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REVIEW PAPER

Magnetic Resonance Imaging (MRI) – A Review

Girish Katti, Syeda Arshiya Ara, Ayesha Shireen

Abstract

Magnetic Resonance Imaging (MRI) has progressed over 30 years from being a technique with great potential to one that has become the primary diagnostic investigation for many clinical problems. Its application was initially limited to the neuro-axis, now covers all regions of the body and an increased knowledge base has provided a better understanding of how it can best be utilized, either alone or in conjunction with other techniques, in order to maximize diagnostic certainty. This article aims to describe brief historical review of magnetic resonance imaging, MRI physics, instrumentation, basic sequences, artifacts, MR safety, MR Contrast agents, advantages /disadvantages of magnetic resonance imaging, its application in the maxillofacial region and recent advances in MR imaging.

Key Words: MRI;Dentistry

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Introduction

MRI is a non-invasive method of mapping the internal structure and certain aspects of function within the body. It uses non-ionizing electromagnetic radiation and appears to be without exposure-related hazard. It employs radio frequency (RF) radiation in the presence of carefully controlled magnetic fields in order to produce high quality cross-sectional images of the body in any plane. The MR Image is constructed by placing the patient inside a large magnet, which induces a relatively strong External magnetic field. This causes the nuclei of many atoms in the body, including Hydrogen, to align them with the magnetic field and later application of RF signal, Energy is released from the body, detected and used to construct the MR image by Computer.(1) Table 1 shows the brief history of the MRI development.

Basic MR Physics

Atomic Structure: The nucleus of an atom consists of two particles;

1. Protons : The protons have a positive charge and
2. Neutrons: The neutrons have a neutral charge.
3. Electrons: Orbiting the nucleus are the electrons, which carry a negative charge

The two properties commonly used to categorize elements are:

1. The atomic number which represents the number of protons in the nucleus and is the primary index used to differentiate atoms.
2. The atomic mass number which is the total number of protons and neutrons.

Atoms with the same atomic number but different atomic weight are called isotopes. A third property of atomic nuclei is called nuclear spin. All of these particles are in motion. Both the neutrons and protons spin about their axis.(2)

1857-1952	Larmor relationship- Sir Joseph Larmor (3)
1930	Isidor Isaac Rabi succeeded in detecting single state of rotation of atoms and molecules, and in determining the mechanical and magnetic moments of the nuclei.(4)
1946	MR phenomenon - Bloch and Purcell(5)
1952	Nobel Prize - Bloch and Purcell(6)
1950,1960-1970	NMR developed as analytical tool(3)
1972	Computerized Tomography(3)
1973	Back projection MRI – Lauterbur(3)
1975	Fourier Imaging - Ernst(3)
1977	Echo-planar imaging – Mansfield(7)
1980	FT MRI demonstrated – Edelstein(3)
1986	Gradient Echo Imaging NMR Microscope(8)
1987	MR Angiography - Dumoulin(3)
1991	Nobel Prize – Ernst(9)
1992 ¹	Functional MRI(3)
1994	Hyperpolarized ¹²⁹ Xe Imaging(3)
2003	Nobel Prize - Lauterbur and Mansfield(3)
Table 1 Brief history of MRI	

Spin: Spin is a fundamental property of nature like electrical charge or mass. Spin comes in multiples of 1/2 and can be + or - Protons, electrons, and neutrons possess spin. Individual unpaired electrons, protons, and neutrons each possess a spin of 1/2.

Properties of Spin: When placed in a magnetic field of strength B, a particle with a net spin can absorb a photon, of frequency ν . The

frequency ν depends on the gyromagnetic ratio, γ of the particle⁷.

$$\nu = \gamma B$$

For hydrogen, $\gamma = 42.58 \text{ MHz / T}$.

Nuclei suitable for MRI are those which have an unpaired proton or neutron which possess net spinning charge or have angular momentum. This is because, as spin is associated with an electrical charge, a magnetic field is generated in nuclei with unpaired nucleons, causing these nuclei to act as magnets with North and South poles (magnetic dipoles).⁽⁶⁾

