A significant drawback related to diagnostics in dentistry is the current dependency on ionizing radiation. Currently, most of the diagnostic imaging methods used by dentists entirely depend on radiographs. This practice exposes the patients to ionizing radiation, associated with increased risk of stochastic cancer development. The drawback is even more relevant for diagnostic tasks, which sometimes demand 3D radiographic examinations associated with more massive exposure doses to the patients than 2D imaging. This is the case for implant-based oral rehabilitation. The age profile of patients typically treated with dental implants positions them within the lower range of age-related radiation-exposure risk. However, the stochastic effects of ionizing radiation must always be considered.

When planning implant-based oral rehabilitation, a thorough radiographic depiction of the region of interest is crucial. Intraoral and panoramic (2D) images may provide dentists with information such as bone height and distance to surrounding teeth and other relevant anatomical structures (eg, maxillary sinus and inferior alveolar nerve). Yet, 2D imaging techniques cannot display complicated anatomical structures and related pathologies in all planes. With the development of radiographic 3D imaging for dentistry (ie, CBCT scanning), other parameters such as bone width, bone tissue structure, and precise distances to nerves, cavities, and foramina may be visualized. CBCT imaging has paved the way for further development concerning virtual surgery planning (presurgical) and image-guided surgery (eg, production of 3D printed surgical guides). However, despite these improvements, CBCT also presents shortcomings, mostly image artifacts, with the most relevant being those related to dense materials such as metals.

Diagnostics in dentistry can benefit from a transition to imaging modalities free of ionizing radiation, which are more robust regarding artifacts in the presence of metal implants. This transition must happen without loss of the diagnostic accuracy needed to perform various treatment planning steps. In this direction,
magnetic resonance imaging (MRI) is a noninvasive, ionizing-radiation–free imaging modality, which has become an indispensable diagnostic method in medicine, for soft tissue–related diagnosis and treatment planning. However, diagnosis and treatment planning for implant-based oral rehabilitation depends on the accurate presentation of bone. In recent years, alternative MRI imaging protocols have been developed and have been shown to be able to, at least to some extent, present calcified tissues such as bone, joints, and even teeth. Therefore, MRI has entered some areas of dentistry—especially those involving diagnosis of the temporomandibular joints, salivary glands, and inflammatory conditions.

Considering implant-based oral rehabilitation, accurate hard tissue depiction is of the utmost importance. MRI has yet to establish itself as a viable imaging modality suitable for replacing CBCT. To clarify the state of the art regarding this novel application of MRI, this study aimed to undertake a systematic review of the literature of MRI in the field of implant-based oral rehabilitation with or without complementary bone augmentation in the three phases of treatment: planning, execution, and follow-up.

MATERIALS AND METHODS

The bibliographic databases MEDLINE (PubMed) and EMBASE were searched in their entirety for publications up to the search date (January 2, 2020). The search strategy was limited to publications in English, using the search string: (“MRI” or “magnetic resonance imaging”) and (“bone augmentation” or “bone graft” or “bone reconstruction” or “dental implant” or “titanium implant” or “sinus lifting” or “sinus lift”). Two investigators (J.M.F. and R.S.N.) performed the electronic search, which was complemented by a second round of literature survey based on the reference list of the selected papers. Relevant papers identified in this manner were then added. Duplicates were removed in dedicated software for reference management (EndNote X7, Thomson Reuters).

The inclusion criteria comprised studies using MRI alone or in connection with CT and/or CBCT in the planning, execution, or follow-up of bone grafting and/or dental implant placement procedures in the maxilla or the mandible. Studies were excluded if based on in vitro designs (eg, nonbiologic materials, also referred to as “phantoms”), if other areas than the maxilla or the mandible were in focus, if the aim only comprised soft tissue assessment, or when the exact information of how and when MRI imaging was used in the process was undisclosed or unclear. Reviews and case reports were also excluded.

