Oral Radiol (2017) 33:92–100
DOI 10.1007/s11282-017-0274-z

REVIEW ARTICLE

Basic principles of magnetic resonance imaging for beginner oral and maxillofacial radiologists

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Received: 24 July 2016 / Accepted: 13 December 2016 / Published online: 27 March 2017

Abstract The basic principles and diagnostic methods of magnetic resonance imaging (MRI) for beginning surgeons are described in this review. MRI is an important technique that is essential for diagnoses in the maxillofacial area. It is a scanning method that obtains tomographic images of the human body using a magnetic field. In contrast to computed tomography, it does not utilize X-rays and, therefore, represents a noninvasive test that lacks radiation exposure. It is particularly effective for soft-tissue diagnoses. MRI involves imaging protons in vivo. Protons emit a signal when a radio frequency pulse is applied in a magnetic field; the MRI device then forms an image from these signals. The basic images produced are T1- and T2-weighted images; comparison of these images is the first step of MRI-based diagnosis. Short-T1 inversion recovery images, which eliminate the signal from fat, are also useful for diagnosis. Gadolinium is used as a contrast agent for MRI. Taking sequential images at fixed intervals while injecting the contrast agent and then graphing the contrast effect along the time axis produces a time–signal intensity curve, which is useful for identifying features such as malignant neoplasms based on the graph pattern.

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Keywords Diagnosis · Magnetic resonance imaging · Maxillofacial

Introduction

Magnetic resonance imaging (MRI) began with the discovery of nuclear magnetic resonance by Bloch [1], followed by the world's first imaging using nuclear magnetic resonance by Lauterbur [2]. At present, MRI and computed tomography (CT) are essential techniques in modern medicine. MRI is an important testing method essential for diagnoses in the maxillofacial area. This technique utilizes a magnetic field to obtain tomographic images of the human body. In contrast with CT, MRI does not utilize X-rays and is, therefore, a noninvasive test that lacks radiation exposure. It is particularly effective for soft-tissue diagnoses, even in the oral cavity, including benign and malignant neoplasms, inflammation, and temporomandibular joint disorders. This review describes the basic principles and diagnostic methods of MRI for beginner oral and maxillofacial radiologists.

MRI machines

MRI machines are based on the same principle as are electromagnets, which produce a magnetic field by passing an electrical current through a massive coil. To eliminate electrical resistance, the coil is enveloped by liquid helium (−273 °C) to bring it into a superconducting state. The strength of the magnetic field of the superconducting magnets in mainstream MRI machines today is 1.5 or 3.0 T (T; a unit quantifying magnetic field density). The type of superconducting magnet used in MRI machines

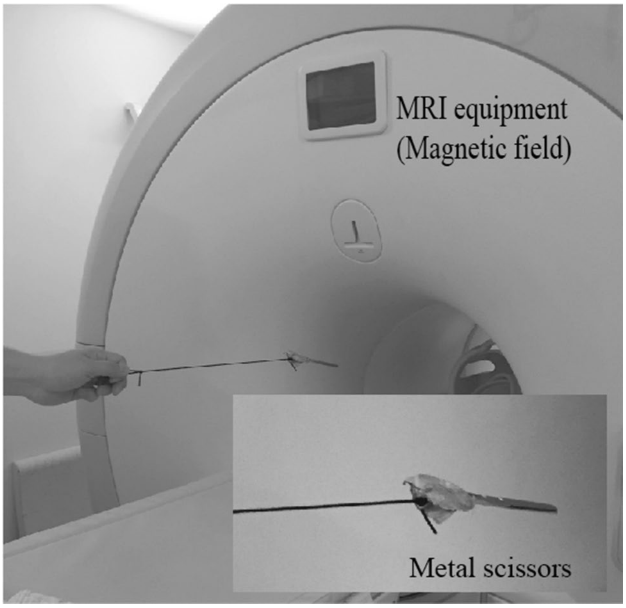

Fig. 1 Metal scissors brought in close proximity to a magnetic resonance imaging machine. Because the machine contains a powerful magnet, magnetic objects are not permitted in the examination room

can produce a very strong magnetic field; however, associated disadvantages include the need for a very large device as well as periodic helium replenishment. In addition, the space in which the patient reclines (the gantry) is a narrow tube, leading to a significant feeling of restriction during scans. Open gantry style MRI machines using permanent magnets have been developed to address this drawback. Nevertheless, their application is limited, because the magnetic field that can be obtained using permanent magnets is only approximately 0.5 T.

