High resolution magnetic resonance imaging anatomy of the orbit
Ettl, A.

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Chapter 9

CONCLUSIONS

Anatomy

Chapter 2 demonstrates that high-resolution MRI using spin-echo sequences without contrast enhancement is capable of delineating the ophthalmic artery and its major branches, ophthalmic veins and sensory and motor orbital nerves. This is mainly based on four principles:
(1) Blood vessels appear mostly dark on images because of the signal void of flowing blood. (2) The bright background of orbital fat on T1-weighted images accounts for an excellent soft tissue contrast in the orbit. Fat appears hyperintense on T1-weighted images and other structures such as vessels, nerves and muscles appear dark (hypointense). (3) Due to partial volume averaging, slice thicknesses of 2-3 mm which were used in this study, enables visualization of relatively long segments of blood vessels and nerves. (4) The use of an orbital surface coil improves the signal-to-noise-ratio and therefore the resolution of details.
In general terms, T1-weighted images depict intraorbital anatomic structures better than T2-weighted images. However, it should be noted that T2-weighted images are very sensitive to pathology and may detect lesions that are not or hardly visible on T1-weighted images.

Chapters 3 and 4 show that high-resolution MRI can also depict details of the extraocular musculature and their connective tissue. The origin and path of the extraocular muscles (EOMs) and their relation to the globe and the orbital walls can be visualized in longitudinal and cross-sections. However, it is difficult to discriminate the tendinous insertions of the EOMs from scleral tissue. Major circular and radial septa may be visualized. The regions of the muscle pulleys can be determined either directly (trochlea, Lockwood's ligament, check ligaments) or indirectly because the pulleys are usually located at the point of greatest curvature or deflection of the muscles.

Chapter 5 describes the anatomy of Whitnall's ligament that consists of 2 distinct parts: The intermuscular transverse ligament (ITL) inferior to the levator palpebrae superioris muscle (LPS) and the superior transverse ligament (STL) superior to the LPS. Since the medial and lateral main attachments of the STL are situated inferior to the level of the culmination point of the LPS, this ligament is unlikely to suspend the levator muscle. However, a suspension of the LPS may be achieved by radial connective tissue septa of the superior orbit. The ITL in connection with the globe may have an additional supporting function. The elasticity of Whitnall's ligament and its connections with highly elastic structures including Tenon's capsule are proposed to provide the morphological substrate for the previously suggested passive (i.e. without orbicularis action) lowering of the lid during downward saccades.

Chapter 6 demonstrates that the STL does not suspend the LPS at its culmination. This result suggests that the ligament is therefore not responsible for the curved course of the muscle. The curved course of the LPS may be due to a suspension by radial connective tissue septa and support from the inferiorly situated intermusculatransverse ligament (ITL).

Chapter 7 investigates the relationship between upper lid elevation and shortening of the LPS and reveals that the levator muscle must contract by 1.4 cm in order to achieve a lid elevation of 1 cm. Therefore, the force of the LPS which is necessary to lift the upper eyelid can be smaller than the lid closing force. This strongly suggests a physiological mechanism that reduces the muscle force necessary for lifting the upper eyelid.

Chapters 5-7 demonstrate that high-resolution MRI is an excellent tool for functional anatomical studies in vitro and in vivo because it enables visualization of extraocular and palpebral muscles with sufficient detail and lacks ionizing radiation so that multiple and prolonged examinations can be performed in volunteers.

Chapter 8 reviews the imaging anatomy of the entire orbit and provides correlative anatomical cryosections. Many clinical applications are mentioned to show that high-resolution MRI may contribute to a specific diagnosis in orbital disease.

The present thesis has provided the basic morphological knowledge which is essential for a successful clinical application of this non-invasive diagnostic technique.

Clinical applications

It is beyond the scope of this thesis to discuss the clinical role of MRI and CT for orbital imaging. However, it seems appropriate to summarize some basic principles in order to underline the clinical importance of our findings.
Based on our experience with imaging of orbital anatomy and clinical experiences, some recommendations on the choice of the appropriate imaging modality in a given clinical situation shall be made.

### Trauma

In the setting of orbital trauma, CT scanning should be the first imaging modality because of its excellent depiction of bony structures. However, there are specific circumstances in which MRI may add important informations. MRI scans should be obtained if organic foreign bodies (e.g. wood) are suspected. Prior to MRI, the presence of ferro-magnetic foreign bodies must be excluded by history, plain X-rays and/or CT.

MRI may also be useful in the presence of orbital hemorrhage. MRI enables localization of tiny hematomas (e.g. intrasheath optic nerve hematoma) and determination of the age of hemorrhages (see chapter 1). Finally, MRI may be helpful in investigating post-traumatic motility disorders owing to its ability of depicting orbital connective tissue septa and multiplanarity. MRI can show entrapment of EOMs or connective tissue septa in orbital fractures and differentiate between restrictive and paretic traumatic motility disorders.

