Application of Magnetic Resonance Imaging in Dental implantation: Technical Advantages and Clinical Challenge

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Abstract. With the swift advancement of dental implant technology, precise and safe radiographic assessment has emerged as pivotal for ensuring treatment success. Despite their widespread use, traditional radiographic methods are fraught with limitations, including exposure to ionizing radiation, metal artifact interference, and inadequate soft tissue resolution. Magnetic Resonance Imaging (MRI) showcases distinctive advantages in the realm of dental implants, thanks to its radiation-free nature, exceptional soft tissue contrast, and capabilities for multi-parameter and multi-sequence imaging. This article comprehensively reviews the latest advancements in MRI applications pertaining to preoperative planning, intraoperative real-time navigation, and postoperative long-term follow-up (early diagnosis of peri-implantitis and osseointegration assessment) in dental implantology. By conducting a comparative analysis of the merits and demerits of MRI versus traditional radiographic methods, and integrating typical cases and clinical research data, the article delves into the core clinical significance of MRI in enhancing implant accuracy, mitigating surgical risks, and refining prognostic evaluations. While MRI still encounters challenges such as cost, artifact issues, and the need for professional interpretation in routine clinical practice within dental implants, with ongoing technological refinements and the accumulation of clinical evidence, it promises vast potential as a pivotal non-invasive and precise imaging modality in the field of dental implants.

Keywords: Dental implantation; MRI; Advantage; Challenge.

1. Introduction

Dental implantation is an oral therapy primarily involving the placement of an artificial root into the alveolar bone of a missing tooth, followed by the restoration of a prosthetic crown on this artificial root. This procedure aims to replicate the form and function of natural teeth. The widespread recognition of dental implants as the preferred treatment for an increasing number of edentulous patients stems from their remarkable advantages.Firstly, the implant abutment exhibits exceptional stability. Through the process of "osseointegration," the implant forms a robust biological bond with the jawbone. This enables the implant-supported prosthesis (such as a crown, bridge, or overdenture) to achieve far superior stability compared to traditional removable dentures or fixed bridges, significantly minimizing risks of loosening or detachment. Consequently, both chewing efficiency and comfort are substantially enhanced.Secondly, dental implantation closely restores the structure and function of natural teeth. The implant-supported crown not only achieves a high degree of aesthetic harmony with adjacent teeth in terms of morphology and color but, more importantly, transmits chewing forces like a natural tooth. This effectively stimulates the alveolar bone, preventing bone resorption and atrophy. Simultaneously, unlike fixed bridges that require grinding down adjacent healthy teeth for support, dental implants maximally preserve the integrity of the natural dentition [1].According to statistics, over 3.8 million implants were placed nationwide in 2020, and the dental implant market is projected to maintain rapid annual growth exceeding 30% over the next five years [2].

For a long time, two-dimensional panoramic radiography and three-dimensional cone-beam computed tomography (CBCT) have been the backbone imaging techniques for preoperative evaluation of dental implants. CBCT has become the gold standard for implant planning due to its relatively low radiation dose, high spatial resolution, three-dimensional visualization capability, and wide availability. However, the existing technological system still has certain limitations, such as radiation exposure, insufficient soft tissue resolution, and the presence of metal prostheses in the

mouth, which affect the accuracy of evaluation. Magnetic resonance imaging (MRI), as an imaging technique based on the physical principle of nuclear magnetic resonance without ionizing radiation, has established a core position in the diagnosis of the central nervous system, musculoskeletal system, abdomen, and pelvis since its inception, thanks to its unparalleled soft tissue contrast resolution and multi-parameter, multi-sequence imaging capabilities. However, it has not been systematically analyzed in the field of dental implants [3]. Therefore, this review aims to systematically summarize the latest research progress and specific practices of MRI technology in the diagnosis and treatment process of dental implants, objectively discuss the current technical challenges and application bottlenecks, and anticipate its future development prospects, providing a reference for clinicians and researchers to fully understand the positioning and value of MRI in dental implants.