Importance of hydrogen nucleons in MRI

It is the major species that is MR sensitive and most abundant atom in the body in the form of water (H_2O). For the hydrogen nucleons which consist of a solitary, unpaired proton acts as a magnetic dipole. These magnetic dipoles, in the absence of external influence, are randomly oriented and as such have zero net Magnetization.⁽⁶⁾ When an external magnetic field is applied to this sample, all the hydrogen nuclear axes true up in the direction of the magnetic field, producing a quantity of net magnetization, and this can result in of 2 ways either in the direction of the field i.e., which parallel the external magnetic field – spin up, or align anti-parallel (opposite) with the magnetic field, spin down. These orientations correspond to lower energy state and highly energy states of the dipole respectively. Nuclei can be made to undergo transition from one energy state to another by absorbing or releasing certain quantity of energy. This energy can be supplied or recovered in the form of electromagnetic energy in RF portion of the electromagnetic spectrum and this transition from one energy level to another is called resonance. ⁽¹⁰⁾

When an external magnetic field is applied, their N and S poles do not align exactly with the direction of the magnetic field. The axes of spinning protons oscillate or wobble with a slight tilt from a position which was parallel with the flux of external magnet. This tilting or wobbling is called precession. The rate or frequency of precession is called the Resonant or Larmor frequency, which is proportional to the strength of the applied magnetic field. The Larmor frequency of hydrogen is 42.58 MHz in a magnetic field of 1 Tesla, where one Tesla is 10,000 times the earth's magnetic field. The magnetic field strengths used for MR imaging range from 0.1 to 4.0T.⁽¹⁰⁾

Larmor equation is expressed as

$$F = \gamma B$$

Where F is the resonant frequency, γ is the gyro magnetic ratio and B is the applied field.

In summary, when nuclei are subjected to the flux of an external magnetic field, two energy states result. Spin-up: which is in the direction of the field and spin-down: This is in the opposite direction of the field. The combined effect of these two energy states is a weak net magnetic moment, or magnetization vector (MV) Parallel with the applied magnetic field. When energy in the form of all electromagnetic wave from a RF antenna coil is directed tissue with protons (hydrogen nuclei) that are aligned in the Z axis by an external static magnetic field (by the imaging magnet), the protons in the tissue that have a Larmor frequency matching that of electromagnetic wave absorb energy and shift or rotate away from the direction induced by the imaging magnet.

If longer the RF pulse is applied, the greater the angle of rotation. If pulse is of sufficient intensity (duration), it will rotate the net tissue magnetization vector into a transverse plane (XY plane), which is perpendicular to longitudinal alignment (Z-Axis) and cause all the protons to precess in phase, this is referred to as a 90° RF pulse or a flip angle of 90° . At this precise moment, a maximal RF signal is induced in a receiver coil. This signal depends on the presence or absence of hydrogen and also all the degree to which hydrogen is bound within a molecule. Eg: Bone – due to presence of tightly bound hydrogen atoms, they do not align themselves with external magnetic field and do not produce a usable signal.

In soft tissues and liquids – due to presence of loosely bound or mobile hydrogen atoms, tilt and align to produce detectable signal. The measure of the concentration of loosely bound hydrogen nuclei available to create the signal is referred to as proton density or spin density of the tissue in question.⁽¹⁰⁾ When the radio waves (RF pulse) are turned off, 2 events occur simultaneously

- The radiation of energy and the return of nuclei to their original spin state at a lower energy. This process is called relaxation and the energy loss is detected as a signal, which is called free induction decay (FID).
- First, the nuclei in transverse alignment begin to realign themselves with the main magnetic field and net magnetization regions to the original longitudinal orientation. This relation is accomplished by a transfer of energy from individual hydrogen nuclei (spin) to the surrounding molecules (Lattice).

- The time constant that describes the rate at which the net magnetization returns to equilibrium by this transfer of energy is called the T_1 relaxation time or spin lattice relaxation time. (T_1 -Short – 500msec–short repetition twice between parallel 20 msec – signal recovery). T_2 – 2000msec R and 80msec 0 long TE.

A T_1 weighted image is produced by a short repetition time between RF pulses and a short signal recovery time. Because T_1 is all exponential growth time constant, a tissue with short T_1 produces all intense MR signal and is displayed as bright white in a T_1 weighted image. A tissue with long T_1 produces a – low intensity signal and appears dark in MR image. Second, the magnetic moments of adjacent hydrogen nuclei begin to interfere with one another; this causes the nuclei to dephase, with a resultant loss of transverse magnetization.(10) The time constant that describes the rate of loss of transverse magnetization is called T_2 relaxation time / transverse (Spin) relaxation time. The transverse magnetization rapidly decays (exponentially) to zero, as do the amplitude and duration of the detected radio signal. A T_2 -weighted image is acquired using a long repetition time between RF pulses and a long signal recovery time. A tissue with a long T_2 produces a high-intensity signal and is bright in the image. One with short T_2 produces a low-intensity signal and is dark in the image.(6)

