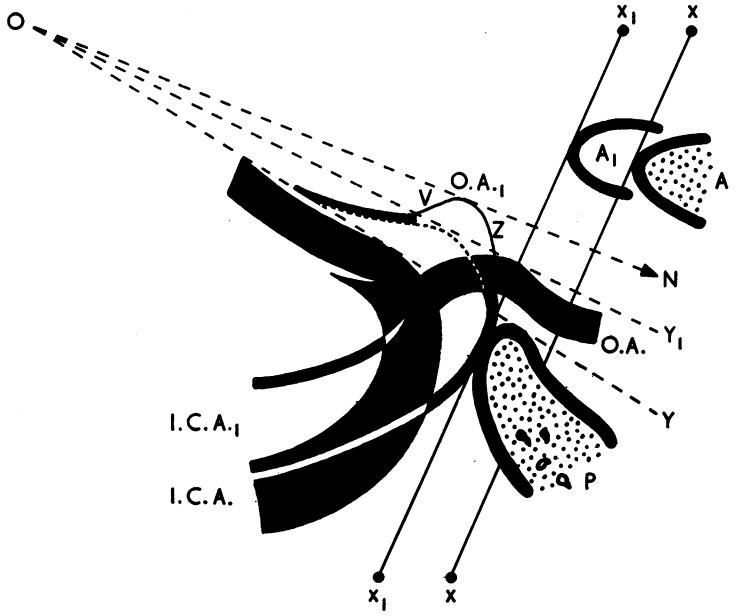


FIG. 22.—(From Sudakevitch, 1947).
I.C.A. and O.A.—Silhouette of internal carotid artery and ophthalmic artery in a child.
I.C.A.$_1$ and O.A.$_1$.—The same in an adult.
A and A_1.—The upper bony edge of the intra-cranial opening of the optic canal.
P.—The lower bony edge.
x, x and x_1, x_1.—Surface tangents to upper and lower edges of opening of canal—the surface tangent to the upper bony edge is the base of the triangle.
ON upper side, and OY lower side of the triangle in childhood.
ON upper side and OY_1 lower side in adults.
V short knee and Z long knee of first part of ophthalmic artery in an adult.

origin of the ophthalmic artery cannot be seen in such cases by lifting up the optic nerve in the ordinary way because of the overhanging of the bone, and hence, according to Sudakevitch, the initial part of the ophthalmic artery will be squeezed into the narrow space between the optic nerve and the upper surface of the internal carotid (between the two sides of the narrowed triangle). He said that this caused changes in the external architecture and lumen of the internal carotid and ophthalmic arteries, with associated

interference with the function of the ophthalmic artery. Whereas the difference in calibre of the internal carotid artery before and after the point of origin of the ophthalmic artery was 2 to 3 mm. and never more than 4 mm., in five of these ten special cases the difference was 5 to 8 mm. This was due to the increased size of the internal carotid artery before the origin of the ophthalmic artery, so that in one case it had the appearance of an ampoule. The ophthalmic artery in these cases showed additional bends in the first part; the lumen in its initial part was narrowed, and in two the short knee showed only a capillary lumen, which caused an incomplete interruption of the intra-cranial part of the ophthalmic artery. This intra-cranial interruption and the interruption in the intra-orbital part reported by Meyer (1887) were thought by him to be embryonic. The intra-cranial interruption may also appear with senile arteriosclerosis. In such cases the blood supply to the orbit is maintained through the various anastomoses of the ophthalmic artery, in accordance with the Law of Krause, who regarded this as the explanation of the various anomalous sites of origin of the ophthalmic artery from places other than the internal carotid. Sudakevitch (1947) saw a case with normal osseo-vascular formations in which the artery suddenly ended in three branches diverging at right-angles; he called this a "diffused form" of the ophthalmic artery.

Linc and others (1955) pointed out that the ophthalmic artery may be compressed between the internal carotid and the optic nerve when the latter cannot deviate upwards because of a superimposed fold of dura mater. The pulse wave on the carotid artery may still further reduce the space between the artery and the nerve. Cerebral angiography has shown that the ophthalmic artery is not filled if the injection is made during a compression phase. This acts as a regulatory mechanism to lower the systolic blood pressure and so avoid any damage to the eyeball from a high systolic pressure. This mechanism is comparable to the rete mirabile situated in the course of the ophthalmic artery in many mammals. These authors have calculated by haemodynamics that the carotid siphon is a mechanism to decrease the blood pressure in the ophthalmic artery. If the site of origin of the ophthalmic artery is not situated beneath the optic nerve, this protective mechanism of the carotid siphon is not so effective, and this may explain the different pressures reported on ophthalmodynamometry by various workers: *e.g.* Bailliart (*cited by* Linc and others, 1955) 25–30 mm. Hg; Duverger and Barré (1920) 50–60 mm. Hg; Bliedung (1924) 68–75 mm. Hg; Abramowicz (1927) 70–90 mm. Hg.