2. Principles of MRI Technology and its Characteristics in Oral Applications

2.1. Basic Imaging Principle

MRI involves collecting and analyzing signals emitted by hydrogen protons in the human body after excitation, thereby generating images that contain high-resolution, multi-planar, and multi-parametric information about internal tissue structure and function. Changes in the biological hydrogen proton groups of human tissues in an external static magnetic field induce induced currents after being received by the receiving coils surrounding the human body. These currents are amplified and converted into digital signals, which are processed by a computer to obtain magnetic resonance images. The brightness of magnetic resonance images directly reflects the intensity of the MR signals from human tissues. Different tissues have different MR signal characteristics. Therefore, in magnetic resonance examination, images that highlight tissue characteristic parameters (i.e., weighted images) are often obtained by adjusting time parameters such as TR (repetition time) and TE (echo time) values within the same sequence. For example, adjusting TR and TE values in the spin echo sequence can obtain images that mainly reflect the proton density characteristics of tissues, namely proton density-weighted images (short TE, long TR); images that mainly reflect the T1 relaxation characteristics of tissues, namely T1-weighted images (short TE, short TR); and images that mainly reflect the T2 relaxation characteristics of tissues, namely T2-weighted images (long TE, long TR) [4,5].

2.2. Signal Characteristics of Normal Oral Structures in MRI

In the transverse T2-weighted imaging, subcutaneous fat and parapharyngeal space fat show high signals; The palatine tonsils, anterior and posterior palatine arches, uvula and parotid glands and other large salivary glands show moderate signals. However, muscle tissues such as the masseter muscle, medial wing muscle, long neck muscle, hyoid muscle of the styloid process, pharyngeal muscle of the styloid process, posterior abdomen of the diabdominal muscle and sternocleidomastoid muscle are of low signal. Blood vessels such as the internal carotid artery, common carotid artery and jugular vein often show low signals due to the empty-flow effect. Coronal T1-weighted imaging showed that subcutaneous fat and retrobulbar fat in the orbit were high-signal. The bone marrow cavity signals in the soft palate and hard palate are also relatively high. The midline palatine suture and the septum of the tongue show high signals due to the presence of fat. The signal in the preepiglottic space containing fat is also relatively high. The submandibular gland and the sublingual gland show moderate signals. Muscles are generally of low signal, but larger muscles such as the masseter muscle, medial wing muscle and lateral wing muscle can show high signal patterns or marbled stripes in a low-signal background. Coronal images can clearly display the lingual septum structure of the internal lingual muscles (with low signal, and relatively evenly distributed point-like or thin strip-like high signal within) and its midline high signal. At the same time, they can also show the external lingual muscles such as the hyoid osteoglossa muscle, stromal tongue muscle, chin tongue muscle, and palatoglossa muscle (all with low signal), as well as the buccal muscle, mandibular hyoid muscle, and deltoid muscle. There is no gas signal on MRI, so both the nasal cavity and paranasal sinuses

show low signals, but the signal of the nasal conchae in the nasal cavity is relatively high. During enhanced scanning, the signals of the mucosa, tonsils and major salivary glands are significantly increased, while the muscle signals are only slightly elevated. This is a normal manifestation rather than abnormal enhancement. When reading the film, it is necessary to pay attention to identifying artifacts and other non-real structures. For example, dentures containing metal substances may produce false appearances by disrupting the uniformity of the magnetic field [6,7].

A systematic review, including 16 clinical studies, explored the application value of MRI in dental implant surgery. Among them, 9 items focused on the preoperative planning and follow-up stage, which also confirmed the feasibility in preoperative planning. 4 items supported the accuracy of image-guided implantation (the deviation of implant position was approximately 1.1-1.3mm). Additionally, New MRI sequences (such as Black Bone and MSVAT-SPACE) can provide high-resolution imaging of hard and soft tissues within a short scan (3-21 minutes), especially having significant advantages in evaluating bone integration, soft tissues around implants, and key anatomical structures (such as the alveolar nerve). Compared with traditional CBCT, MRI has no radiation exposure and can effectively reduce metal artifacts, and it performs well in imaging titanium/zirconium implants [8].