Image contrast among the various tissues in the body is manipulated in MRI by varying the rate at which the RF pulse is transmitted. A short repetition time (TR) of 500msec between pulses and a short echo of signal recovery time (TE) of 20msec produces T_1 weighted image. A long TR (2000msec) and a long TE (80msec) produces T_2 weighted images for every diagnostic task, the operator must decide which imaging sequence will bring out optimal image contrast. (10) T_1 weighted images are called fat images because the fat has the shortest T_1 relaxation time and the lightest signal relative to other tissues and thus appear bright in the image. High anatomic detail is possible in this type of image because of good image contrast. T_1 weighted images are thus useful or depicting small anatomic regions (eg: TMJ) where high spatial resolution is required.(10)

T_2 Weighted images are called water images because water has the longest T_2 relaxation time and thus appear bright in the image. In general, the T_2 time of abnormal tissues is longer than that of normal tissues. Images with T_2 weighting are most commonly

used when the practitioner is looking for inflammatory changes and tumors.

T_1 Weighted images are more commonly used to demonstrate anatomy. In practice, images often must be acquired with both T_1 and T_2 weighting to separate the several tissues by contrast resolution. Localization of MRI to specific part of the body (selecting a slice) and the ability to create a 3 dimensional image depends on the fact that the Larmor frequency of a nucleus is governed in part by the strength of the external magnetic field.

The magnetic gradient is produced by three electromagnetic coils within the bore of imaging magnet. The coils surround the patient and produce magnetic field that oppose and redirect the magnetic flux in 3 orthogonal or right angle directions to delineate individual volumes of tissues (volumes), which are subjected to magnetic fields of unique strength. Partitioning the local magnetic fields lines all the hydrogen protons, in particular voxel to the same resonant frequency. This is called selective excitation, when a RF pulse with a range of frequencies is applied, a voxel of tissue tuned to one of the frequencies is excited, when the RF radiation is terminated, the excited voxel radiates that distinctive frequency, identifying and localizing it. The band width or spectrum of frequencies of the RF pulse and the magnitude of slice selecting gradient determine the slice thickness. (10) Slice thickness can be reduced by increasing the gradient strength or decreasing the RF band width (frequency range). How does a patient attain the results of the MRI scan? After the MRI scanning is completed, the computer generates visual images of the area of the body that was scanned and these images are transferred to film (hard copy), this film is interpreted by the radiologist.

Signal localization: techniques for building images: encoding process, two concepts need to be separated. The physical relationship that makes building up an image possible is the proportional relationship of the resonant frequency to the strength of the magnetic field (Larmor equation).

In understanding the MR Spatial

1. Resonant frequency (as given by the Larmor Equation spins processing at a high resonant frequency when in a high magnetic field)
2. Spatial frequency (the high spatial frequency components of an image corresponding to the fine detail in that image).(6)

Imaging is performed using the properties of the Larmor relationship but, in addition to this,

the data are encoded in the spatial frequency domain. The latter refers to the sampled signal being in the wonderful world of K-Space.

The steps involved in the production of an MRI study may be summarized as follows(1):

1. A powerful, uniform, external magnetic field is employed to align the normally randomly oriented water contained in the tissue being examined.
2. This alignment (or magnetization) is next perturbed or disrupted by introduction of external RF energy at an appropriate frequency so as to induce resonance. Spatial localization is obtained through application of a spatially dependent magnetic field (referred to as a gradient) during the same time that RF energy is introduced into the tissue. The gradient field selectively modulates the resonant frequency of the patient in accordance to the Larmor equation.
3. The nuclei return to their restive alignment through various relaxation processes and in so doing emit RF energy proportional to the magnitude of their initial alignment or magnetization.
4. After an appropriate period following initial RF deposition, the emitted signals are measured or read out.
5. A mathematical process called Fourier transformation is used to convert the frequency formation contained in the signal from each location in the imaged plane to corresponding intensity levels, which are then displayed as shades of gray in a matrix arrangement of, for example, 256 X 256 pixels.
6. Protons in the various tissues in the imaged slice realign with the magnetic field at different rates, so that at any given moment there is difference in signal strength between various tissues. This difference in signal strength from region to region constitutes the basis of tissue contrast and forms the substrate for interpretation of the image.

