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Review

Modern concept of orbital radiological imaging

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Summary

Radiological imaging modalities, particularly computed tomography (CT) and magnetic resonance imaging (MRI), play a pivotal role in the diagnosis of orbital diseases. CT remains the gold standard for the evaluation of orbital trauma, including fractures, calcifications, and metallic foreign bodies, whereas MRI is superior for assessing soft tissues and the optic nerve. Characteristic radiological signs include the "I'M SLOW" pattern in Graves' ophthalmopathy, the "tram-track" sign in optic nerve sheath meningioma, the "teardrop" sign in blowout fractures, and the "empty delta" sign in cavernous sinus thrombosis. An apparent diffusion coefficient (ADC) threshold value of 0.84×10^{-3} mm^2/s has been shown to differentiate malignant from benign orbital lesions. The presence of a metallic intraocular foreign body represents an absolute contraindication to MRI examination. Artificial intelligence is increasingly contributing to orbital imaging through automated muscle segmentation, fracture detection, and prediction of tumor histology. Appropriate selection of imaging modality and recognition of these characteristic findings significantly improve diagnostic accuracy.

Key words: orbit, CT, MRI, diffusion-weighted MRI, ADC, Graves' ophthalmopathy, fractures, artificial intelligence

Introduction

The orbit is an anatomically complex region where the eyeball, optic nerve, extraocular muscles, blood vessels, secretory glands and fat tissue are located within a small bony space [1, 2]. Because of the dense packing and overlapping of these structures, clinical examination alone is often not sufficient to establish an etiological diagnosis [3]. Two modern radiological methods, computed tomography (CT) and magnetic resonance imaging (MRI), enable non-invasive visualization of

orbital structures with high resolution [4]. CT is based on X-rays and is characterized by a short scan time and particularly good visualization of bones, calcifications and foreign bodies [5]. MRI uses a strong magnetic field and radiofrequency pulses, does not expose the patient to ionizing radiation, and provides superior contrast of soft tissues, especially the optic nerve and extraocular muscles [6, 7]. The choice between these two methods depends on the clinical question, the urgency of the condition, the availability of equipment and the individual characteristics of the patient [8, 9]. This review aims to outline the main indications, strengths and limitations of CT and MRI in orbital imaging and to suggest a practical approach to modality selection [1, 4].

Orbital anatomy from the radiological perspective

The bony orbit has a pyramidal configuration. The orbital floor is the thinnest and most often affected in trauma, resulting in the so-called blow-out fracture [10]. The medial wall, also known as the lamina papyracea, is also extremely thin and susceptible to injury. The orbital apex is a narrow bony channel through which the optic nerve and ophthalmic artery pass; any expansive lesion in that region can quickly lead to nerve compression and vision loss [11]. Among the soft tissue structures, the most important for radiological interpretation are the optic nerve, which is surrounded by a myelin sheath and meningeal layers [12], the four rectus muscles and two oblique muscles that enable eye movements [13], the retrobulbar fat tissue [4], the lacrimal gland located in the superolateral quadrant, and the ophthalmic artery with its branches [14]. The optic nerve is divided into four segments: intraocular, intraorbital, intracanalicular and intracranial. The intraorbital segment is surrounded by cerebrospinal fluid within the optic nerve sheath, which can be visualized on T2-weighted MRI. The extraocular muscles have variable thickness and signal intensity; the medial rectus is often the thickest. The ophthalmic artery arises from the internal carotid artery and enters the orbit with the optic nerve. These anatomical relationships are crucial for interpreting radiological findings correctly.

Computed tomography of the orbit

CT is based on measuring the attenuation of X-rays after passing through tissues [5]. Modern multidetector CT allows submillimeter slice thickness and isotropic resolution [9]. Imaging of the entire orbit takes less than one second [10]. The protocol involves axial acquisition with multiplanar reconstructions [8]. The native phase shows bone, calcifications, foreign bodies and acute hemorrhage. The contrast phase using iodinated contrast is indicated when inflammation, tumor, abscess or vascular malformation is suspected [5]. For specific vascular indications, such as carotid-cavernous fistula, CT angiography is used [14]. The effective radiation dose for orbital CT is 1-3 mSv, and the dose to the lens of the eye is 10–30 mGy per examination [8]. In children and in patients requiring multiple follow-ups, the ALARA principle (as low as reasonably achievable) is applied [9].