### Table 1

<table>
<thead>
<tr>
<th>Level</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>F&amp;T Level 1</td>
<td>Technical efficacy parameters, eg, image resolution, sharpness, and grayscale range (often subjective image quality studies)</td>
</tr>
<tr>
<td>F&amp;T Level 2</td>
<td>Diagnostic accuracy efficacy, eg. evaluation of sensitivity and specificity of a new method (often ex vivo studies)</td>
</tr>
<tr>
<td>F&amp;T Level 3</td>
<td>Diagnostic thinking efficacy, eg. changes in diagnosis when a new and a known method are compared (often questionnaire or paper clinics where diagnostics is performed on the basis of a new and already recognized method; no treatment is performed)</td>
</tr>
<tr>
<td>F&amp;T Level 4</td>
<td>Therapeutic efficacy (choice of treatment strategy), eg. changes in the treatment strategy when a new and already recognized method are compared (often clinical studies; treatment choice is first based on an already recognized method and thereafter on the new method. Treatment is performed based on the new method.)</td>
</tr>
<tr>
<td>F&amp;T Level 5</td>
<td>Patient outcome efficacy, eg. changes in treatment quality, patient discomfort, or prognosis comparing a new and already recognized method (often randomized clinical trials [RCT]). Treatment is performed based on either the new or recognized method decided by lot.</td>
</tr>
<tr>
<td>F&amp;T Level 6</td>
<td>Societal efficacy, eg. economic consequences of the introduction of a new method to the patient, clinician, and society (often prospective clinical studies or RCTs. Cost-efficiency/cost-benefit assessment: the consequences of the new method and treatment evaluated from a health-economy point of view).</td>
</tr>
</tbody>
</table>

The literature analysis was performed by the same two reviewers performing the electronic search. They decided exclusion and inclusion of the studies, and in case of doubt, consensus was reached. The final selection of studies was checked and accepted by the rest of the authors. When the final selection of publications was completed, the diagnostic efficacy level of the included studies was assessed according to the model suggested by Fryback and Thornbury (F&T). The six-level model by F&T is presented in Table 1.

RESULTS

The search strategy yielded 704 (in PubMed) and 2,545 (in EMBASE) studies for filtering. After title and language screening, a total of 2,070 studies fulfilled the first-level inclusion criteria and were subjected to more in-depth assessment for inclusion by a screening of abstracts. After reading the abstracts, 29 studies were considered relevant for full-text reading. Nineteen of these were excluded for reasons presented in Table 2,
resulting in the final inclusion of 10 articles for assessment. A PRISMA 2009 flow diagram of the study selection is presented in Fig 1.

Six of the included studies focused on the implant planning phase. One study focused on the immediate follow-up phase (checking for possible inferior alveolar nerve [IAN] damage). Three studies focused on both the planning and follow-up phases, ranging from artifact formation from dental material and implants to tissue composition in extracted bone specimens from the implant drilling procedure, and assessing peri-implant bone formation. No study evaluated steps combining the use of MRI and the execution (ie, image-guided-surgery) of the surgical procedure.

The included studies used various MRI field strengths (measured in Tesla [T]), objects of study and sample sizes, scan sequences, implant types, additional imaging other than MRI, outcome parameters, and reference standards. These parameters are presented in Table 3, along with the present assessment of their F&T11 efficacy level. Further, it was evaluated whether the signal was obtained from the crystalline structures (ie, signal from bone), or if bone was assessed based on negative contrast (ie, the lack of signal was the output for bone tissue). Overall, field strength varied among the studies from 1 T to 9.4 T: two studies used 1 T, three studies used 1.5 T, one study used 7 T, and one study used 9.4 T.

The objects of the study included extracted bone cores (ex vivo), porcine heads (ex vivo), human cadaver heads (ex vivo), and patients (in vivo). In summary, six studies were conducted ex vivo, performing preclinical tests and five in vivo, performing clinical tests. One study included both ex vivo and in vivo samples. The MRI sequences used in the 10 studies (Gradient Echo [GE], Gradient Echo combined with Volumetric Interpolated Breath-hold Examination [GE+VIBE], Spin Echo [SE], Short tau inversion recovery [STIR], Fast Spin Echo [FSE], and Turbo Spin Echo [TSE]) allow the acquisition of signal from nonmineralized (soft) tissues, thus presenting the crystalline tissues (eg, teeth and bone) as dark voids or regions with a “lack of signal.” No studies acquired actual MR signal from bone.

