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Chapter 2

HIGH RESOLUTION MAGNETIC RESONANCE IMAGING
OF NEUROVASCULAR ORBITAL ANATOMY

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INTRODUCTION

Imaging techniques have become an indispensable diagnostic tool in ophthalmology. In most centers, computed tomography is still the method of choice for orbital imaging because of its low costs and excellent depiction of bony details.\textsuperscript{1,2} The resolution in computed tomography within the orbit has been shown to be sufficient to demonstrate structures such as the ophthalmic artery and some of its branches, the superior ophthalmic vein, branches of the frontal nerve, or oculomotor nerves.\textsuperscript{3,4} Compared with computed tomography, orbital magnetic resonance imaging (MRI) provides a better soft-tissue contrast resolution and is capable of multiplanar imaging, but has the disadvantage of poor delineation of bones.\textsuperscript{5,6} Because there is no exposure to ionizing radiation, high-resolution MRI is an excellent tool for anatomical studies in vivo.\textsuperscript{7,8} Additionally, biochemical information may be obtained during the same examination by means of proton magnetic resonance spectroscopy\textsuperscript{9} in the future. Although many papers have been published regarding the diagnosis of orbital space occupying lesions using MRI,\textsuperscript{10-12,14-16} there is not much detailed information about MRI anatomy of the orbit in the literature. There are descriptions of the gross anatomy of the orbit on MRI scans and early surface-coil studies of orbital anatomy.\textsuperscript{11,12,17,18} We find some high resolution MRI scans of the orbit in Dutton's anatomic atlas\textsuperscript{2} and the textbook by De Potter and Shields\textsuperscript{3}; however, a discussion regarding the anatomic interpretation of the structures in the images is not available. In this study, the MRI anatomy of the arteries, veins and cranial nerves of the orbit is described. We do not focus on imaging details of the optic nerve because this has been described previously.\textsuperscript{13,12,18} To facilitate the interpretation of the magnetic resonance images, we briefly recall the neurovascular orbital structures that can be visualized in imaging studies (Figs 1 and 2).

MATERIAL AND METHODS

Six healthy subjects, aged 29 to 32 years, and one 54-year-old patient with chronic oculomotor nerve paralysis on the left side (which minimized motion artifacts) were examined after informed consent had been obtained (n = 7 orbits). Magnetic resonance imaging of the orbit was performed on a 1 Tesla scanner (Impact, Siemens, Germany) using a surface coil with a diameter of 10 cm. T1- weighted images of the orbit were obtained using spin-echo sequences with an echo time (TE) of 15 msec and a repetition time (TR) of 440 to 520 msec. Imaging planes included axial, coronal and oblique-sagittal (parallel to the optic nerve) sections. Contiguous 2- to 3-mm slices were obtained. The field of view in the original images ranged between 140 x 140 mm with a 256 x 256 matrix and 230 x 230 mm with a 512 x 512 matrix, resulting in a pixel size and theoretical spatial resolution of 0.4 to 0.5 mm.
Fig. 1. Three-dimensional reconstruction of orbital vessels. The numbers refer to the nomenclature (see Appendix). A, arteries; B, veins (the superior vorticos veins are not shown). Modified and used with permission.

The acquisition time ranged between 2 and 17 minutes for the different sequences. Most images were taken with closed lids and the eyes in resting position (slight down-gaze).

The structures in the magnetic resonance images were identified by comparison with the collection of histologic sections of the orbit from Koornneef. The collection includes hematoxylin-azophloxin stained 60-μm thin sections and 5-mm thick cleared sections. Furthermore, we analysed the magnetic resonance images by comparison with correlative anatomical cryosections from the literature and spatial reconstructions of orbital anatomy that were based on serial histologic sections.