3. The Core Value of MRI in Dental Implant Surgery

3.1. Preoperative Evaluation

Accurate preoperative evaluation is the cornerstone of successful implantation. MRI can provide multi-dimensional information at this stage, making up for the deficiencies of traditional imaging techniques.

A retrospective study evaluated the diagnostic value of 3D dual-echo steady-state (DESS) MRI in measuring the thickness of the labial bone in the anterior maxillofacial region before immediate implant surgery. Data from 120 anterior teeth (incisors and canines) of 10 healthy volunteers (aged 19-59 years) were included to compare the performance of standard-dose CBCT and radiation-free DESS-MRI. The results showed that both methods exhibited high diagnostic reliability (CBCT score 3.72; MRI score 3.65), with minor artifacts and no significant difference ($p>0.05$). In the measurement of maxillary bone density, CBCT measured the thicknesses of M1 (2mm rootward of the enamel-cementum junction), M2 (middle of the root), and M3 (apical foramen) as 0.99mm, 1.07mm, and 2.24mm, respectively; MRI measured them as 1.042mm, 1.14mm, and 2.18mm, respectively. In the measurement of mandibular bone density, CBCT measured 0.53 (M1), 0.88 (M2), and 4.83 (M3); MRI measured them as 0.57mm, 0.99mm, and 4.93mm, respectively. The differences were not statistically significant ($p>0.05$), but MRI showed a slight non-significant increase (approximately 0.04-0.11mm). It is concluded that 3D-DESS MRI can provide diagnostic accuracy in the preoperative assessment of bone density and has no disadvantage compared to CBCT [9].

Another clinical study compared the evaluation results of 21 alveolar bone samples by CBCT, micro-CT and 14T MRI, and explored the correlation of the three imaging techniques. The study employed surgical guides to precisely locate the biopsy area, ensuring that the preoperative CBCT scan was consistent with the subsequent bone sample position. The results showed that micro-CT was highly positively correlated with 14T MRI ($r=0.943$), indicating that high-field MRI could indirectly reflect bone volume by detecting bone marrow fat. However, the radiological density value of CBCT had no significant correlation with micro-CT ($r=-0.133$) and 14T MRI ($r=-0.068$), confirming that CBCT could not provide reliable quantitative data of bone mineral density. Although neither micro-CT nor 14T MRI are particularly practical clinical tools, the results support the potential of MRI in radiation-free bone mass assessment, laying the foundation for the future development of clinically applicable techniques (such as dedicated oral coils), and providing a new direction for precise preoperative assessment of implants [10].

3.2. Intraoperative Navigation

Although the application of MRI in intraoperative real-time navigation is not as widespread as preoperative assessment, its unique advantages make it have potential for development in these fields. Navigation systems based on preoperative high-resolution MRI data theoretically do not produce drift or positioning errors during surgery even when metal instruments are used, unlike navigation based on CT/CBCT (as MRI itself is not interfered by metal instruments). This is particularly valuable for cases requiring high-precision operations or those with a large amount of metal restorations in the mouth.

A prospective study involving 45 implants from 30 researchers evaluated the accuracy and reliability of static guidance for dental MRI implant surgery planning. The results showed that the treatment plan decision based on MRI (implant type, size or bone increment) had inter-evaluator consistency and inter-modal consistency. The deviation of the implant entrance point is 1.1mm, the deviation of the root tip is 1.3mm, and the Angle deviation is 2.4°. Additionally, 29.5% of the implant sites require CBCT to adjust the position (average 1.8mm), and 6.8% need to adjust the implant axis (average 10°). It further confirmed that MRI can generate reliable surgical guides, but more evidence-based evidence is still needed to improve its accuracy before it is applied to implant plans other than clinical trials [11].

