Intraoral Approach for Imaging Teeth Using the Transverse $B_1$ Field Components of an Occlusally Oriented Loop Coil

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Purpose: The signal-to-noise ratio and resolution are two competing parameters for dental MRI and are highly dependent on the radiofrequency coil configuration and performance. The purpose of this work is to describe an intraoral approach for imaging teeth with the radiofrequency coil plane oriented orthogonally to the Zeeman field to use the transverse components of the $B_1$ field for transmitting and receiving the NMR signal.

Methods: A single loop coil with shape and size fitted to the average adult maxillary arch was built and tested with a phantom and human subjects in vivo on a whole-body 4 T MRI scanner. Supporting Biot-Savart law simulations were performed with Matlab.

Results: In the occlusal position (in bite plane between the upper and lower teeth), the sensitive volume of the coil encompasses the most important dental structures, the teeth and their supporting structures, while uninteresting tissues containing much higher proton density (cheeks, lips, and tongue) are outside the sensitive volume. The presented images and simulated data show the advantages of using a coil in the orthogonal orientation for dental applications.

Conclusion: The transverse components of the $B_1$ field of a surface coil can effectively be used for imaging of teeth and associated structures. Magn Reson Med 000:000–000, 2013. © 2013 Wiley Periodicals, Inc.

Key words: MRI; dental imaging; RF coil; SWIFT; UTE

X-ray based imaging modalities have dominated the practice of dentistry since their invention over a century ago. Modern dentists are increasingly embracing three-dimensional techniques such as cone-beam computed tomography, while public awareness and concern about cumulative exposure to ionizing radiation are also increasing. These factors, in combination with recent advancements in electronics and methodologies, are motivating researchers to reconsider the potential of MRI in clinical dentistry. Studies have shown how conventional MRI can be used clinically to visualize the mandibular neurovascular bundle (1,2), study pulp structure, and vitality (3–5), reveal the anatomy and pathology of the dento-alveolar region (6), detect osteomyelitis in the mandible (7), and indirectly image highly mineralized tissue through contrast produced by an MRI-visible medium (6,8–13). The potential uses of MRI in dentistry have increased with the development of methods allowing the direct imaging of densely calcified tissues of the human body, including dentin and enamel, that have low water content (i.e., low fraction of protons from which to obtain signal) and quickly decaying signal (i.e., very short $T_2$ relaxation times). There are at least four different and clinically applicable MRI methods for obtaining images of densely calcified dental tissues: (a) ultrashort TE (UTE) (14–17), (b) sweep imaging with Fourier transformation, SWIFT, (18–21), (c) FID-projection imaging also called BLAST, RUFIS, WASPI, or zero TE (ZTE) (22–26), and (d) combined PETRA techniques (27). These methods now make it feasible to image these tissues, but further RF coil refinement is still needed to optimize MR signal from the teeth and supporting structures.

Dental MRI has the potential to be even more informative than x-ray imaging techniques by visualizing, noninvasively and simultaneously, both hard and soft tissues in all three spatial dimensions. However, clinical MRI has yet to attain the resolution of cone-beam computed tomography imaging, from 0.1–0.3 mm. SNR and resolution are two competing parameters for dental MRI and are highly dependent on the RF coil configuration (filling factor) and performance. To attain the needed resolution, patient motion must be highly restricted (including avoiding swallowing); this requirement can only be met when the coil positioning does not create excessive discomfort for the patient. In addition, the pulse sequence cannot use slice- or slab-selective pulses, both to preserve signal from hard tissues having ultra-short $T_2$ and due to the 3d radial free-induction decay acquisition strategy of the above methods. Thus, the acquired field-of-view (FOV) must include the entire sensitive volume of the RF coil to avoid signal folding onto areas of interest in the image. In terms of linear size, the resolution of an image voxel depends on the FOV and the reconstructed matrix size. To reach the
needed resolution, of ~0.3 mm, the FOV should not exceed about 80–120 mm with 256×384 matrix sizes, respectively. An increase in matrix size is a less satisfactory way to increase resolution because it also increases the required number of radial views and therefore increases scan time. Due to these constraints, standard coils such as head or neck coils fail to achieve the spatial resolution needed for practical dental applications. Hence, a coil configured to provide a limited and sculpted FOV is highly desirable to solve this problem.

A logical approach to imaging teeth might be to adopt existing surface coil designs with extra-oral placement adjacent to the area of interest (28,29). The diameter of such a receive coil should not exceed about 120 mm because it is limited by the size of the optimal FOV. The depth of the sensitive region in the axial direction, which is perpendicular to the plane of the surface coil, is limited to about the radius of the coil. To obtain an image of, for example, a right molar tooth, the coil could be positioned on the right cheek. For an average-sized patient the distance between the coil and molar teeth is about 30–50 mm, and as a result, sensitivity is significantly diminished. In addition, with the coil in this configuration, the cheek and buccal fat produce intense signals. Hence, the resulting images will contain more signals from less important tissues.