Of the included studies, eight evaluated different types of dental materials (eg, titanium implants, bone substitute materials, tooth restoration materials, and alloys used for crown production). Five studies evaluated complementary CT or CBCT images of the objects of study (eg, bone cores, dry skulls, cadaver heads, and patient anatomy). Four studies compared anatomical distances measured in MRI and CT: Three of these studies assessed bone height.
and one both height and width. No study performed a direct comparison between measurements in MRI and CBCT. Two of the four studies compared MRI and CT and presented distances in millimeters; one presented mean distance of the total height of the mandible at specific sites in MRI and CT, and the other a range in bone height measurements before and after sinus elevation procedures. One study presented intraobserver reliability in IAN canal detection (measured by Cohen kappa) and bone distance measurements in four directions from the center of the mandibular canal to the outer borders of the cortical bone comparing MRI and CT. Finally, one study compared bone height measurements between CT and MRI prior to implant placement.

Three studies assessed the impact of artifacts on image quality. One study concluded that restoration material did not reduce the quality of the MRI images. Another concluded that the IAN could be depicted reliably and that it was possible to locate lesions on the IAN, accidentally caused during implant placement. Finally, one study concluded that MRI improved surgeons' presurgical confidence in the procedure and that the method is reasonably tolerant of artifacts caused by metal pins and amalgam fillings.

One study showed comparable results between MRI and histomorphometry for quantification of peri-implant bone volume and soft tissue volume following the insertion of polyether ether ketone implants. One study found an excellent relationship between IAN detection in MRI when superimposed on CT images. The last study found that micro-CT and micro-MRI can be merged to provide information about a bone core sample (ie, bone micromorphology and composition).

Only 3 of the 10 studies presented results with reference to a gold standard, ie, the study metric being truly assessed/measured. One study used a digital caliper to measure the true anatomical height of the bone sites of interest; one validated through histomorphometry showing comparable results for quantification with MRI and differentiation between soft tissue, fatty tissue, and mineralized bone; and one study used histologic validation of the relevant slices with regard to bone phases.

In evaluating the efficacy level of the 10 studies in accordance with the F&T model, one study reached the technical efficacy level (F&T level 1), eight studies were considered to match the diagnostic accuracy efficacy level (F&T level 2), and one study reached the diagnostic thinking efficacy level (F&T level 3). No studies reached the therapeutic efficacy level (F&T level 4), patient outcome (F&T level 5), or societal outcome (F&T level 6) level.

**DISCUSSION**

**Imaging in Implant Dentistry**

Imaging is essential for treatment planning and determination of successful implant surgery. The information from the imaging method may positively affect the invasiveness of the surgical procedure due to enhanced planning and guiding, and optimize treatment outcome. Three-dimensional imaging can also increase the surgeon's confidence prior to and during the procedure.

Research is continuously conducted to provide evidence on how to use and optimize imaging modalities regarding oral rehabilitation and implant dentistry. In this field, for the time being, most imaging modalities are based on ionizing radiation (eg, CT and CBCT). CBCT is considered an appropriate diagnostic method for the planning and execution of implant-based oral rehabilitation, also commonly employed for follow-up. However, as ionizing-radiation 3D imaging in dentistry becomes popular, there is an increased risk associated with the exposure.

In all imaging modalities, CT and CBCT included, the presence of artifacts must be considered. In clinical practice, the measurement accuracy and reliability of linear measurements in 3D images may most likely be reduced through factors such as patient motion, metallic artifacts, device-specific exposure parameters, the software used, and manual vs automated procedures. Metallic artifacts appear in CT and CBCT images as black-and-white stripes, mostly due to x-ray scattering and photon starvation. Even minute debris from drilling procedures can cause severe image quality deterioration. This is a concern because drilling for implant placement has been shown to produce metal debris that tend to embed in the surrounding tissues, creating metallic artifacts in the images. Another material, zirconia, which is gaining attention in the implant industry, has been found to be worse than titanium-originating metal-like artifacts in CBCT images and should also be taken into consideration.