Another clinical study was conducted on five patients undergoing implant placement. 3T MRI was used to obtain jawbone images, combined with optical scanning or intraoral scanning of virtual dental models, and the data were manually registered using anatomical landmarks in the coDiagnostIX software. MRI clearly displayed key implant structures (cortical bone/cancellous bone/maxillary sinus floor/inferior alveolar nerve, etc.), with only minor artifacts from metal prostheses. Based on the bone measurement results, implant positions were designed, and then CAD was used to design and 3D print resin surgical guides, ultimately achieving full-process guided implantation (all five cases were implanted at 100% of the planned size, with four cases involving flap surgery and one case involving immediate implantation). This further confirmed the feasibility of MRI-guided implantation, with its advantages being zero radiation and excellent soft tissue contrast. However, there are also certain limitations, such as the current software's insufficient support for MRI three-dimensional reconstruction (only one case was successfully manually segmented), as well as the high cost of MRI and low clinical popularity, which require further research on its accuracy (compared to CBCT) and the impact of metal artifacts. In the future, it may become an alternative solution for specific patients [12].

3.3. Postoperative Sssessment and Complication Diagnosis

Although oral implant treatment has been highly mature, the precise assessment of postoperative osseointegration status and potential complications remains a core concern in clinical practice. Traditional imaging methods such as apical radiography and CBCT have advantages in bone structure imaging, but they have significant limitations in evaluating peri-implant soft tissue inflammation, early bone marrow lesions, and nerve injury. MRI is increasingly becoming an important supplementary means in the field of postoperative assessment and complication diagnosis after implantation due to its advantages.

A retrospective analysis was conducted on 66 lymph nodes from 12 patients (5 in the peri-implantitis group, 7 in the control group) to evaluate cervical lymph node lesions induced by peri-implantitis using diffusion-weighted magnetic resonance imaging (DWI). Results showed that lymph nodes in the peri-implantitis group exhibited significantly larger short-axis diameters (6.06 mm, 5.91 mm) and higher ADC values (1.15×10^{-3} mm²/s, 1.15×10^{-3} mm²/s) in level IB (submandibular) and level IIA (upper jugular) regions compared to the control group ($P<0.01$). ROC curve analysis established diagnostic thresholds: Level IB: short-axis diameter >4.78 mm (AUC=0.96), ADC $>1.12\times10^{-3}$ mm²/s (AUC=0.85);Level II: short-axis diameter >4.84 mm (AUC=0.79), ADC $>1.09\times10^{-3}$ mm²/s (AUC=0.88).This pattern aligns with characteristics of inflammatory lymph

node lesions (increased diffusivity due to cellular edema), indicating that peri-implantitis can trigger non-neoplastic lymph node reactions [13].

Although traditional panoramic films and CBCT can assess bone structure, they cannot directly display neural tissue. Emerging MRI sequences (such as 3D-DESS), with their high spatial resolution and excellent soft tissue contrast, can simultaneously and clearly present bone tissue and nerves (such as nerve course, morphology and pathological signal changes), provide direct evidence of nerve injury (such as nerve dissociation, neuroma, inflammatory changes), assist in formulating individualized treatment plans, and promote early intervention. Improve prognosis [14].

4. Combination of MRI and New Technologies

MRI has been applied in medical diagnosis for over 40 years and is the fastest-growing specialty within imaging examination techniques. It is developing towards intelligence, precision, and networking. As reflected in the theme of the 2021 RSNA Annual Meeting, "Redefining Radiology," future MRI imaging will advance through new concepts, new technologies, and new methodologies. Deep learning, leveraging its advantages in fields such as image recognition, natural language processing, and predictive analysis, is being widely applied in the medical field. This technology can efficiently process and analyze vast amounts of medical imaging data, assisting physicians in improving diagnostic accuracy, optimizing treatment planning and prognostic assessment, and significantly advancing the precision and standardization of the diagnosis and treatment process. Similarly, the introduction of artificial intelligence technology, particularly deep learning, has brought significant transformations to the diagnosis, treatment, and prognosis of oral implantology. Through its high-precision image analysis and data processing capabilities, it has significantly enhanced the accuracy of oral surgeons in designing and evaluating implant plans, ultimately promoting the realization of personalized and precision treatment [15].