Cautionary notes before MRI imaging

Because all MRI devices constantly utilize a powerful magnetic field, bringing magnetic materials into the examination room is prohibited (Fig. 1). Medical equipment such as stretchers, wheelchairs, scissors, and gas cylinders used in the same room as the MRI device must be made from special-purpose nonmagnetic materials. In addition, MRI examinations are contraindicated for patients with cardiac pacemakers, implantable cardioverter defibrillators, and artery clips [3]. Caution is also required when examining patients with tattoos or those wearing colored contact lenses, mascara, or eye shadow, because all of these materials include minute iron particles that cause image artifacts and can become heated due to the magnetic field, potentially resulting in patient burns [3–6]. Burns resulting from loops in the coiled cord have also been reported [7, 8].

Basic principles of MRI

More than 80% of bodily tissue are composed of water and fat. As can be seen in the chemical formulas for water (H_2O) and fat [CH_2(OCOR)–CH(OCOR′)–CH_2(OCOR″)],

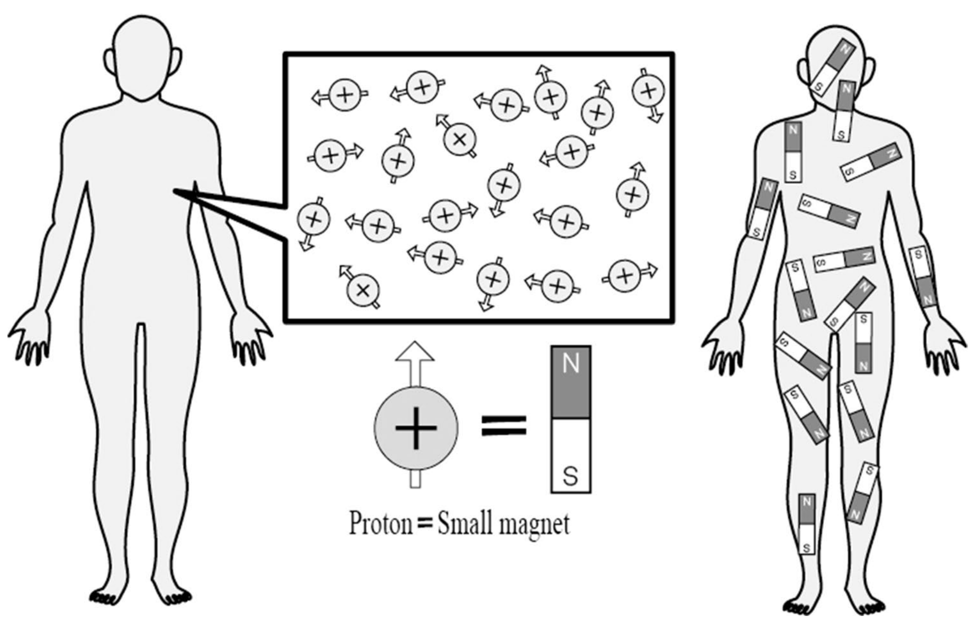

Fig. 2 Protons inside the human body. The inside of the human body contains a vast amount of protons. The proton is a small magnet in itself. Because protons are oriented in various directions in the body, magnetization is not manifested in the normal state

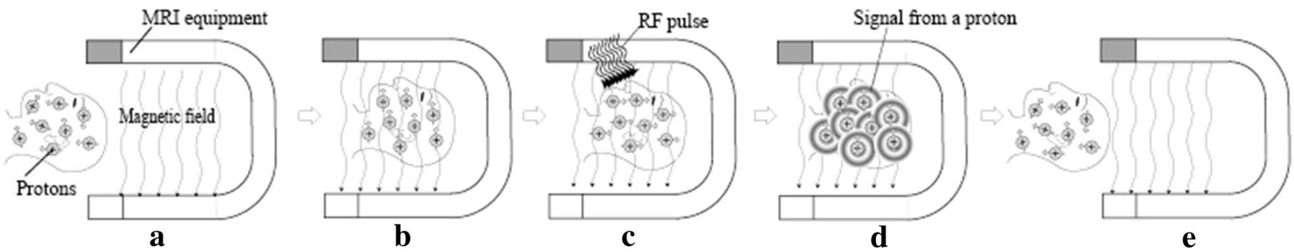

Fig. 3 Conceptual diagram of obtaining signals from protons in the body. **a** Protons are generally oriented in a variety of directions within the body. **b** When entering a powerful magnetic field, they change from having a scattered orientation to being aligned within the magnetic field. **c** If an RF pulse is applied in this state, the protons become deflected by 90°. The deflected protons then continue to store the energy of the RF pulse. **d** If the RF pulse is suspended, the deflected protons return to their previous orientation while emitting their stored energy. **e** After the scan, when exiting the MRI machine, the protons become reoriented in scattered directions within the body

these tissues contain many hydrogen atoms. MRI machines produce images based on the nuclei of these hydrogen atoms (also known as protons). The hydrogen nuclei have a magnetic field; therefore, they can each be considered as a tiny magnet (Fig. 2).