Positioning a coil intraorally, in the buccal vestibule that is between the teeth and adjacent cheek, increases both resolution and SNR (11). By sacrificing some comfort, as well as SNR, the intense signal from the cheek can be shielded out (19). However, due to an inability to position the coil in the restricted space optimally, the root tips of the teeth appear outside the sensitive volume of such coils. Normal intraoral anatomy makes it difficult to position the coil posterior enough to obtain images of the most distal teeth in the mouth, and common variations of intraoral anatomy, such as the presence of buccal tori and frena, pose additional difficulties in positioning the coil. This suggests that using the buccal vestibule approach for RF coil placement is problematic for patient comfort and limits visualization of oral structures. Accommodating all patient sizes and anatomical variations would likely require multiple types and sizes of coils as well as repeated scans in order to obtain needed images.

In most standard uses of surface coils, the plane of the coil is oriented parallel to $B_0$, and it is the $B_1$ field component in the direction of the coil axis that produces the majority of the field used for MRI. For most applications, this orientation is optimal because the sensitive volume of the coil is close to spherical and allows images within the area to be captured. Historically, even though the sensitive volume of a loop coil is approximately spherical, it is called a surface coil, because images are usually obtained from only one side of the loop.

Interestingly, the most comfortable coil position between the teeth in the occlusal plane was never seriously considered previously. This is likely due to thoughts that in this orientation the longitudinal component (normal to the plane of the coil loop) of $B_1$ becomes useless, because NMR signal interacts only with $B_1$ components directed orthogonally to $B_0$. Conveniently, the transverse components (in the plane of the coil loop) of $B_1$ produce a sensitive volume optimally suitable for imaging of the most important dental structures. Note that only a couple of prior attempts (not related to dental imaging) of orienting a surface coil orthogonally to $B_0$ have been reported. (30,31). We present $B_1$ simulations of the coil as well as images of teeth and supporting structures. These show the advantages of using a loop coil in the occlusal position for applications of interest to dentists.

**METHODS**

**RF Coil Design**

We constructed a single loop utilizing copper foil of 10 mm width (Fig. 1a). The shape and size was chosen to fit the average adult maxillary arch (with radius about 25 mm). The foil was covered with sticky foam for comfort.

![Fig. 1](image.png)

**FIG. 1.** Intraoral dental RF loop coil (a) and in-vivo experimental coil set between the upper and lower jaw bite planes in the occlusal position (b).
Simulations

The Biot-Savart magnetostatic approximation of the RF field was calculated by using an in-house modified version of the Biot_3d.m program written in Matlab (Copyright © 2011, Sathyanarayan Rao: http://www.mathworks.com/matlabcentral/fileexchange/33409-magnetic-field-of-a-current-loop-using-biot-savarts-law).

Figures 2 and 3a,b present Biot-Savart simulations for one-wire loop coils of radius $R$ centered at (0, 0, 0). To simulate a coil with a wide foil (Fig. 3c), five one-wire loops with appropriate radii, each with the same current, were positioned equidistantly to fill the width of the foil. The longitudinal and transverse components of the $B_1$ field (defined relative to the coil axis) were calculated. Isocontour lines of the field strength in the YZ plane were calculated, normalized to the maximum value of the longitudinal component, and presented in 10% steps in the same scale. The magnetostatic approximation used in this work does not include the waveguide, dielectric, and skin effects inevitable at high frequencies; however, it is sufficient to allow the presented qualitative discussion and conclusion (please read more in the Discussion section).

MRI Experiments

The phantom and in vivo images were all acquired using a 4 T (90 cm-bore) MRI scanner equipped with a Varian (Agilent) DirectDrive™ console. The available ramp time and field gradient strengths were 0.5 ms and 50 mT/m, respectively.

The phantom used was a 150 mm diameter glass cylinder loaded with tap water. The coil was isolated electrically by using a plastic bag, and then immersed in the water and fixed to the edges of the cylinder. The orientation of the entire cylinder (including the coil) was changed in order to obtain the longitudinal and transverse components at identical load conditions.

The in vivo images were obtained from a normal adult volunteer with the intraoral RF loop coil in the occlusal position. The coil was isolated from intraoral structures, and saliva, by being inserted within a MPTFE bag (Welch Fluorocarbon) of $0.06 \times 127 \times 102$ mm size. The patient lay in supine position with head in a holder specifically designed for restriction of head motion and fixation of the RF coil (Fig. 1b). All in vivo experiments were performed with approval from our university’s Institutional Review Board.

For imaging, the SWIFT sequence (18) was used (http://www.cmrr.umn.edu/swift/). Acquisition parameters for the phantom experiment were as follows: $b_w = 104$ kHz, TR = 3.1 ms, number of projections = 32,000, FOV = $22^3$ cm$^3$, and total acquisition time = 110 s. Parameters for the in vivo experiment were as follows: $b_w = 125$ kHz, TR = 2.65 ms, number of projections = 131,000, FOV = $123^3$ cm$^3$, and total acquisition time = 4.5 min. The general parameters: nominal flip angle = 8°, with acquisition of 128 complex points during a gapped HS2 pulse (32,33) and continuous acquisition.