CT is the method of choice in orbital trauma because it accurately demonstrates blow-out fractures and retrobulbar hematoma [10]. It is particularly valuable for the detection of metallic and glass foreign bodies [5]. It is also indicated for the evaluation of calcifications such as those in meningioma and retinoblastoma, for bone lesions, for orbital cellulitis and subperiosteal abscess, and for preoperative planning [3, 5, 9]. In patients with contraindications to MRI, CT is the only available option [8]. CT offers clear advantages in speed, bone detail, detection of calcifications and metallic

foreign bodies, and is widely available at relatively low cost [5, 8, 10]. On the other hand, it carries the burden of ionizing radiation (particularly to the lens), offers limited soft tissue contrast on non-contrast scans, and is susceptible to metal and dental artifacts [5, 8].

Beam hardening from dense bone or metal implants causes dark stripes, and partial volume effects may create false lesions at the apex of the orbit. A normal variant consisting of intraorbital fat herniation through a dehiscence of the lamina papyracea can simulate a mass. Partial volume artifact, though rare on thin sections, can mimic erosion of the optic canal. Dental amalgam produces streak artifacts that may mask the orbital apex. CT can give a false impression of optic nerve thickening in optic neuritis because of poor soft tissue contrast.

Magnetic resonance imaging of the orbit

Given CT's limitations in soft tissue contrast and radiation exposure, MRI provides a complementary approach. MRI uses a strong magnetic field of 1.5 or 3 Tesla and radiofrequency pulses. The signal emitted by excited hydrogen protons depends on proton density and on the T1 and T2 relaxation times, which gives different tissues a different appearance and enables outstanding contrast of soft tissues [6, 15]. The following sequences are used to image the orbit: T1-weighted imaging for anatomy and adipose tissue, T2-weighted imaging for edema, inflammation and fluid, STIR for fat signal suppression with emphasis on edema, T1 with fat saturation after gadolinium for inflammation and tumor detection, DWI and ADC to differentiate abscesses from cysts and cellular tumors [16, 17], and time-of-flight MRA for angiography without contrast [14]. The examination time usually ranges from 25 to 40 minutes [3].

MRI is usually the method of choice for optic nerve lesions, including optic neuritis, glioma and meningioma [12]. In thyroid ophthalmopathy, MRI not only demonstrates muscle thickening but also assesses inflammatory activity using STIR sequences [6, 1]. Clear indications include soft tissue tumors such as cavernoma, lymphoma and metastases [19, 5], inflammatory diseases such as idiopathic orbital inflammatory syndrome, Tolosa-Hunt syndrome and IgG4-related orbital disease [20–22], vascular malformations [14], congenital anomalies [1], and orbital apex syndrome [11]. In the pediatric population, MRI is preferred over CT because it uses no ionizing radiation [1].

Topographic differential diagnosis on MRI: Lesions are described in relation to the muscle cone. Intraconal lesions (within the muscle cone) include optic nerve disorders (glioma, meningioma, neuritis, sarcoidosis), vascular lesions (cavernoma, varicose veins, arteriovenous malformation), and inflammatory conditions (idiopathic orbital inflammatory syndrome). Extraconal lesions involve the lacrimal gland (dermoid, adenoma, carcinoma, sarcoidosis, IgG4 disease) or the adipose tissue (lipoma, liposarcoma, orbital pseudotumor). Conal lesions affect the extraocular muscles and are seen in Graves' ophthalmopathy (thickening of muscle bellies with spared tendons), as well as in myositis, lymphoma and metastases. At the orbital apex, one may encounter Tolosa-Hunt syndrome (granulomatous inflammation of the cavernous sinus and apex), apex meningioma, or perineural tumor spread such as from adenoid cystic carcinoma. This topographic classification helps narrow the differential diagnosis [1, 2, 5].