### Tumors

Soft tissue tumors of the orbit are best delineated using MRI because of its superior contrast resolution and differentiation of soft tissue details compared with CT. Many solid tumors appear with low signal intensity on T1-weighted images and medium to high intensity on T2-weighted images. Fluid-filled cysts appear bright on T2-weighted images and dark on T1-weighted images. Lymphangiomas are heterogenous masses consisting of solid and cystic portions. Lipomatous tumors or oil within dermoid cysts exhibit isointensity to orbital fat on T1-weighted and T2-weighted images. However, tumors can vary considerably in its appearance depending on their histology, vascularity and the amount of edema or necrosis. The MR-signal characteristics of orbital lesions are often nonspecific, so that in many cases the exact diagnosis can only be made on the basis of histopathology. There are exceptions, such as lipomatous hamartomas which may be diagnosed using MRI alone. Additional CT scans should be obtained, if bony tumors (e.g. osteoma), tumors with calcifications or hyperostoses (e.g. retinoblastoma, meningeoma) or tumors eroding the orbital bones are suspected. CT enables depiction of the complex bony anatomy of the orbital apex but CT scans of the orbital apex may be distorted by beam-hardening artifacts and artifacts from dental fillings. Therefore, MRI is superior to CT in imaging soft tissue details of the orbital apex. High-resolution MRI is more sensitive than CT in detecting small inflammatory lesions at the orbital apex (e.g. Tolosa-Hunt variant of orbital pseudotumor). Because of superior definition of the cavernous sinus and intracranial structures (see addendum), MRI should be applied in all orbital tumors with suspected intracranial extension. The possible amount of bone destruction can be determined using additional CT scans.

### Optic nerve lesions

MRI is superior to CT in imaging the intracanicular and intracranial optic nerve. It can delineate the subarachnoid space of the intraorbital optic nerve, especially on T2-weighted images. Enhancement following the intravenous application of Gd-DTPA, is observed in optic nerve sheath meningiomas (diffuse enhancement of thickened nerve sheath), sometimes in optic nerve gliomas (enhancement of thickened optic nerve) and often in optic neuritis (diffuse or patchy enhancement of optic nerve).

### Vascular lesions

In contrast to CT, MRI without contrast enhancement enables differentiation between flowing and stagnant blood. Therefore, MRI is superior to CT in evaluating orbital vascular lesions. Magnetic resonance angiography (MRA) is safer than catheter angiography but it has not yet reached a state where it can replace conventional angiography. MRA is indicated when a carotid-cavernous-fistula or an aneurysm is suspected. However, there are certain drawbacks to MRA. First, it may be difficult to distinguish the hyperintense signal of flow from a hyperintense thrombus. However, T1-weighted MR images may help in differentiating flowing from thrombotic blood. Second, low-flow (e.g. dural shunts) will not always result in a high signal and may therefore be missed. Third, catheter angiography is necessary in addition to MRA, if a neuro-radiological intervention is planned. If MRI, MRA or color Doppler ultrasonography of orbital vascular lesions shows evidence of fast-flowing blood, a catheter angiography is still indicated in most cases to obtain the precise detail usually needed for treatment planning.

### Motility disorders

High-resolution MRI may be a powerful diagnostic tool in cases of complex motility disorders where even a thorough clinical examination may not lead to a correct diagnosis. According to Demer and Miller, high-resolution MRI may be applied in the following clinical situations:

1. MRI can visualize the path of lost, detached or avulsed EOMs. The contractile potential of EOMs may be determined by measuring cross-sectional areas of the EOMs in different gaze positions. This information enables appropriate surgical planning (reanastomosis with or without spacers versus muscle transposition).

2. MRI can visualize congenital or acquired abnormalities of the EOMs, their paths and pulley locations. For instance, EOM heterotopy may cause A- and V-patterns thus mimicking oblique muscle dysfunctions. Another example is the large-
angle horizontal and vertical strabismus occurring in high axial myopia which is caused by downwards-displacement of the horizontal recti.

Sometimes, strabismus may be caused by aplasia or hypoplasia of EOMs, dystopic muscle insertions or supernumary EOMs which may only be diagnosed by imaging techniques.

(3) MRI may reveal EOM paralysis by determining changes of the cross-sectional area of the EOMs in different gaze-positions as an index of contractility.\(^7\)

(4) MRI may also demonstrate tumorous swelling or infiltration of the EOMs or their surrounding. For instance, a small cyst in the superior oblique tendon, may produce the restriction of elevation in adduction clinically known as Brown syndrome.\(^7\)

(5) In the presence of Graves disease, MRI may distinguish between the acute stage of muscle edema and infiltration and the chronic stage with fibrosis.\(^7\) This differentiation is important for treatment planning.

In conclusion, high-resolution MRI is a fascinating noninvasive diagnostic technique that allows exact delineation of space occupying orbital processes in relation to surrounding anatomical structures. This feature is important for surgical planning, especially when neuronavigation systems\(^8\)-\(^11\) are used. In addition to that, high-resolution MRI has the potential of demonstrating anatomical causes of motility disorders. Therefore it should be performed in complex cases of strabismus in addition to routine clinical examinations.

REFERENCES