The examination time, which sometimes is as long as 20 seconds, may frequently cause patient motion artifacts that present as double contours and stripes in CBCT image sections.

**MRI and Implant Dentistry**

MRI is a nonionizing diagnostic imaging method, yet to be explored in depth within dentistry. It has become an indispensable modality in medicine for soft tissue–related diagnosis and treatment planning. However, its viability for those procedures related to planning, execution, and follow-up of oral implants has yet to be determined. As presented in this review, it is clear that an interest in nonionizing methods...
exists, but there is much work ahead before MRI can replace or even supplement the well-established methods used today, such as CBCT and CT. One simple, major limitation is the size and costs of running an MRI suite compared with the compact CBCT systems. Until more compact and affordable MRI systems emerge, the use of MRI is likely to be limited to a few research-related topics and extremely complex surgeries. However, the transition from ionizing-radiation–based radiology to MRI has already happened in most other medical fields. There is undeniable value in having an overview of the current state of the technology concerning dentistry. One of the challenges before MRI may be acknowledged is the issue of depicting hard tissues (eg, teeth and bone), which are generally the tissues of interest for dental diagnostics.

Diagnosis and treatment planning in implant-based oral rehabilitation depends mostly on the accurate presentation of bone, and most MRI techniques do not present bone with the desired accuracy. Conventional medical MRI tends to depict bone and other hard tissues as black voids or “lack of signal” due to the rapid signal decay in these structures compared with the echo times employed in conventional MRI pulse sequences (on the order of tens of milliseconds). Another limitation stems from the low proton density of hard-calcified tissues. In recent years, sequences capable of capturing these rapidly decaying signals have emerged, such as the Zero Echo Time (ZTE) and Ultra-short Echo Time (UTE) techniques. These sequences enable MRI of materials with very rapidly decaying signals such as plastics and bone, and have been demonstrated to allow MRI-based bone depiction and teeth. Promising

Table 3 Included Studies and Sample Characteristics: Field Strength, Object of Study and Sample Size, Study Design and Setting, Scan Sequence, Direct MR Signal from Bone, Implant Types, Whether Complementary CT Was Done, Outcome Parameters, Findings, Gold or Reference Standard, and Efficacy Level According to F&T

<table>
<thead>
<tr>
<th>Study</th>
<th>Field strength (T)</th>
<th>Object of study (sample size)</th>
<th>Ex vivo</th>
<th>In vivo</th>
<th>Scan sequence</th>
<th>Signal from bone</th>
<th>Implant type</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aguiar et al30</td>
<td>1</td>
<td>Dry human mandibles (5)</td>
<td>+</td>
<td>–</td>
<td>GE (T2w)</td>
<td>No</td>
<td>None</td>
<td>+</td>
</tr>
<tr>
<td>Eggers et al37</td>
<td>1.5</td>
<td>Pig’s head (1)</td>
<td>+</td>
<td>–</td>
<td>GE (VIBE), TSE, SE</td>
<td>No</td>
<td>Ti, Au, and dental amalgam</td>
<td>–</td>
</tr>
<tr>
<td>Eggers et al31</td>
<td>1.5</td>
<td>Human cadaver heads (2)</td>
<td>+</td>
<td>–</td>
<td>GE (VIBE), TSE, SE</td>
<td>No</td>
<td>Au</td>
<td>+</td>
</tr>
<tr>
<td>Imamura et al33</td>
<td>1.5</td>
<td>Mandible (11 patients)</td>
<td>–</td>
<td>+</td>
<td>GE (T1w)</td>
<td>No</td>
<td>Ti</td>
<td>+</td>
</tr>
<tr>
<td>Probst et al36</td>
<td>1.5, 3</td>
<td>4 single implant (4 patients), no implant (3 control patients)</td>
<td>+</td>
<td>+</td>
<td>STIR, TSE, GE (VIBE)</td>
<td>No</td>
<td>Straumann Standard Plus</td>
<td>–</td>
</tr>
<tr>
<td>Korn et al39</td>
<td>7</td>
<td>Mini-pig mandible (3)</td>
<td>+</td>
<td>–</td>
<td>SE</td>
<td>No</td>
<td>Ti-coated PEEK</td>
<td>–</td>
</tr>
<tr>
<td>Pompa et al34</td>
<td>1.5</td>
<td>Edentulous sites (30 patients)</td>
<td>–</td>
<td>+</td>
<td>SE</td>
<td>No</td>
<td>Prior implants (amalgam, ferrous)</td>
<td>+</td>
</tr>
<tr>
<td>Gray et al32</td>
<td>1</td>
<td>21 maxillary sites, 5 mandibular sites (12 patients)</td>
<td>–</td>
<td>+</td>
<td>SE (T1w)</td>
<td>No</td>
<td>Ti</td>
<td>–</td>
</tr>
<tr>
<td>Senel et al35</td>
<td>1.5</td>
<td>13 maxillary sites (8 patients)</td>
<td>–</td>
<td>+</td>
<td>FSE (T2w)</td>
<td>No</td>
<td>None</td>
<td>–</td>
</tr>
<tr>
<td>Sinibaldi et al38</td>
<td>9.4</td>
<td>Human jawbone cores (3 patients)</td>
<td>+</td>
<td>–</td>
<td>SE</td>
<td>No</td>
<td>Bone regeneration scaffold</td>
<td>+</td>
</tr>
</tbody>
</table>