Specific MRI findings in orbital conditions: Sarcoidosis shows characteristic T2 hypointensity due to granulomas and often affects the optic nerve and lacrimal gland. Vascular malformations are divided into capillary, cavernous and arteriovenous types; MRA is useful, and digital subtraction angiography is indicated for arteriovenous malformations [14]. Optic glioma in neurofibromatosis type 1 requires treatment when there is progression on volumetry, involvement of the chiasm, or vision

loss. Optic neuritis in neuromyelitis optica typically presents with long lesions extending over more than half the length of the nerve, frequent involvement of the chiasm, and positive AQP4 antibodies.

Extended MRI sequences: Susceptibility-weighted imaging (SWI) is useful for the detection of bleeding, melanin and calcium, which is helpful in melanoma metastases and cavernomas. Magnetization transfer improves contrast in demyelinating diseases of the optic nerve such as multiple sclerosis and neuromyelitis optica. Constructive interference in steady state (CISS) allows visualization of the intracanalicular optic nerve and the cerebrospinal fluid space with near myelographic resolution. Diffusion tensor imaging (DTI) and tractography allow visualization of the optic pathway and assessment of axonal damage, particularly in post-traumatic optic neuropathy when conventional MRI is normal. Perfusion techniques help to distinguish tumors from inflammatory changes and from radiation necrosis [16, 17].

Artifacts on MRI: Susceptibility artifacts from metal (titanium produces less artifact than steel) appear as dark holes on T2* or SWI sequences. Pulsation artifacts from the carotid artery or cerebrospinal fluid often appear in the direction of phase encoding. Normal contrast enhancement of the meibomian glands and iris can give false positive findings. The high signal of orbital fat on T1 and T2 may simulate a lipoma but is physiological. Pulsation artifact from the carotid artery can simulate a cavernous sinus lesion. MRI may miss small calcifications in retinoblastoma.

MRI is distinguished by the absence of ionizing radiation, superior soft tissue contrast, and the capacity to provide functional information using advanced sequences [6, 15–17]. The disadvantages are the long imaging duration, which makes the examination susceptible to motion artifacts, the presence of contraindications such as pacemakers, ICDs, cochlear implants, ferromagnetic clips and intraocular metallic foreign bodies, poor visualization of bones and calcifications, claustrophobia occurring in 2–5% of patients, higher cost and more limited availability [8, 9, 3].

Comparative analysis and economic perspective

When the two modalities are compared, CT uses X-rays and delivers 1–3 mSv of ionizing radiation, whereas MRI uses a magnetic field and no radiation. The scan duration for CT is less than one minute, while MRI takes 20–40 minutes. CT provides excellent spatial resolution (0.5 mm) and superior depiction of bone and calcifications, but only moderate soft tissue contrast. MRI has good spatial resolution (1–2 mm) and superior soft tissue contrast, but bone and calcifications are poorly seen. The optic nerve and extraocular muscles are moderately visible on CT but more clearly displayed on MRI. Metal foreign bodies are safely detected by CT but are contraindicated for MRI. CT is available 24 hours a day, 7 days a week, almost everywhere, while MRI availability is more limited. CT has lower cost, but repeat imaging is restricted by radiation; MRI is two to five times more expensive, but repeat imaging is possible.

From an economic and organizational perspective, orbital CT has lower cost, greater 24-hour availability, and a shorter imaging duration. Orbital MRI costs 2–5 times more than CT, has a longer imaging duration, but does not use ionizing radiation. Early CT in emergency situations such as trauma and cellulitis reduces unnecessary hospitalizations and speeds up the decision between conservative and surgical treatment.

Diagnostic algorithm

Building on the comparative strengths and weaknesses of CT and MRI, a clinically oriented algorithm can guide modality selection. The selection of the appropriate imaging modality

should follow a stepwise, clinically oriented approach. First, the urgency of the condition must be assessed. In an emergency such as blunt or penetrating trauma, native CT is indicated [10]. Sudden exophthalmos with pain requires CT angiography to rule out a carotid-cavernous fistula [14]. Orbital cellulitis with exophthalmos calls for native and contrast CT [3]. Sudden vision loss with ophthalmoplegia should start with CT, and if the CT scan is normal, MRI should be performed next [11, 12]. If the situation is not urgent, the next question is whether bone, calcification or a foreign body is suspected. If yes, native CT with contrast if needed is the appropriate choice [5]. If not, and soft tissue evaluation of the nerve, muscle, inflammation or tumor is required, then MRI with gadolinium, DWI, ADC and STIR is indicated [1, 12, 11, 16, 17]. For purely vascular questions, either CTA or MRA can be used depending on availability [14]. In the specific case of trauma with a normal CT but persistent symptoms, MRI should be performed.