Protons are generally oriented in a variety of directions within the body (Fig. 3a). However, when entering a powerful magnetic field, they change from having a scattered orientation to being aligned within the magnetic field (Fig. 3b). If a radio frequency (RF) pulse is applied in this state, the protons become deflected by 90° (Fig. 3c). This phenomenon is known as nuclear magnetic resonance. When the RF pulse is applied, a large sound unique to the MRI scan is emitted. The deflected protons then continue to store the energy of the RF pulse. If the RF pulse is suspended, the deflected protons return to their previous orientation while emitting their stored energy. The duration of this return differs depending on the type of tissue (muscle, blood, fat, etc.) in which the protons are bonded. This energy is received by a receiver as a signal, and an image is formed by analyzing this signal and the time duration of the return (Fig. 3d). After the scan, when exiting the MRI machine, the protons become reoriented in scattered directions within the body (Fig. 3e).

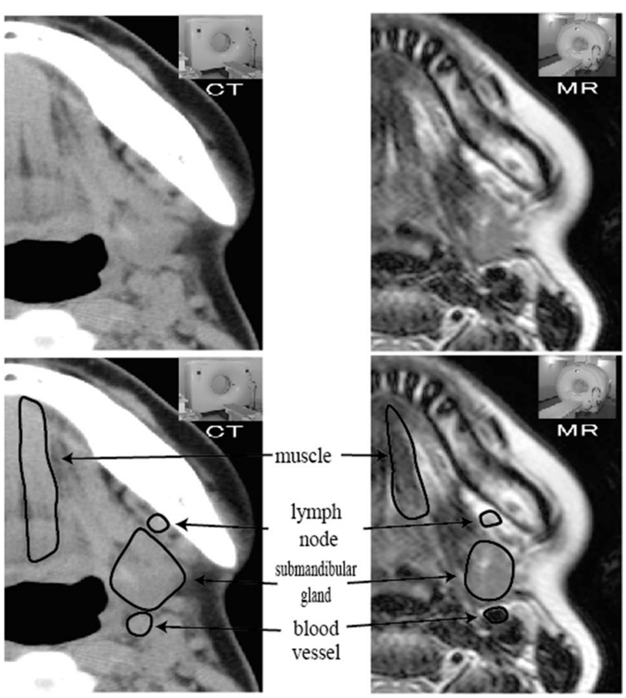

Fig. 4 Computed tomography (CT) and magnetic resonance imaging (MRI) of the same slice. MRI has a lower spatial resolution than CT; therefore, tissue boundaries are difficult to ascertain. In contrast, MRI has a high ability to resolve tissues. While CT scans do not indicate density differences among tissues, the differences in density among tissues are clear in MRI scans

Advantages and disadvantages of MRI

The advantages of MRI include its (1) noninvasiveness and lack of radiation exposure, (2) ability to produce any given tomographic image, and (3) ability to display blood vessels without using a contrast agent. In addition, MRI scans provide higher tissue resolution and a lower temporal resolution than do CT scans, which also produce tomographic images (Fig. 4). The disadvantages of MRI include the (1) long scan time (approximately 30–60 min), (2) inability to obtain a signal from cortical bone and calcifications, (3) inability to perform the test when metal is present in the body, and (4) difficulty in scanning claustrophobic patients.

MRI artifacts caused by metal

Because MRI examinations utilize a magnetic field, artifacts can occur due to the presence of magnetic metals in the imaging area. Even if the magnetic metals themselves