VIBE (volumetric interpolated breathhold examination [VIBE12, VIBE15]) is an ultrafast gradient echo sequence with gradient spoiling. IAN = inferior alveolar nerve; GE = Gradient Echo; TSE = Turbo Spin Echo; SE = Spin Echo; STIR = Short tau inversion recovery; nd = not defined.
results have been shown concerning the shoulder and spine, head trauma, and temporomandibular joint (TMJ) imaging.Obviously, MRI is also challenged by artifacts presented in the images. While these may originate from the same sources (e.g., metallic debris and screws), their physical basis (mainly magnetic field distortions) and appearance in the images are vastly different from the artifacts seen in CT and CBCT. Compared with the typical CT and CBCT streak artifacts, the artifacts typically seen in MRI may be less severe, but their presence can nevertheless render the images useless for diagnostics. Studies have mentioned that zirconia does not generate severe artifacts in MRI images and that signal-to-noise ratio (SNR) was less affected by zirconia than titanium implants, but none of the studies included in this review assessed zirconia implants.

### Evidence Level and Quality of Studies

When introducing a new imaging modality, a health technology assessment should be undertaken. Universally, the F&T model is accepted as an indicator of existing evidence when evaluating a new technology or methodology. The majority of the included studies assessed no further than the diagnostic accuracy efficacy level (F&T level 2). Only one study was designed to potentially reach the diagnostic thinking level (F&T level 3). This is a clear indication that the area is in its infancy and not yet applicable alone without a reference modality. Obviously, the different methodologies of the included studies constitute a challenge when attempting to compare their findings and rank their diagnostic evidence level. The most interesting challenge is the fact that none of the included studies obtained actual signal from bone, and this is an issue that
needs exploration before MRI can be recommended for implant dentistry diagnosis. The “lack of signal” can, as has been done in the included studies, be defined as “bone,” and bone height and width measurements may be provided. However, abnormalities, pathology, and other issues may be concealed in this manner, as this interpretation assumes normal, known anatomy. Ideally, if the goal is to assess the quantity, quality, or composition of bone tissue, there should be signal from this tissue to be evaluated in the final volume.

Another point is the lack of gold standard in most of the included studies. Only three studies presented results compared with a gold standard, all of these in ex vivo models. All three, however, had different assessment parameters (ie, bone height and composition), and therefore different gold standards (ie, direct measurement, histomorphometry, and histology). Ex vivo or in vitro studies are ranked low in the spectrum of strength of evidence within the hierarchical pyramid in a clinical setting. However, the importance of ex vivo studies must not be underestimated, as it is often the case that direct measurement of, eg, human specimen is paramount in the validation process of new imaging modalities or techniques. When the accuracy of a new modality has been established, clinical studies may be the next step. Unfortunately, no study focusing on engaging MRI images for the execution of implant treatment was found. MRI would be a feasible source of information to produce surgery guides, but solid data on its accuracy or clinical use are not yet available.