RESULTS

Arteries

On sagittal images (Fig. 3), the intraorbital portion of the ophthalmic artery appears at the lateral side of the optic nerve, where it branches to the central retinal artery (Fig. 3A). Axial images (Fig. 4) show the further course of the ophthalmic artery: Distal to the lateral knee, it crosses over the optic nerve (Fig. 4E), bends again, and courses forward - first at the medial side of the superior oblique muscle and then between the superior oblique muscle and the medial rectus muscle (Fig. 4F). The tortuous central retinal artery courses forwards inferiorly to the optic nerve and enters its dural sheath approximately 10 to 12 mm behind the globe (Figs. 3A and 4H). At the crossing with the optic nerve, the ophthalmic artery gives off the posterior ciliary arteries on either side of the optic nerve (Fig. 4F). Part of the lacrimal
Fig. 3. Oblique-sagittal T1-weighted magnetic resonance images of the orbit. On T1-weighted images, the orbital fat appears bright (hyperintense), whereas vitreous and cerebrospinal fluid appear dark (hypointense). Muscles, vessels, and nerves are hypointense relative to orbital fat. The numbers refer to the nomenclature (see Appendix). A, imaging plane along the optic nerve (up-gaze, healthy subject) showing the central retinal artery (11) originating from the knee of the ophthalmic artery (10). B, imaging plane along the posterior part of the optic nerve (white arrow) and parallel to the lateral rectus muscle. The presumed inferior division of the oculomotor nerve (36) is situated between the optic nerve and the inferior rectus muscle. The superolateral and inferolateral vorticose veins (33) are also visualized. (Patient with oculomotor nerve paralysis.)

The trunk of the superior ophthalmic vein (SOV) starts just posterior to the reflected part of the superior oblique tendon and courses from anteromedially to posterolaterally, crossing over the optic nerve and superior to the ophthalmic artery (Fig. 4C). Proximal to the junction with the lacrimal vein, the SOV runs posteriorly, directing to the superior orbital fissure (Fig. 4C). In axial images, the diameter of the SOV in the region of the junction with the lacrimal vein was estimated to range between 1.5 and 2.0 mm. Because the margin of the blood vessels in our images was rather ill-defined, exact measurements were not possible. Serial coronal sections show that the SOV traverses the orbit along a connective tissue septum. This septum, called the superior ophthalmic vein hammock, courses from the lateral rectus muscle closely inferior to the superior rectus muscle toward the superomedial orbital wall (Fig. 5B-C). The medial ophthalmic vein, a common variation,24 is seen in one subject coursing parallel to the medial orbital wall just superior to the superior oblique muscle belly (Fig. 4C). In two subjects, an elongated, hypointense structure (Fig. 4H) that originates from the medial rectus muscle and courses inside the muscle cone was observed. It was interpreted as the "veine ophthalmique moyenne".25 We were unable to correlate this structure to any other known structures in the anatomic or histologic sections. Less likely, it may represent the inferior branch of the oculomotor nerve supplying the medial rectus muscle. Branches of the inferior ophthalmic vein following circularly coursing connective tissue septa are seen in the inferomedial orbit (Fig. 4I). The trunk of the inferior ophthalmic vein is appreciated at the lateral side of the inferior rectus muscle (Fig. 4I). The vorticose veins can be seen in appropriate sections. For example, parasagittal sections temporally to the anterior part of the optic nerve demonstrate the superior and inferior temporal vortex vein (Fig. 3B). The medial and the lateral collateral veins connecting the inferior ophthalmic vein with the superior ophthalmic vein are visible in axial sections (Fig. 4F-H).
Fig. 4. T1-weighted axial images (left orbit, healthy subject). The numbers refer to the nomenclature (see Appendix). A, section inferior to the orbital roof showing the frontal nerve (43) and its branches: the supratrochlear nerve (46) and the medial (44) and lateral (45) branches of the supraorbital nerve. B, section just inferior to the plane of Figure 4A showing the lacrimal nerve (52) running toward the lacrimal gland (arrows). C, section 2 mm inferior to the section of Figure 4B. The superior rectus muscle (2) and the levator muscle (1) are visible. The superior ophthalmic vein (27) traverses the orbit from the trochlea (white arrow) to posterolaterally inside the muscle cone. Lacrimal gland (black arrow). D, section at the level of the trochlea (white arrow). Lacrimal vessels (28, black arrows), presumed nasociliary nerve (47). E, section at a level between the superior rectus muscle and the optic nerve showing the ophthalmic artery (10) crossing over the optic nerve. Anterior and posterior ethmoidal foramen (white arrows). F, section at the level of the optic nerve (ON) showing the ophthalmic artery (OA) (10), the posterior ciliary arteries (13, 18), the dorsal nasal artery (21) and the anterior ethmoidal artery (19). Structure (12) could not be identified with certainty. It may represent a partial volume averaging or anastomosis of the OA.\footnote{22}
meningeal branch\textsuperscript{20,27-29}. Presumed posterior ethmoidal artery (small white arrow). G, section at the level of the optic nerve showing the presumed abducens nerve\textsuperscript{29} between the optic nerve and the lateral rectus muscle,\textsuperscript{31,32} the medial and lateral collateral veins,\textsuperscript{31,32} and presumably the ciliary ganglion\textsuperscript{30} anterior to the knee of the ophthalmic artery.\textsuperscript{30} Superior orbital fissure (SOF). H, section at the level of the horizontal rectus muscles, inferior to the posterior optic nerve, showing the central retinal artery (11) and the presumed "veine ophthalmoique moyenne" (34), a variation that originates from the medial rectus muscle to drain into the cavernous sinus.\textsuperscript{29} I, section through the posterior part of the inferior rectus muscle (3) and the inferior orbital fissure (IOF), showing the inferior ophthalmic vein (30), the medial and lateral collateral veins (31, 32), the orbital muscle of Müller (M), and the lacrimal sac (white arrow heads). J, section at the level of the inferior orbital fissure (IOF). The structure (36), which courses along the lateral border of the inferior rectus muscle (3), either represents the branch of the oculomotor nerve supplying the inferior oblique muscle (9) or a muscular branch of the inferior ophthalmic vein. Orbital muscle of Müller (M).