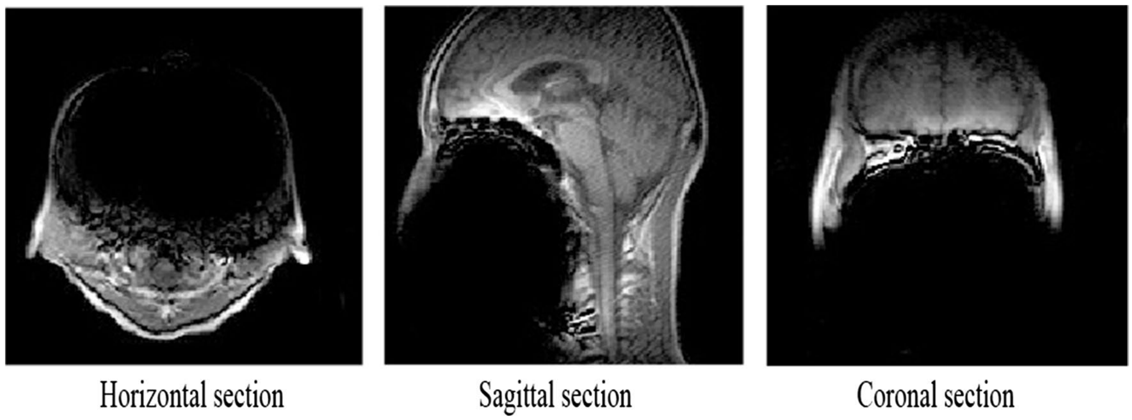

Fig. 5 Conception diagram of a metal artifact. Artifacts caused by metals in computed tomography scans appear only within slices, but they appear in three-dimensional directions in magnetic resonance imaging scans

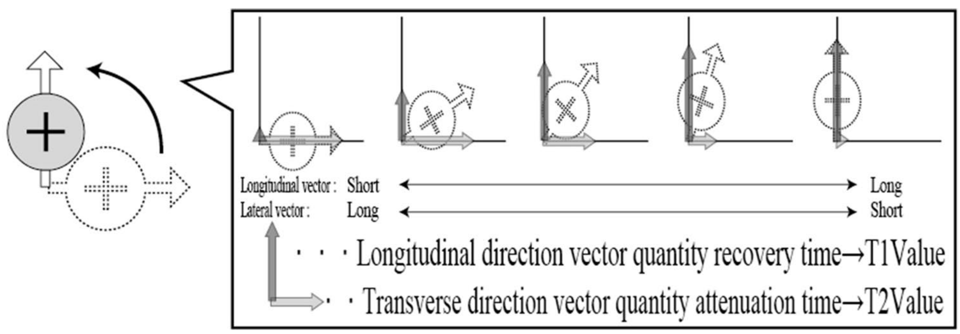

Fig. 6 Proton phase and vector quantity. When deflected protons revert to their original states, the longitudinal and transverse vector quantities change. The duration of time required for recovery of the vector quantity in the longitudinal direction is known as the T1 value, and that required for recovery of the vector quantity in the transverse direction is the T2 value

do not exhibit magnetism, they become magnets in the magnetic field. As a result, they form their own magnetic fields that cause the local magnetic field to become nonuniform. Therefore, while artifacts only appear in the direction of slices in CT scans, they appear as three-dimensional missing signals in MRI examinations (Fig. 5).

Basic MRI images

T1- and T2-weighted images

As explained earlier, protons in the body are deflected by an RF pulse in the magnetic field of an MRI device. When the RF field is removed, the protons return to their original state. The duration of time required to return to the vector quantity in the longitudinal direction is known as the T1 value, and the time required to attenuate to the vector quantity in the transverse direction is the T2 value (Fig. 6). Graphs of vector quantity changes in the longitudinal and transverse directions over time are called the T1 curve and T2 curve, respectively (Fig. 7). Changes in these vector quantities over time vary according to the type of tissue. T1-weighted images (T1WI) represent tissues with a higher signal of the shorter T1 value (short longitudinal relaxation time and rapid signal recovery). T2-weighted images (T2WI) represent tissues with a higher signal of the longer T2 value (long transverse relaxation time and slow signal attenuation). T1WI and T2WI signals in normal tissue are shown in Table 1.

Diagnoses using T1WI and T2WI

T1WI and T2WI are the basic images used for MRI diagnoses, the first step of which is comparison of the two images. Some basic cases are shown in Figs. 8 and 9. Figure 8

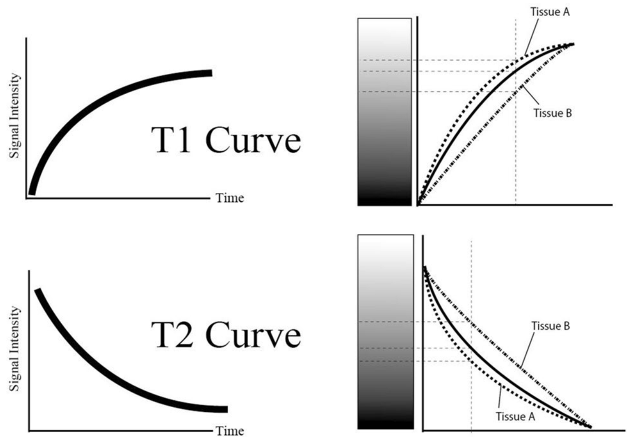

Fig. 7 T1 and T2 curves. The T1 curve *graphs* the changes in the longitudinal vector quantity over time. The T2 curve *graphs* the changes in the transverse vector quantity over time. The difference between the signals for each tissue corresponds to the difference in density in the image. Tissue A shows a high signal intensity due to the short relaxation time along the T1 curve, whereas it shows a low signal intensity along the T2 curve because of the long relaxation time. Furthermore, Tissue B shows a low signal intensity on the T1 curve because of its long relaxation time, whereas it shows a high signal intensity on the T2 curve because of the short relaxation