In the present series the picture was quite different from that described by Sudakevitch (1947). No particular difference in the siphon of the internal carotid artery was seen in children, except that it was slightly opened out, thus resembling the "infantile" type of Curtis (1951), though there were individual variations in shape. The site of origin did not vary with age

The short limb was seen in 52 of the 56 specimens (92·9 per cent.) and was

bilaterally absent in the other four, in one of which the ophthalmic artery arose anterior to "D", and "P" was anterior to "A". The length of the short limb varied from 0·7 to 2·7 mm. (usually 1·4 mm.) and was the same on both sides in 42·9 per cent. Its direction was never perpendicular, as pointed out by Sudakevitch (1947); it nearly always ran forwards, being parallel with the inferior surface of the optic nerve in about one-third, and showing a variable upwards inclination in about one-half (Table IX). In five of the six specimens from children, the short limb ran parallel with the inferior surface of the nerve, and in the sixth it ran upwards with a forward and lateral inclination, showing no significant difference with age. The relative positions of "A" and "P", and of the site of origin and "A" or "D" did not affect the direction and length of the short limb. The angle "a" varied from 90° (in 45 per cent.) to 150°, and was usually inferior to the medial part or medial border of the optic nerve.

The long limb (1·4 to 5·2 mm. in length) was marked off from the distal part of the ophthalmic artery by the angle "b". It ran horizontally and parallel with the inferior surface of the nerve; it usually ran forwards or sometimes laterally with varying degrees of obliquity and slightly downwards.

Table XV (opposite) shows that the relative positions of "A" and "P" and of the site of origin to "A" and "D" did not affect the origin, short limb, long limb, narrowing of the internal carotid beyond the point of origin of the ophthalmic, or the lumen of the ophthalmic artery in the present series. These findings are unlike those of Sudakevitch (1947). There was no difference with age or sex, nor was any "diffuse" form of the ophthalmic artery seen.

It is not possible, therefore, to attach any significance to the so-called "osseo-vascular relationship" regarded as important by Sudakevitch (1947).

Fawcett (1895) and Whitnall (1932) described the ophthalmic artery as lying medial or lateral to the inferior surface of the optic nerve during its intra-cranial course, depending on whether it arose nearer to or further from the optic foramen. Kershner (1943) found that the artery was closer to the medial than to the lateral border of the nerve in its initial intra-cranial course. Quain (1892) found it lying beneath the optic nerve.

The relationship of the site of origin with the inferior surface of the optic nerve was not affected by the distance between the point of origin and the optic canal in the present series, but it was observed that, when the site of origin was further from the optic canal, it tended to be located below the medial side, and *vice versa*.

Intra-canalicular Course of the Ophthalmic Artery

The artery has usually been described as lying in the optic canal beneath the lateral aspect of the optic nerve, and separated from the latter by a thin sheath of dura in which it is embedded. According to Wolff (1954), the relationship of the artery to the inferior surface of the optic nerve varies at

TABLE XV

SITE OF ORIGIN OF OPHTHALMIC ARTERY AND CALIBRE OF INTERNAL CAROTID RELATED TO THE POSITIONS OF "A" and "P"

Relative Position of "A" and "P"	Percentage of Specimens	Site of Origin of Ophthalmic Artery	Reduction in Calibre of Internal Carotid beyond Point of Origin of Ophthalmic Artery
"A" Anterior to "P"	82·14	Under "D" in one 1·0 to 3·0 mm. anterior to "D" in two 0·4 to 4·8 mm. posterior to "D" in 43 0·7 to 9·4 mm. posterior to "A" in 45 1·6 mm. anterior to "A" in one	0 to 1·3 mm. in about half (41 per cent.) 0·4 to 0·8 mm. in about half (41 per cent.)
"A" and "P" in Vertical Plane	5·36	0·7 to 2·7 mm. posterior to "D" and 3·0 to 5·5 mm. posterior to "A" — in all	0·5 to 1·0 mm. (5·4 per cent.)
"P" Anterior to "A"	12·50	Under "D" in two 2·4 to 2·7 mm. anterior to "D" in two 1·0 to 2·7 mm. posterior to "D" in three 0·7 to 4·1 mm. posterior to "A" in all seven	0·3 to 1·2 mm. (12·5 per cent.)
Total	100	0·4 to 4·8 mm. posterior to "D" in 87·5 per cent. Under D in 5·4 per cent. 1·0 to 3·0 mm. anterior to "D" in 7·1 per cent. 0·7 to 9·4 mm. posterior to "A" in 98·2 per cent. 1·6 mm. anterior to "A" in 1·8 per cent.	0 to 1·3 mm. (100 per cent.)