Another issue, which was not explored in depth in the included studies, is that MRI offers a unique possibility to make an in vivo follow-up on the healing process of implants and grafts, without exposing the patient to ionizing radiation.

While the literature documents the potential of MRI as a diagnostic method in dentistry, at present, much work is needed before MRI can enter the field on a large scale. Extensive ex vivo studies comparing MRI to current standards (CT and CBCT) and histology are necessary to identify methods suitable for application with in vivo models for research before the translation into clinical use with patients. These efforts do not necessarily happen sequentially (in vivo dental MRI studies are starting to appear), and therefore, in the following, the authors set out to provide a set of recommendations for both of these types of studies based on the results and pitfalls identified in the present systematic review.

**Recommendations for Ex Vivo Studies**

Ex vivo samples can be substantially reduced in size and can be imaged by experimental MRI systems operating at very high field strength (eg, 9.4 T, as in the study by Sinibaldi and coworkers). High field strengths offer the advantage of yielding data with a higher SNR than can be obtained in clinical MRI systems. In ex vivo studies, it is possible to eliminate sample motion almost fully. Finally, the authors believe the value of ex vivo studies relies to a large extent on the novelty of the method (eg, a new experimental sequence for image acquisition), the comparison to current methods, and unbiased comparison to a gold standard, such as histology.

**Recommendations for In Vivo Studies**

MRI in subjects presents several practical challenges, and lower-quality data (compared to the ex vivo case) must be accepted. This stems from limitations in MRI hardware, where lower field and gradient strength typically causes in vivo studies to be based on lower-resolution images and/or lower SNR data than ex vivo studies. More importantly, the total acquisition time for the images is a bottleneck due to patient discomfort. Image acquisition time depends on the sequence type and the amount of averaging. In MRI, longer scan time allows higher SNR to be achieved through averaging. Although total scan time was not a reported result in any of the included studies, from a careful reading of the method sections, acquisition times ranging from 2 to 9 minutes were found. However, there is no clearly stated rationale behind the scan times chosen in the included studies. The acquisition time range (2 to 9 minutes) is in line with what is typically considered acceptable for a single clinical MRI scan. The presence of artifacts is also a major concern for in vivo MRI, with patient movement (breathing, swallowing, head rotation, etc) being the leading cause of this problem. The nature of this problem is different from motion artifacts in CBCT due to one of the fundamental properties of MRI, where the data are acquired in the so-called k-space, which is the Fourier inverse of the image space. The consequence of this is that motion during the recording of a segment of k-space affects the entire image and not just an isolated (discountable) frame. These artifacts can occur in the form of ghosting or blurring, which is especially critical in low SNR acquisitions or small lesion pathology.

In vivo studies are also challenging, as here the comparison is limited to other imaging modalities (each with their shortcomings), which can hardly be defined as the “gold standard.” Here, the crucial role of ex vivo validation studies supporting in vivo studies cannot be overstated.