shows a 48-year-old man who presented with the chief complaint of swelling in the right cheek. A lesion with a high T1WI signal and high T2WI signal was found in the right cheek. This lesion comprised fatty tissue as indicated by both high T1WI and T2WI signals; therefore, a lipoma was diagnosed. Figure 9 shows a 24-year-old woman who presented with the chief complaint of swelling in the left submandibular region. A lesion with a low T1WI signal and high T2WI signal was found in the left submandibular region. The lesion comprised water-based tissue as indicated by the difference in T1WI and T2WI signals, resulting in the diagnosis of a ranula. As demonstrated by these cases, the interior structure of lesions is inferred by comparing the T1WI and T2WI signal strengths.

Table 1 Magnetic resonance imaging signals of normal tissue

	T1WI	T2WI
High intensity (light gray)	Fat Bone marrow (adult)	Fat Water Bone marrow (adult) Bone marrow (child)
Low intensity (dark gray)	Water Muscle Bone marrow (child)	Muscle
No signal intensity (black)	Cortical bone•calcium deposition Enamel•dentin Air•blood vessel	

Signal values differ in each type of tissue depending on the amount of protons present. Understanding the T1-weighted image (T1WI) and T2-weighted image (T2WI) signal values (image density) in normal tissue is important for achieving correct diagnoses. Because the bone marrow signal differs between children and adults and blood vessels do not produce a signal, caution is required for interpretation, especially with T1WI

Fat-suppression images

Various fat-suppression techniques are available, including selective fat suppression, water/fat separation, and nonselective fat suppression; however, short-TI inversion recovery (STIR) is frequently used for the head and neck region. STIR images increase the ability to detect lesions and are useful for visualizing organs with boundaries contacting fatty tissue. STIR is relatively tolerant of magnetic field inhomogeneity, but care is needed, because lesions mixed with blood components (blood metabolic products) are suppressed together with fat.

Figure 10 shows a 29-year-old man who presented with the chief complaint of pain and swelling in the right cheek. In T2WI, inflammatory exudate and fat were both depicted with a high signal, and the range of inflammation was, therefore, difficult to ascertain. However, STIR suppressed the signal from fat; hence, the range of inflammation became clear.

Contrast-enhanced MRI

A gadolinium preparation is used as the contrast agent in MRI; typically, 0.2 ml/kg is administered intravenously. Gadolinium has a high T1-shortening effect and is, therefore, used as a contrast agent to increase the diagnostic ability [9, 10]. The gadolinium contrast agent has an adverse effect rate of approximately 1–2% and is thus considered safer than iodine contrast agents. However, it is contraindicated for asthmatic patients. In addition, caution is required because of the risk of nephrogenic systemic fibrosis in patients with severe renal impairment [11, 12].

Capturing sequential images at fixed intervals while injecting the contrast agent and then graphing the contrast effect along the time axis produces a time–signal intensity curve (TIC). This curve is useful for identifying features such as malignant neoplasms based on the graph pattern [13–17]. The main lesions and TIC patterns are shown in Fig. 11.

Figure 12 shows a 21-year-old man who presented with the chief complaint of swelling in the floor of the mouth. Even after some time had elapsed, the contrast agent did not enter the lesion. The TIC exhibited a plateau shape, and