Neural networks (U-Net) represent an adaptive deep learning framework based on the U-Net architecture. Through automated workflows, adaptive network adjustments, patch-based training and inference, and other techniques, they achieve full-process automation in medical image segmentation. Some studies suggest that deep learning can achieve precise segmentation of the three key components of the temporomandibular joint (TMJ) in MRI images. Furthermore, positional changes between open- and closed-mouth images did not affect the model's segmentation ability, indicating that this segmentation result can be used for the diagnosis of anterior disc displacement (ADD) [16].

5. Current Challenge and Future Prospects

In the daily clinical work of stomatology, the method of using metal materials to repair dental arch defects, missing dental arches and maxillofacial defects has a long history. Before the MRI examination, dentists often need to remove metal restorations from the patient's mouth. However, for patients undergoing implant restoration, the high cost, complex restoration methods, difficult removal and significant trauma can cause considerable mental burden and economic losses to the patients. Moreover, not all dental clinics or imaging centers have the capacity to be equipped with MRI, and it requires professional radiologists and oral radiologists to operate and interpret it, which limits its popularity. More in-depth research in health economics is needed to prove that its long-term benefits in reducing complications, increasing success rates, and avoiding secondary surgeries are sufficient to offset the initial costs [17].

There is a significant difference in magnetic susceptibility between human tissue and metal implants, which leads to an uneven local magnetic field, causing a shift in resonance frequency and accelerating proton dephasing, resulting in partial information loss. Simultaneously, the change in proton frequency leads to spatial signal matching errors, resulting in local information accumulation and geometric distortion of the image. The overall manifestation is bright and dark artifacts, distortion of tissue anatomical structures, and failure of fat suppression. The causes include physiological

reasons and technical issues. MRI artifacts seriously affect the detection effect. Researchers should continuously understand and deeply explore metal artifact reduction techniques to specifically address the problems exposed in the current application process. It is believed that magnetic resonance imaging can be more widely applied in dental implants.

At present, the MRI scanning protocols (optimal sequences, parameters) and assessment criteria (MRI grading of bone quality, MRI diagnostic criteria for peri-implantitis) for oral implants have not been fully unified and popularized. More prospective, large-sample and long-term follow-up clinical studies are needed to clarify the exact relationship between each MRI parameter and the success rate of implantation, the quality of bone combination, the occurrence, development, and prognosis of peri-implantitis. Based on evidence-based medical evidence, establish indications, standardized scanning protocols and interpretation guidelines for oral implant MRI examinations.

6. Conclusion

MRI is demonstrating increasingly broader application prospects and significant clinical advantages in the field of dental implants, thanks to its unparalleled safety (no ionizing radiation), excellent soft tissue contrast, and unique evaluation value for the intrinsic physiological state of bone tissue. These prospects and advantages span the entire cycle of implant treatment: preoperative MRI can provide "bone quality" information beyond traditional imaging, comprehensively assessing soft tissue conditions and pathological states; intraoperative MRI aids in guiding and completing the implantation process; and in postoperative follow-up, MRI exhibits significant advantages in the early diagnosis of peri-implantitis, providing a valuable time window for timely intervention.

Despite facing practical challenges such as cost, artifacts, accessibility, and standardization, the rapid development of MRI technology is continuously breaking through bottlenecks and expanding its application boundaries in dental implant clinical practice, laying a more solid foundation for the success and long-term stability of dental implant treatment. Meanwhile, future research should focus on optimizing scanning protocols, establishing quantitative evaluation standards, verifying clinical prognostic correlation, and promoting its standardized application in clinical practice.

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