**The Need for Training in Evaluating Image Contrast in Dental MRI**

The image contrast provided by MRI is fundamentally different from ionizing-radiation–based imaging modalities. Moreover, MRI contrast is flexible in that the final image contrast is strongly dependent not only on the choice of scan sequence but also on the sequence parameters. Therefore, training programs need to be...
developed to give the interpreter (ie, clinician or dento-maxillofacial radiologist) the knowledge to interpret MRI information correctly. It is crucial to take into account the lack of routine in interpretation by the interpreter when it comes to MRI, as a new modality in dentistry, in comparison to the evaluation of CBCT images, which has become a natural part of dentistry throughout the last two decades. The unfamiliar perception of MRI image contrast for those used to radiographic images stems from the differences in the physical origin of the “signal” in these modalities. X-ray–based methods rely on detecting the amount of radiation passing through a sample (bone absorbs the photons) to resolve the object’s internal structure. Contrarily, the MRI signal stems from a magnetization formed by nuclei (typically protons in water) formed within the sample or subject when placed in the scanner’s strong magnetic field. As bone contains relatively little water compared with soft tissue (and the scarce signal it produces is very short-lived), bone presents as dark regions, ie, void of signal, in typical MRI images. To address this issue, different approaches have been taken to make the MRI contrast more “CT- or CBCT-like” in appearance, without losing information. Typically, this involves an inversion of the MR image grayscale so that bone becomes bright. However, more recent acquisition strategies (ZTE/UTE) have emerged to provide MRI images from actual signal detection in bone. These sequences are able to capture the very rapidly decaying MRI signal from bone, which conventional MRI sequences are unable to detect. In these sequences, soft tissues continue to provide signal. However, the soft tissue signal can be effectively eliminated by subtraction of two UTE images obtained with slightly different echo times (TE, the time when the MRI signal is recorded). The reason for the efficacy of this method is that the soft tissue signal is mostly unaffected by this slight change in TE (so the subtraction eliminates signal from these tissues), whereas the short-lived signal components from bone and teeth are only present in the shortest of the two TE images (can be very short; eg, ZTE has TE = 0) and therefore survive the subtraction step. In this manner, MRIs with very x-ray–like contrast can be obtained.

Overall Recommendations for Future Implant-Related Studies

Independently of the study model, some overall recommendations for which parameters must be disclosed (and tested) in implant dentistry–related MRI studies should also be considered. Information such as field strength, data quality measures (eg, signal-to-noise ratio), and total examination time are indispensable in order for a study to be reproduced and critically evaluated. “Basis” studies, defining the accuracy of MRI for implant planning, execution, and follow-up, and all possible metrics that these tasks demand, are missing. Further, the focus of this systematic review was the proper visualization of the mineralized tissues by means of MRI. However, soft tissue contrast can be valuable for presurgical planning in cases where the soft tissue contours are relevant for the esthetic outcome or when visualizing the nerve bundles would help to define the proper implant length and width. In other words, ideally, there should be the possibility of observing both mineralized and nonmineralized tissues with accuracy. Other topics of interest would be shortening the examination times and making MRI more clinic-friendly and less prone to patient-movement artifacts. Finally, it would be reasonable to speculate that in the future, MRI units would “fit” the dental offices worldwide; highly portable technologies will fundamentally change head-and-neck MRI. Obviously, understanding the possible impact of MRI on implant dentistry is one of the next frontiers to be explored.

It must be kept in mind that, years ago, numerous efforts helped clinicians make the transition from CT to CBCT with regard to implant planning, execution, and follow-up. A paramount feature was the small footprint of CBCT devices and the possibility of “in-office” imaging. Noticeably, this is not the case with the available MRI units. Adding to that, several years were necessary to establish the regulations (ie, laws) guiding and supporting the professionals operating CBCT units. It is expected that, over the next decades, the same efforts will be taken, if MRI is to be routinely used in dentistry. Also, the institution of dedicated educational programs, teaching dentists to transition from 2D to 3D imaging, which was relevant, creating the proper scenario to employ 3D imaging during implant-based rehabilitation, must be considered. In order for MRI to become a feasible tool in implant-based rehabilitation, these same issues (eg, in-office accessibility, regulations, and education) must be considered. Finally, to provide the same possibilities currently offered by CBCT imaging, future studies must test MRI in terms of digital (interactive) surgery planning, guided implant surgery, and real-time surgical navigation.

CONCLUSIONS

MRI could potentially be a viable diagnostic method regarding planning, execution, and follow-up of implant-based oral rehabilitation. This systematic review initiates a possible paradigm shift in dental imaging, where the use of magnetic resonance is still a novelty, and there is much work ahead before MRI can replace or supplement the current methods of choice (panoramic imaging, CT, and CBCT). Although promising, more studies are needed on the accuracy of the available MRI.
techniques when applied for implant planning, execution, and follow-up before this diagnostic method can be considered as a reality for the clinician.

ACKNOWLEDGMENTS

The authors declare no conflict of interest.

REFERENCES

55. Havsteen I, Olhues A, Madsen KH, Nybing JD, Christensen H, Christensen A. Are movement artifacts in magnetic resonance imaging a real problem?—A narrative review. Front Neurol 2017;8:232.