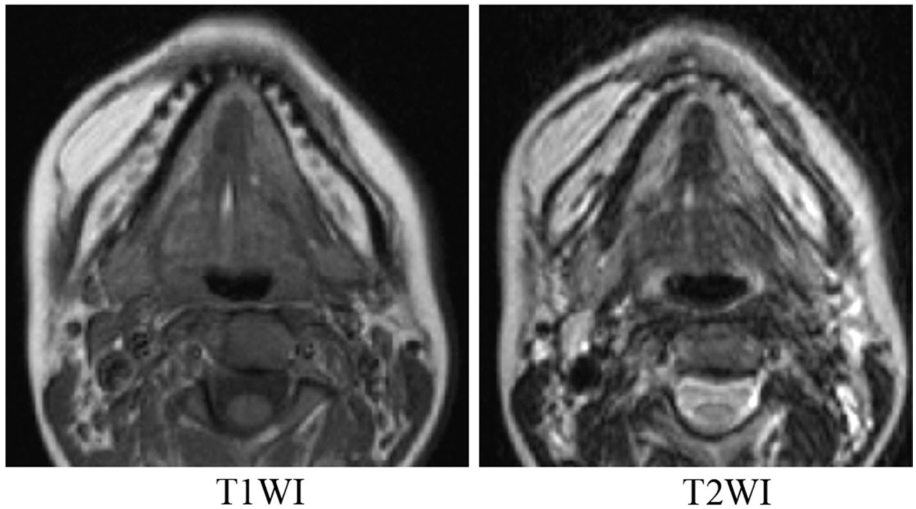

Fig. 8 Magnetic resonance imaging of a lipoma. The lesion in the right cheek is depicted as a high signal in both T1-weighted and T2-weighted images; therefore, the contents can be diagnosed as fatty tissue

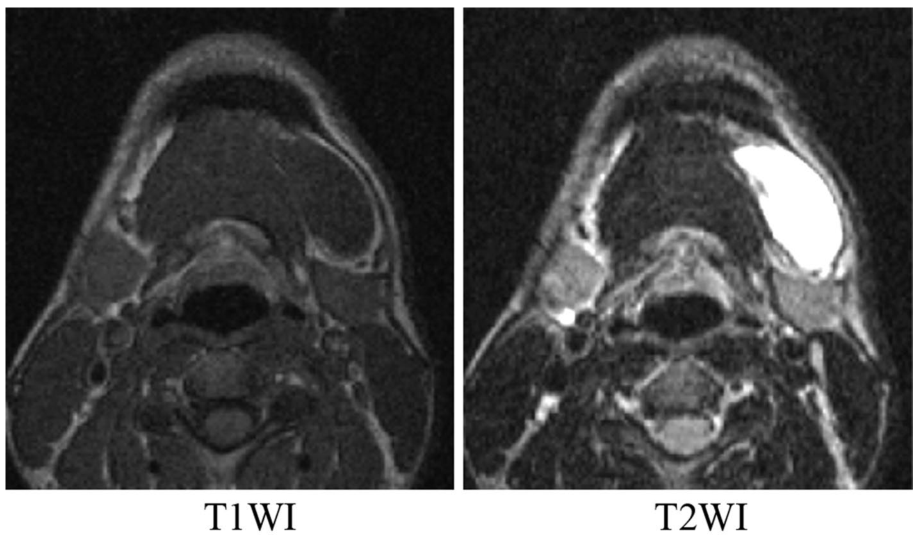

Fig. 9 Magnetic resonance imaging of a ranula. The lesion in the left submandibular region is depicted as having a low signal in T1-weighted images and high signal in T2-weighted images. Therefore, the contents can be defined as water

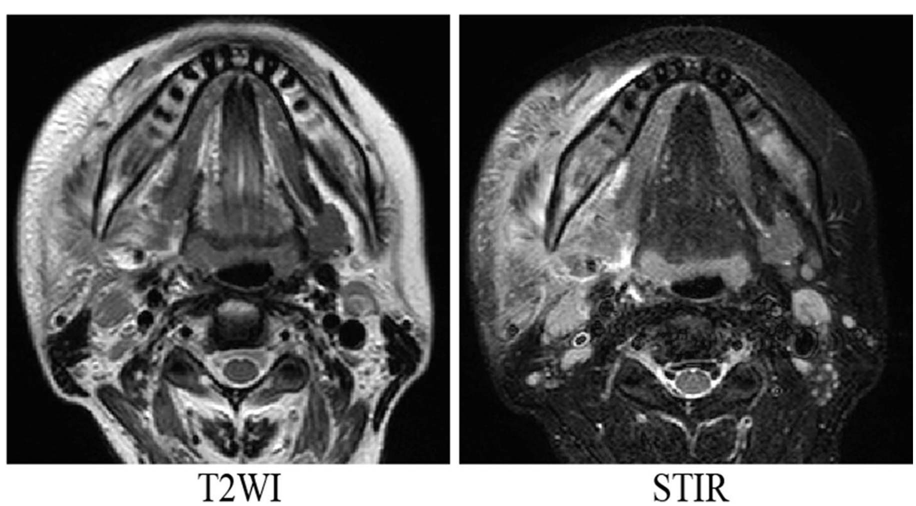

Fig. 10 Magnetic resonance imaging of inflammation in the right cheek. In the T2-weighted image, fatty tissue and water-based tissue are both depicted as having high signals. Therefore, the range of inflammation is difficult to determine. Because short-TI inversion recovery cancels the signal from fatty tissue, the range of inflammation is easy to ascertain