Motor nerves

Because of the crowding of anatomic structures in the orbital apex, the inferior division of the oculomotor nerve cannot reliably be distinguished from other structures. However, in one subject with paralytic atrophy of the rectus muscles, an elongated structure between the optic nerve and the inferior rectus muscle was observed in sagittal magnetic resonance images (Fig. 3B). This was interpreted as the trunk of the inferior division of the oculomotor nerve.

The structure that can be seen on axial images, and more consistently on coronal images at the lateral border of the inferior rectus muscle, most likely represents the branch of the inferior division of the oculomotor nerve to the inferior oblique muscle (Fig. 4J and 5B). Correlative anatomic sections in the frontal plane\textsuperscript{20,23} and spatial reconstructions\textsuperscript{20,24} show the branch of the oculomotor nerve supplying the inferior oblique muscle in this location. On axial images, the abducens nerve may be visible between the optic nerve and the lateral rectus muscle (Fig. 4J). The 2- to 3-mm long, hypointense structure that is situated between optic nerve and lateral rectus muscle just anterior to the lateral knee of the ophthalmic artery and approximately 1 cm anterior to the superior ophthalmic fissure might be the ciliary ganglion (Fig. 4G). The superior division of the oculomotor nerve and the trochlear nerve are not visualized in the magnetic resonance images.

Sensory and Autonomic nerves

The ophthalmic division of the trigeminal nerve branches into the frontal, lacrimal, and nasociliary nerves that can be clearly seen on MRI. The frontal nerve with its three branches (supratrochlear nerve, medial and lateral branch of supraorbital nerve) is noted on axial (Fig. 4A) and coronal (Figs 5B-C) slices superior to the levator palpebrae superioris muscle. The lacrimal nerve is seen in the upper tier of the orbit on axial sections (Fig. 4B). Axial sections at the level of the SOV (Fig. 4D) demonstrate the nasociliary nerve as it travels anteriorly between the superior oblique and medial rectus muscles.

Fig. 5. Coronal T1-weighted magnetic resonance images (right orbit, healthy subject). The numbers refer to the nomenclature (see Appendix). A, imaging plane at the level of the trochea (8 = superior oblique tendon inside trochea) showing the supraorbital (17, 44, 45), the supratrochlear (pair of arrows superior to trochea) and "infratrochlear" (pair of arrows inferior to trochea) neurovascular structures. An exact differentiation between arteries, veins, and the accompanying supra- and infratrochlear nerves is not possible. Lacrimal gland (L). B, imaging plane through the posterior pole of the globe: the structure at the lateral border of the inferior rectus muscle most likely represents the branch of the inferior division of the oculomotor nerve (36), which supplies the inferior oblique muscle. Alternatively, it may be a muscular artery or vein. Frontal nerve (43), infraorbital neurovascular bundle (22, 53), supratrochlear vessels (20, 26), presumed lacrimal nerve (52). The hypointense signal superior to the posterior pole of the eye is caused by cerebrospinal fluid in the subarachnoid space around the optic nerve (arrow). C, imaging plane 3 mm behind the globe showing the ophthalmic artery (10), the lateral posterior ciliary artery (13), the superior (27) and inferior (30) ophthalmic veins, the presumed inferior division of the oculomotor nerve (36), and the nasociliary nerve (47).
A reliable identification of the tiny ciliary nerves was not possible in the magnetic resonance images.
The infraorbital neurovascular bundle consisting of the infraorbital nerve and vessels is visualized inside the infraorbital canal on coronal images (Fig. 5B).