In non-urgent clinical situations, the following guidance applies. Subacute vision loss is best investigated with contrast MRI [12]. Unilateral exophthalmos is initially studied by MRI, and CT can be added if a bone lesion is suspected [5]. Bilateral exophthalmos suggests thyroid ophthalmopathy, so MRI is the first choice [1, 12]. Diplopia without trauma should be evaluated first by MRI, and CT is reserved for suspected post-traumatic fracture [10]. Orbital tumors are assessed with MRI including DWI, and CT can be added if calcifications are sought [16, 19, 17, 5]. Orbital apex syndrome requires contrast MRI [11]. A child with leukocoria should first have ultrasound and CT to detect calcifications of retinoblastoma, followed by MRI [5]. Vascular malformations are well shown by MRA or CTA alone [14].

For orbital trauma with deformation, CT is the first choice because of its speed and bone visualization [10]. For acute vision loss with pain, CT angiography is used to exclude fistula or hematoma [14]. For subacute vision loss, MRI with gadolinium is preferred to evaluate the optic nerve, inflammation or tumor [12]. For exophthalmos in a child, MRI is chosen because there is no radiation and it provides excellent soft tissue detail; CT is used only if retinoblastoma is suspected [5]. For diplopia without trauma, MRI is the first choice to examine the muscles, nerves and apex, and CT is reserved for fractures only [10].

Special populations and postoperative evaluation

Beyond the general diagnostic algorithm, certain patient groups and postoperative situations require additional considerations. Children: MRI should be used whenever possible [1]. CT should be used only when clinically necessary, such as for suspected retinoblastoma to detect calcifications, for orbital trauma, or for suspected metallic foreign body. MRI is the first choice for exophthalmos, optic glioma in neurofibromatosis type 1, inflammatory diseases and congenital anomalies. Children often require short sedation with propofol or sevoflurane, or anesthesia, for MRI, whereas CT can often be performed without sedation using immobilization and a short imaging duration. CT protocols in children adhere to the ALARA principle with parameters adapted to age and weight. The differential diagnosis of leukocoria includes retinoblastoma (calcifications on CT), Coats disease (no calcifications, exudates), persistent hyperplastic primary vitreous (microphthalmos, hyaloid artery), and toxocariasis (granuloma with inflammatory changes).

Pregnancy: MRI may be performed in the second and third trimesters at 1.5 Tesla without gadolinium when clinically indicated, while CT should be avoided unless absolutely necessary (e.g., life-threatening retrobulbar hematoma with nerve compression) [8].

Renal insufficiency: In severe renal failure, native CT is an option but iodinated contrast

carries a risk of nephropathy. Native MRI can be used but there is a risk of nephrogenic systemic fibrosis in severe kidney disease; an alternative is DWI, ADC and T2 STIR for lesion characterization [17].

Claustrophobia: Affecting 2-5% of patients, options include CT if diagnostically sufficient, open MRI (lower signal-to-noise ratio but often adequate for the orbit), or sedation with an anxiolytic such as midazolam combined with a closed MRI using a mirror and ventilation [3].

Cardiac devices: For a patient with a heart pacemaker or ICD, MRI may be contraindicated depending on device compatibility, so CT is the alternative [8].

Absolute contraindications for MRI include implanted pacemakers or ICDs that are not MRI-compatible, older types of cochlear implants, ferromagnetic clips of cerebral aneurysms, and intraocular metallic foreign bodies (especially in patients with history of metal work or welding). Relative contraindications include older stents (depending on metal type), artificial heart valves (mostly safe except the older Starr-Edwards model), tattoos with ferromagnetic pigments (rare), and pregnancy before 12 weeks (MRI avoided unless clinically necessary).