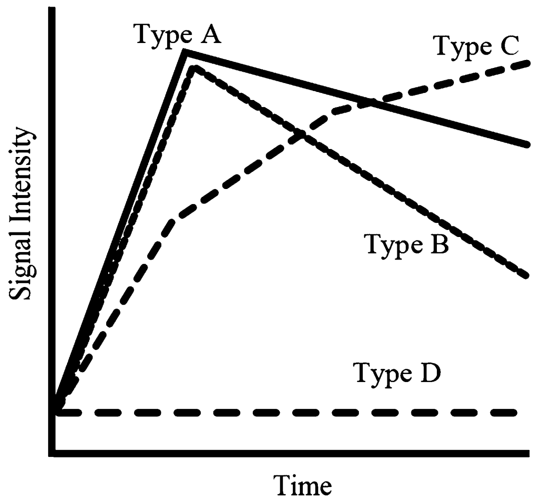

Fig. 11 Pattern of the time–signal intensity curves. Time–signal intensity curves reflect the state of blood flow within a lesion. By observing the signal within a lesion at regular time intervals, it is possible to infer the blood flow state within the lesion, which is useful for identifying diseases. *Type A* rapid initial enhancement followed by a gradual decrease in enhancement (e.g., squamous cell carcinoma). *Type B* rapid initial enhancement followed by a rapid decrease in enhancement (e.g., Warthin tumor, malignant lymphoma). *Type C* gradual increase in enhancement (e.g., pleomorphic adenoma). *Type D* no enhancement (e.g., cyst)

a ranula was consequently diagnosed. Figure 13 shows a 67-year-old woman who presented with the chief complaint of a tongue ulcer. The contrast agent was rapidly absorbed by the lesion over time, and the peak was reached within 90 s after the start of contrast administration. The contrast agent within the lesion was then released gradually. The TIC exhibited a gradual decline; therefore, oral squamous cell cancer was diagnosed.

Diffusion-weighted image

Diffusion-weighted imaging is characterized by the visualization of Brownian motion of water molecules (Fig. 14). The quantification of diffusion-weighted imaging is called an apparent diffusion coefficient map (ADC map). ADC maps are useful for establishing a differential diagnosis by measurement of ADC values [16, 18, 19]. In patients with cysts and inflammation, ADC values run high due to the large numbers of water molecules. Low ADC values are exhibited in tumors, because the cellular components are quite dense (Fig. 15).

MRI is an important testing method that is essential for diagnoses in the maxillofacial area. To some extent, however, the principles underlying MRI examinations can be difficult to understand for beginners. MRI produces a variety of images other than those mentioned in this review, including those involving fluid-attenuated inversion recovery, diffusion-weighted imaging, apparent diffusion coefficients, and magnetic resonance angiography. Furthermore, new imaging techniques are being developed every year; therefore, it is difficult to stay up-to-date with the latest MRI knowledge. It is important to learn about these new images based on a solid understanding of the basics of MRI examinations presented herein.

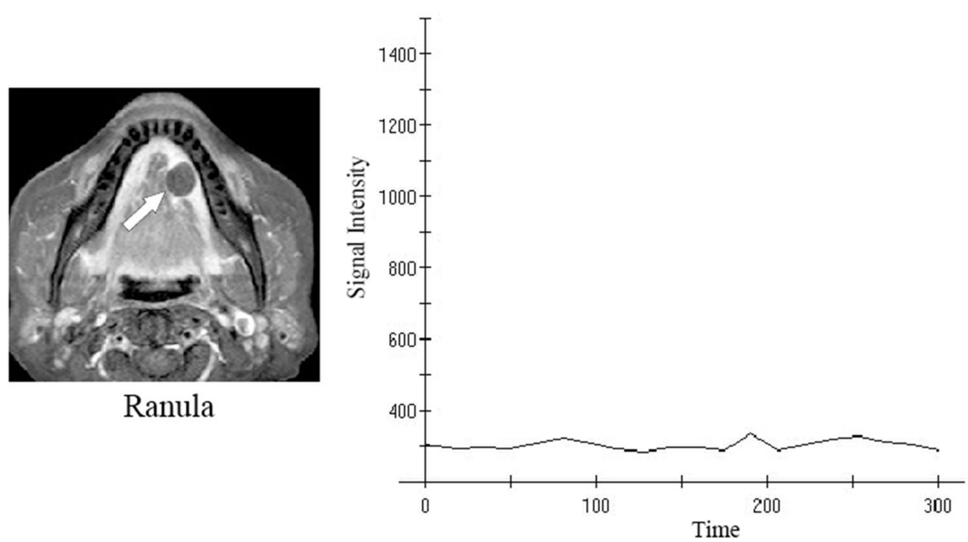

Fig. 12 Time–signal intensity curves of the ranula. Ranulas have no internal blood flow; therefore, contrast agent does not flow into the lesion. The time–signal intensity curve consequently exhibits a plateau shape