Advantages of MRI(6)

1. No Ionizing Radiation: RF pulses used in MRI do not cause ionization and have no harmful effects of ionizing radiation. Hence can be used in child bearing ladies and children.
2. Non-invasive: MRI is non-invasive.
3. Contrast resolution: It is the Principle advantage of MRI, i.e. ability of an image process to distinguish adjacent soft tissue from one another. It can manipulate the contrast between different tissues by altering the pattern of RF pulses.
4. Multiplanar image: With MRI, we can obtain direct, sagittal, coronal and oblique image which is impossible with radiography and CT.
5. It could differentiate between acute and chronic transit and fibrous phases parallel with histopathological changes.
6. Absence of significant artifact associated with dental filling.

7. No adverse effect has yet been demonstrated.
8. Image manipulation can be done.
9. Useful in determining intramedullary spread.

Disadvantages of MRI(6)

1. Claustrophobia i.e. morbid fear of closed places because the patient is within the large magnet up to one hour.
2. MRI equipment is expensive to purchase, maintain, and operate. Hardware and software are still being developed.
3. Because of the strong magnetic field used in patient electrically, magnetically or mechanically activated implants such as cardiac pacemakers, implantable defibrillators and some artificial heart valves may not be able to have MRI safely.
4. The MRI image becomes distorted by metal, so the image is distorted in patients with surgical clips or stents, for instance.
5. Bone does not give MR signal, a signal is obtained only from the bone marrow. Long scanning time and requires patient's co-operation.
6. The very powerful magnets can pose problems with sitting of equipment although shielding is now becoming more sophisticated.
7. MRI scanners are noisy.
8. Patient could develop an allergic reaction to the contrasting agent, or that a skin infection could develop at the site of injection.
9. MRI cannot always distinguish between malignant tumors or benign disease, which could lead to a false positive result.
10. Facilities are not widely available, but with the development of small open systems suitable for district general hospitals.
11. Bone, teeth, air and metallic objects all appear black, making differentiation difficult.

Characteristic Normal MR Appearance of Oral and Maxillofacial Region:

MR images are commonly acquired using Spin echo pulse sequence. T1 and T2 Weighted images are obtained for examinations of oral and maxillofacial regions. T1-Weighted images are used for anatomical evaluation and T2- weighted images are for the detection of pathological processes. Both T1 and T2 - Weighted images are studied for disease detection, extent and character. Images in the Coronal and Axial planes are routinely obtained for three-dimensional evaluation of disease in MR examinations. Images in the Sagittal plane are sometimes added. To understand normal MRI Anatomy of Oral and Maxillofacial regions, it is necessary to be familiar with some terms that express MR signal intensities.

Signal intensity: The intensity of signal from each tissue on MR images is termed the "Signal Intensity".(11)

- 1) Low signal intensity: If the signal intensity from a tissue is lower than that of muscle on T1 or T2

- Weighted images, it is referred to as “low signal intensity”.
- 2) High signal intensity: If the signal intensity from a tissue is same or higher than that from fat tissue on T1 or T2 –Weighted images, it is referred to as “High signal intensity”.
 - 3) Intermediate signal intensity: If the signal intensity from a tissue is somewhere between muscle and fat tissue signals on T1 or T2 –Weighted images, it is referred to as “Intermediate signal intensity”.

Signal intensity for each tissue(10, 11):

1. Fat tissues: Fat tissue appears as high signal intensity on T1-Weighted images and low signal intensity on T2-Weighted images with fat suppression.
2. Muscle tissue: Muscle commonly appears as low signal intensity on both T1 and T2-weighted images with fat suppression except Lingual muscles, which have intermediate signal intensity on T1-weighted images due to their relatively high fat component compared to other muscles.
3. Cortical bone tissue: Cortical bone tissue is indicated as a signal intensity void on T1 and T2-weighted images. Cancellous bone tissue demonstrates high intensity on T1-weight images and low intensity on T2-weighted images with fat suppression.
4. Lymph nodes and tonsils: Lymph nodes and tonsils have low intensity on T1-Weighted images and intermediate –high signal intensity on T2-Weighted images with fat suppression.
5. Teeth: The teeth, except pulp tissue, appear as a signal void on T1 and T2-weighted images; pulp tissue has intermediate signal intensity on T1 –Weighted images and high signal intensity on T2 weighted images with fat suppression. The dental follicle of an unerupted tooth has signal intensity on T1-weighted images and high signal intensity on T2-weighted images with fat suppression.
6. Parotid gland: Signal intensities differ among the tissues of the salivary glands. The parotid glands have relatively high signal intensity on T1-weighted images and low signal intensity on T2-weighted images with fat suppression. While the parotid ducts have high signal intensity on T2-weighted images with fat suppression and low signal intensity on T1-weighted images.
7. Submandibular gland: The submandibular glands have intermediate signal intensity on T1 –weighted images and low signal intensity on T2-weighted images with fat suppression. Ducts have high signal intensity on T2-weighted images with fat suppression and low signal intensity on T1-weighted images.
8. Sublingual gland: The sublingual gland has intermediate signal intensity on T1-weighted images and high signal intensity on T2-weighted images with fat suppression.
9. Temporo-Mandibular Joint (TMJ): The discs of the TMJ have low signal intensity on T1 and T2-weighted images. TMJ effusion appears as low