Postoperative and posttraumatic evaluation: Imaging after orbital decompression for Graves' ophthalmopathy assesses the extent of the bone defect and the position of the muscles. After enucleation or evisceration, the normal appearance of implants (porous polyethylene, ceramic, spherical implants) must be distinguished from pathological findings such as infection, migration or extrusion. In post-traumatic optic neuropathy, DTI and fractional anisotropy play a role in assessing axonal damage when conventional MRI is normal.

Advanced and new techniques

In addition to the standard clinical protocols discussed above, several advanced techniques have expanded diagnostic capabilities. Dual-energy CT (DECT) allows distinguishing calcium from iodine and reducing metal artifacts from orbital plates after fracture [9]. At 3 Tesla, the signal-to-noise ratio is increased, enabling thinner slices (up to 1 mm) and better visualization of small structures [15]. Radiomic analysis of MRI sequences represents a promising new method for the characterization of orbital lesions [23]. PET/CT and PET/MRI combine metabolic information from fluorodeoxyglucose with anatomical information and are useful for the detection of lymphoma, metastases and sarcoidosis [19]. Orbital ultrasound remains useful as a first-line tool for rapid differentiation of solid from cystic lesions and for evaluation of papilledema [4].

Newer technologies continue to evolve. Photon-counting CT offers spatial resolution up to 0.2 mm with a dose less than 50% of conventional CT, but it is still primarily a research technology. Ultra-high-field MRI at 7 Tesla allows visualization of the laminar structure of the optic nerve and of orbital microvessels without contrast using time-of-flight MRA. Radiomics and artificial intelligence are being used for automatic segmentation of extraocular muscles in Graves' ophthalmopathy, for prediction of response to corticosteroids based on muscle T2 signal, and for prediction of orbital tumor malignancy from T2 and post-contrast sequences [23].

Conclusion

CT and MRI should be regarded not as competing modalities, but as complementary imaging tools. Each modality has specific advantages and limitations, and their correct application requires good knowledge of the clinical context. CT continues to serve as the first-line modality in emergencies, for trauma, for visualization of bone structures and calcifications, for detection of metal and glass

foreign bodies, and for patients in whom MRI is contraindicated. Its main limitations are ionizing radiation (especially risky for the lens and in children) and poor soft tissue contrast. MRI is the preferred modality for evaluating the optic nerve, extraocular muscles, and inflammatory and neoplastic changes. It uses no radiation, which makes it safe for children and pregnant women in the second and third trimesters, as well as for long-term monitoring. Its limitations are the long imaging duration, sensitivity to motion artifacts, strict contraindications, poor visualization of bone and calcifications, and higher cost. Modern analytical techniques, such as radiomics and artificial intelligence, further increase the diagnostic value of MRI. In complex cases, including orbital tumor with suspected bone invasion, retinoblastoma, and orbital apex syndrome, combined use of CT and MRI is recommended. Advanced techniques such as dual-energy CT, DWI, ADC, SWI, magnetization transfer, CISS, radiomics, artificial intelligence, PET/CT and PET/MRI further expand diagnostic capabilities. When the appropriate modality is chosen, an accurate diagnosis is achieved, unnecessary biopsies and invasive procedures are avoided, and appropriate therapy is introduced in a timely manner, thereby contributing to vision preservation and improved patient outcomes.

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Moderni koncept orbitalnog radiološkog snimanja

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Radiološke metode (CT i MRI) često su ključne u dijagnostici orbitalnih bolesti. CT je zlatni standard za traumu (frakture, kalcifikacije, metalna strana tijela), dok je MRI superioran za meka tkiva i optički nerv. Patognomonični znaci uključuju *I'M SLOW* (Gravesova oftalmopatija), *tram track* (meningiom), *teardrop* (*blow out* fraktura) i *empty delta* (tromboza kavernoznog sinusa). Granična ADC vrijednost od 0,84 × 10^{-3} mm^2/s razlikuje maligne od benignih lezija. Metalno strano tijelo u oku je apsolutna kontraindikacija za MRI. Vještačka inteligencija sve više pomaže u segmentaciji mišića, detekciji fraktura i predviđanju histologije tumora. Pravilan odabir modaliteta i poznavanje ovih znakova poboljšavaju dijagnostiku.

Ključne riječi: orbita, CT, MRI, difuzijski MRI, ADC, Gravesova oftalmopatija, frakture, vještačka inteligencija