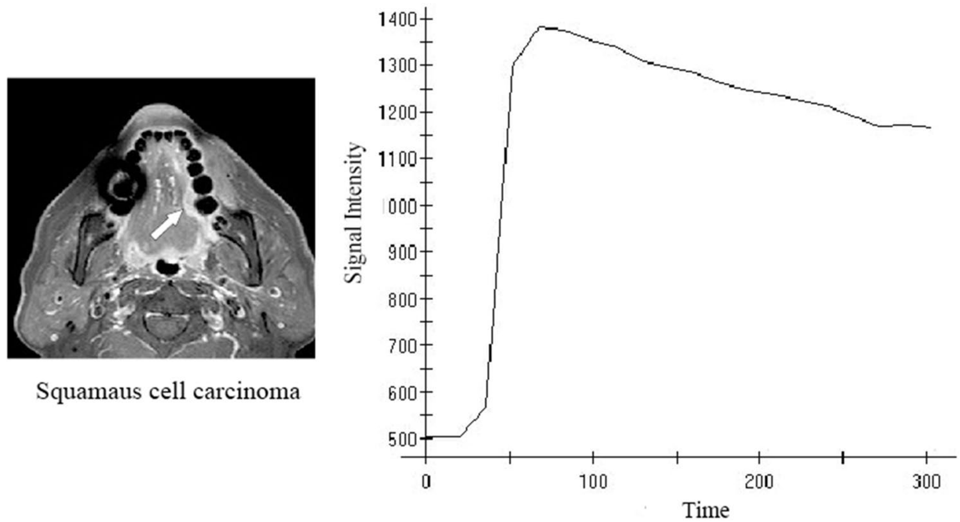

Fig. 13 Time–signal intensity curve of squamous cell carcinoma. Squamous cell carcinoma comprises tumor tissue with significant blood flow inside; therefore, the contrast agent flows rapidly into the lesion. Thereafter, the contrast agent slowly flows out from the tumor. The time–signal intensity curve exhibits a sudden increase and then a gradual decrease

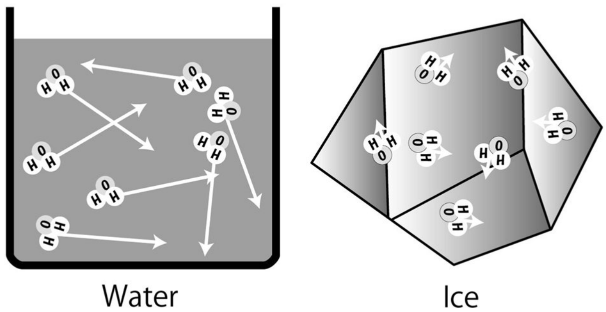

Fig. 14 Movement of water molecules in liquids and solids: apparent diffusion coefficient (ADC) values. Water molecules are more easily diffused in liquids because of their vigorous Brownian motion. Therefore, ADC values are high. In contrast, because of the lack of Brownian motion in solids, diffusion of water molecules does not readily occur and the ADC values are correspondingly low

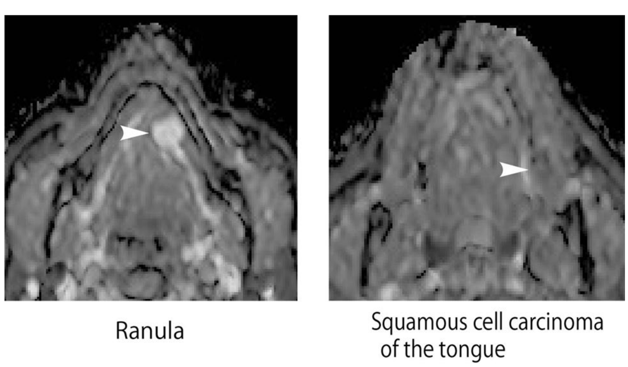

Fig. 15 Apparent diffusion coefficient (ADC) values in ranula and squamous cell carcinoma. Due to the high cellular density in squamous cell carcinoma, the ADC value is low. The ADC value in this case is 1.31×10^{-3} mm^2/s. Because the ranula contains liquid, the ADC value is high. In this case, it is 2.87×10^{-3} mm^2/s

Compliance with ethical standards

The authors declare no conflict of interest associated with this manuscript.
This article does not contain any studies with human or animal subjects performed by the any of the authors.

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