**DISCUSSION**

The fat content of the orbit is responsible for the excellent contrast in orbital MRI, allowing for better detection of small anatomic structures. Fat appears bright (hyperintense) on T1-weighted images, and other structures such as muscles, vessels, and nerves are darker (hypointense) than orbital fat. The optic nerve exhibits MRI signal characteristics similar to those of white matter of the brain because of its myelinated nerve fibers. Blood vessels (especially arteries) appear dark in T1-weighted magnetic resonance images. This is because the protons of flowing blood that have been excited by a radiofrequency pulse pass outside the imaging slice before their signal can be detected.

Although we have used a slice thickness of 2 to 3 mm, partial volume averaging enabled a visualization of relatively long parts of vascular structures, such as the superior ophthalmic vein (Fig. 4C). When the examined structure is partially out of the imaging slice, hypointense or thin segments within its course (Fig. 4E-F) are the consequence. Thus, partial volume averaging is a potential source of error during the identification of anatomic structures in MRI. To circumvent this problem and avoid mistakes, we have always analyzed series of adjacent imaging slices and the corresponding coronal sections or other orientations.

Because of the aforementioned signal void of flowing blood, major vessels in our images were usually darker than other structures such as muscles and nerves. In general, arteries showed a curved course compared with the more straight veins and nerves. These facts, together with a detailed knowledge of orbital topography and sectional anatomy, allowed the identification of various vascular structures on MRI. Knowledge of the mean diameters of the different arteries (e.g., ophthalmic artery: 1.3-1.4 mm, lacrimal artery: 0.7 mm, central retinal artery: 0.5 mm) was also useful for the analysis, although the vessel diameters estimated in the magnetic resonance images slightly exceeded the real anatomical diameter. This discrepancy in the vessel diameter between MRI studies and anatomic studies may be due to the fact that the MRI-system measures not only the blood flow but also minimal motions of the vessel, resulting in a slightly larger vessel diameter than the real diameter. In contrast to that, the anatomist measures the vessel diameter postmortem, which may be smaller than the in vivo diameter. Exact measurements of the vessel diameters were not performed in this study because of partial volume artifacts causing changes in the caliber of the vessels.

The orbital arteries that form a radiating system diverging from the orbital apex traverse through the adipose tissue compartments and perforate the orbital septa. In contrast, the veins are arranged in a ring-like system that reflects their incorporation into the fibrous septa of the orbital connective tissue system. Because many of the septa of the orbital connective tissue system were visible in the magnetic resonance images (Fig. 5A-C), the knowledge of the different spatial arrangement of arteries and veins and their relations to the connective tissue system was also helpful for the analysis of the magnetic resonance images. The SOV traverses the orbit inside the „superior ophthalmic vein hammock“, a connective tissue septum which is located just inferior to the superior rectus muscle. Therefore, a swollen, inflamed superior rectus muscle may cause venous outflow obstruction. This has been suggested to be the cause of orbital soft-tissue swelling in patients with Graves disease in whom the proptosis is out of proportion to the enlargement of the muscles.

The ophthalmic artery and its branches are subjected to marked anatomic variations. It crosses over the optic nerve in 72 % to 95 % of individuals and under it in 5 % to 28 %. The magnetic resonance images showed no significant variations concerning the main intraorbital course of the ophthalmic artery and in all investigated subjects, the artery crossed over the optic nerve. In fact, the number of examined probands in our study was too small to draw conclusions on anatomical variations of orbital vessels.

The ophthalmic veins and their branches were well visualized. The diameter of the SOV in magnetic resonance images of normal subjects was estimated to be 1.5 to 2 mm. Disorders with enlargement of the ophthalmic veins include arteriovenous malformations, carotid cavernous fistulae, dural shunts, cavernous sinus thrombosis and Graves ophthalmopathy.

Most of the orbital sensory and motor cranial nerves were visualized in the magnetic resonance images. The superior division of the oculomotor nerve was not seen, which is most likely because of its early ramification into numerous tiny fascicles that pierce the muscle sheath and course anteriorly embedded between muscle fibers. The trochlear nerve also escaped visualization on MRI because of its thinness and the lack of orbital fat (which would improve the contrast in the images) along its course between the superior oblique muscle and the periorbit.