different levels. According to Fawcett (1895), the artery lies at its origin under the middle of the nerve, and as it runs forwards and the nerve runs forwards and laterally, the artery appears under the medial border of the nerve, and ultimately passes laterally. During its intra-canalicular course, the artery lies within the dural sheath of the nerve, at first below the nerve and then lateral to it, until it emerges from the sheath near its entrance into the orbit. Kopsch (1933) described the artery as lying either latero-caudal or medio-caudal to the optic nerve. Whether the artery, in this part, runs more on the medial or on the lateral side is unimportant according to Meyer (1887). von Haller (1781) once saw the ophthalmic artery passing over the optic nerve in this part of its course, but this was not seen in the present series.

von Haller (1781) quoted Cassebohm (1734) as having described a special bony canal separate from the optic canal through which the ophthalmic artery might pass. A similar special canal was also described by Dubrueil (1847). Meyer (1887) saw no such canal in his series, but Le Double (1903) found

twelve cases reported in the literature which occurred singly and bilaterally and in either sex. White (1924) saw three such cases, and found the artery more commonly grooving the posterior part of the floor of the canal. In eight specimens in the present series, the ophthalmic artery arose extra-durally, and in three of them (two in one subject) it travelled from the cranial cavity to the orbit in a special canal separated by a bony lamina from the optic canal (Fig. 15C). This special canal was lined by dura; it was thought to have been formed by ossification of the fibrous tissue between the ophthalmic artery and the optic nerve (Meyer, 1887; Whitnall, 1932; Wolff, 1954). According to Whitnall (1932) and Wolff (1954), this is a very rare anomaly, and Whitnall called it a "double optic foramen".

Meyer (1887) described the anatomical relationship of the artery and the dura in detail. The ophthalmic artery arises inside the dura and the two layers of dura are fused with one another in the optic canal, but at the orbital end of the canal they separate, the inner layer forming the dural sheath of the nerve and the outer layer the orbital periosteum. Thus the artery lies between the two layers in the orbital cavity, and during its intra-canalicular course it has to penetrate the inner layer of the dura. It passes through this inner layer very gradually, and has often already started to do so at the beginning of the optic canal. It seems that when the ophthalmic artery arises extra-durally in the cavernous sinus (*i.e.* between the outer and inner layers of the dura), it passes between the two layers to enter the orbit and never has a chance to penetrate the inner layer as it normally does.

In the present series, the walls of the ophthalmic artery were seen to be very thin during its course within the substance of the dural sheath. It was, in fact, so thin and transparent that the lumen of the artery was usually seen through it, and it was easily torn on handling. This part of the artery was generally not very much adherent to the surrounding dural sheath in which it lay and to which it was attached by areolar tissue. It could be very easily separated from the sheath and picked up from its bed. The only place where it sometimes adhered was the point of its penetration into the substance of the sheath.

The ophthalmic artery, instead of passing through the optic canal or this separate canal, may also pass through the superior orbital fissure (Meyer, 1887; Quain, 1892; Wolff 1954); this was seen in one of our specimens.

Summary

The origin, and intra-cranial and intra-canalicular course of the ophthalmic artery were studied in 106 specimens of the human orbit. In all except six specimens, the ophthalmic artery arose from the internal carotid. In four it originated by two trunks—one from the internal carotid and the other from the middle meningeal, the latter being more prominent. In the remaining two, it arose from the middle meningeal only. The diameter of the internal carotid artery narrowed beyond the point of origin of the ophthalmic artery.

The intra-cranial and intra-canalicular course of the ophthalmic artery has been sub-divided from the origin onwards into short limb, angle "a", long limb, angle "b", and the part distal to angle "b", and these sections have been studied in detail.

The findings of earlier anatomists are analysed and discussed.

The intra-cranial and intra-canalicular parts of the optic nerve and the cranial opening of the optic canal have also been studied.

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