signal intensity on T1-weighted images and high signal intensity on T2-weighted images.

10. Cavities: The cavities (maxillary sinus and nasal cavities) appear as void signal on T1 and T2-weighted images.
11. Blood vessels: Blood vessels usually have void signal intensity due to blood flow, termed ‘signal void’, on both T1 and T2 –weighted images, however, some vessels with lower flow rate appear with high signal intensity on T2-weighted images with fat suppression and low intensity on T1-weighted images, like the signal from water.

Indications of MRI in the oral and maxillofacial region(10, 11)

1. For the diagnosis and evaluation of benign and malignant tumors of jaws.
2. Tumor staging evaluation of the site, size and extent of all soft tissue tumors and tumor like lesions, involving all areas including.
 - The salivary glands
 - The pharynx
 - The Sinuses
 - The orbits.
3. To evaluate structural integrity of trigeminal nerve in trigeminal neuralgia.
4. In surgery of parotid gland MRI can detect the cause of facial nerve within the glandular tissue and help lessen the likelihood of post-operative facial nerve palsy.
5. For the assessment of intracranial lesions involving particular posterior cranial fossa, the pituitary and the spinal cord.
6. For non-invasive evaluation of the integrity and position of articular disk within the TMJ.
7. Investigation of the TMJ to show both the bony and soft tissue components of joint including disc position:
 - a. When diagnosis of internal derangement is in doubt,
 - b. As a preoperative assessment before disc surgery,
 - c. Implant assessment.

Recent advances in MR imaging(12):

Every year seems to bring a new application of MRI or a new pulse sequence which opens up new imaging opportunities with MRI.

1) Volume imaging – 3D imaging: Volume imaging is the requisition of magnetic resonance data from a volume rather than a tomographic slice. It can be thought of as collecting several contiguous slices through a region of imaged object.

2)Flow imaging (MRI angiography MRA): Angiography is the imaging of flowing blood in the arteries and veins of the body. MRA produces images of flowing blood. The intensity in these images is proportional to the velocity of the flow. There are 3 general types of MRA – time of flight, phase contrast angiography and contrast enhanced angiography.

3)Fast spin: Echo imaging is a multi-echo spin echo sequence where diff parts of space are recorded by diff

spin echoes. The benefit of the technique is that a complete image can be recorded in 1/4th of the time.

4)Chemical shift imaging (fat suppression): Is the production of an image from just one chemical shift component in a sample.

5)Echoplanar imaging (functional MRI) (fMRI): Is a rapid MRI technique which is capable of producing tomographic images at video rates. Its greatest application appears to be in the area of functional MRI of the brain. Functional imaging is the imaging which relates body function or thought to specific locations in the brain.

6)Magnetization transfer contrast: Is a method of increasing the contrast between tissues by physical rather than chemical means.

7)MR Elastography: It is the imaging of shear waves using MRR. Contrast in MRE is related to the elastic modulus of the tissue. MRI is recorded while ultrasound waves are being sent into the imaged volume. This technique is expected to find applications in locating pathology in soft tissue based on difference in the elastic modulus of tissues. Hence it is referred to as 'magnetic resonance palpation'.

8)Electron spin resonance (ESR) or electron paramagnetic resonance: ESR is based on the spin of with and rather than the nucleon. ESR imaging is the study of the spatial distribution of ESR signal bearing substance. Very few substances can be studied with ESR.

Nitroxide spin probes and some transition metals have an ESR signal. These substances have been studied directly by ESR, but are commonly used to probe biologic process with ESR.(13)

Conclusion

MRI is a complex but effective imaging system that has a variety of clinical indications directly related to the diagnosis and treatment of oral and maxillofacial abnormalities. While not routinely applicable in dentistry, appropriate use of MRI can enhance the quality of patient care in selected cases. Further advances in 3D imaging and dynamic scanning will enhance the use of this imaging technique even further.

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