The ophthalmic artery, the SOV, and some of their branches have previously been visualized by means of MRI. Some of the orbital nerves, such as the frontal nerve or the nasociliary nerve, have also previously been visualized on MRI. However, the resolution on the magnetic resonance images in most previous studies was limited because of earlier magnetic resonance technology.

We have demonstrated that surface coil MRI on a clinical magnetic resonance unit is capable of imaging the anatomy of the vessels and nerves in the orbit with sufficient detail. The best anatomic detail is obtained by the use of T1-weighted (short TR/TE) pulse sequences. T2-weighted
(long TR/TE) and proton density (long TR/short TE) images were not used in our study because they take a longer time to produce, which leads to motion artifacts and therefore results in a poorer image quality.

The use of surface-coil technology for orbital MRI allows high-resolution imaging by increasing the signal-to-noise ratio. However, there are certain limitations. First, the signal drop-off strongly depends on the distance of the region of interest from the coil and also on the diameter of the coil. Therefore, when additional imaging of the cranio-orbital junction and the brain is required, the use of a standard head coil is recommended. Second, a surface coil is more sensitive to motion artifacts. Motion artifacts can represent a considerable problem in high-resolution MRI of the orbit. Orbital MRI with a resolution that is sufficient for anatomic considerations is currently restricted to cooperative subjects who are able to lie still for up to 20 minutes in the scanner, which presently hampers its use for clinical routine. With improved software and hardware technology, one may imagine its use for delineation of space-occupying orbital lesions in relation to various anatomic structures, thus facilitating better surgical planning. Additionally, MRI can reveal information on the flow in blood vessels. A differentiation between flowing and stagnant blood in orbital vascular lesions is crucial for treatment planning. Therefore, a potential clinical application of high-resolution orbital MRI will be the evaluation of orbital vascular lesions. Future improvements in magnetic resonance angiography may also be helpful in gaining further clinical information in these patients.

Another clinical application, would be the diagnosis of peripheral nerve sheath tumors that cannot reliably be differentiated from other orbital tumors because of their unspecific signal characteristics. Here, high-resolution MRI might help to demonstrate a relation of a space-occupying process to an orbital nerve, thus suggesting the diagnosis of a peripheral nerve sheath tumor.

Finally, the ability of delineating anatomic details in the orbit will be important for computer-assisted orbital surgery.

APPENDIX

Nomenclature

The numbers in the figures refer to the following structures:

1 Levator palpebrae superioris muscle
2 Superior rectus muscle
3 Inferior rectus muscle
4 Medial rectus muscle
5 Lateral rectus muscle
6 Superior oblique muscle
7 Trochlea
8 Superior oblique tendon
9 Inferior oblique muscle
10 Ophthalmic artery
11 Central retinal artery
12 Recurrent meningeal artery
13 Lateral posterior ciliary artery
14 Lacrimal artery
15 Muscular arterial branch
16 Posterior ethmoidal artery
17 Supraorbital artery
18 Medial posterior ciliary artery
19 Anterior ethmoidal artery
20 Supratrochlear artery
21 Dorsal nasal artery
22 Infratrochlear artery
23 Facial vein
24 Angular vein
25 Nasofrontal vein
26 Supratrochlear vein
27 Superior ophthalmic vein
28 Lacrimal vein
29 Medial ophthalmic vein
30 Inferior ophthalmic vein
31 Medial collateral vein
32 Lateral collateral vein
33 Vorticosc vein
34 "Veine ophthalmique moyenne" (see legend Fig. 4H)
35 Oculomotor nerve (superior division)
36 Oculomotor nerve (inferior division)
37 Short ciliary nerves
38 Ciliary ganglion
39 Abducens nerve
40 Trochlear nerve
41 Ophthalmic branch of trigeminal nerve
42 Maxillary branch of trigeminal nerve
43 Frontal nerve
44 Supraorbital nerve (med. branch)
45 Supraorbital nerve (lat. branch)
46 Supratrochlear nerve
47 Nasociliary nerve
48 Long ciliary nerves
49 Posterior ethmoidal nerve
50 Anterior ethmoidal nerve
51 Infratrochlear nerve
52 Lacrimal nerve
53 Infratrochlear nerve
54 Optic nerve
REFERENCES