FIG. 2. Intensities of the longitudinal (red) and transverse (black) components of the $B_1$ field in the YZ plane, as created by a one loop coil of radius $R$ within the XY plane, based on Biot-Savart calculations. Arrows indicate the directions of $B_1$ field components.

FIG. 3. Schematic of MR effective components of $B_1$ and objects of interest for dental imaging with conventional coil orientation (coil plan parallel to $B_0$) in extraoral position ($R = 80$ mm; a); conventional intraoral position ($R = 15$ mm; b); and with coil in occlusal position ($R = 25$ mm, coil plan orthogonal to $B_0$; c), based on Biot-Savart calculations.
of 128 complex points after the pulse. The time delay between the end of acquiring one projection and the start of the next was fixed at 0.6 ms. The field gradients changed values at the beginning of that delay. Each spoke acquisition results in one center-out line of k-space after pre-processing (radial center-out k-space trajectory). The terminus of the radial spokes grouped in 128 interleaved spirals and acquired with Halton view order (34) forms isotropically distributed points on a sphere. 3D radial SWIFT data were processed using an in-house program developed in LabVIEW (National Instruments) and interpolated with a Kaiser-Bessel function onto a Cartesian grid utilizing in-house MATLAB (Mathworks) mex code to a matrix of 384^3 (yielding 0.3 mm nominal resolution for in vivo experiment). The panoramic slices were created by using the “straighten” plugin (35) in ImageJ, which is a Java based image processing program (36).

RESULTS

Figure 2 presents the calculated isocontour lines of the longitudinal and transverse components of the $B_1$ field in the YZ plane created by a single-loop surface coil located in the XY plane. In the XY plane and parallel planes, the isocontour lines are radially symmetric, tracing out circles (not shown). Viewed in the YZ plane the contours have differing symmetry for the two orthogonal components. The longitudinal component describes a mirrored shape for each contour, with XY plane of symmetry. The transverse components are presented as two circular shapes (also mirrored) at the position of each crossing of the coil element of the YZ plane. They can be described as two toroidal volumes or “doughnuts” of sensitivity above and below the XY coil loop plane. The longitudinal component has higher values at the center of the coil (and Z axis) relative to the transverse component, and overall has about 10% deeper penetration (measured from the Y plane) relative to transverse component. For excitation and detection in MRI either the longitudinal or transverse components (or combination) of the surface coil $B_1$ can be used, and this depends only on the orientation of the coil plane relative to Zeeman field, $B_0$.

Figure 3 schematically shows the field profiles and relative sizes of molar teeth to estimate the relative efficiency of the different approaches using longitudinal components extraorally (Fig. 3a) and intraorally (Fig. 3b), as well as the intraoral approach using transverse components (Fig. 3c).

Figure 4 presents the results of a phantom experiment that compares the sensitive volumes achieved with the coil oriented in the two different orthogonal positions. The experiment was done in exactly the same surrounding media and with the same coil loading, but with rotation by 90°. The expected noise contribution is the same in both cases. For the small flip angle used, the intensity profiles in Figure 4e provide a measure of the $B_1$ distributions and/or SNR. The absolute intensity profiles plotted for these different coil orientations are within about 10% of each other (Fig. 4e). All of these results match well with the simulated data. 3D in vivo images with the coil loop plane in the occlusal position (using the transverse $B_1$ field components relative to the coil loop plane) are shown in Figure 5. As was predicted, the teeth and jaw bones are nicely positioned within the sensitive volume of the coil, while the signal from cheek and tongue appear with low intensity.
DISCUSSION

Traditionally the plane of an MRI surface coil loop is oriented parallel to $B_0$ to exploit the longitudinal component of $B_1$ with extraoral or intraoral positioning, as schematically presented in Figure 3a,b, respectively. The main advantage of extraoral positioning (Fig. 3a) is patient comfort, while disadvantages include low filling factor, low resolution, and the included (noninformative) high amplitude signal from the cheek located next to the coil (29). With intraoral positioning (Fig. 3b), SNR is high and the cheek signal is still high, but can be shielded out (19). However, a main disadvantage could be lower SNR at the position of the tips of teeth.

As was shown with these preliminary images (Fig. 5) dental structures can effectively be covered using the transverse components of $B_1$ (relative to the loop plane) produced by a single loop coil in the shape of the human arch. The sensitive volume of this coil configuration in the occlusal position includes the most important dental structures, including the teeth and jaws, and excludes large portions of the cheeks, lips, and tongue, which usually have less informative but very intense confounding signals.

The teeth and supporting structures of the dental arches are within the two sensitive toroidal volumes or “doughnuts,” while tissues of less interest (e.g., cheeks, lips, and tongue) are not. This has two significant advantages: (i) maximum coil sensitivity corresponds to the regions of most interest (teeth and supporting structures); and (ii) minimum coil sensitivity corresponds to structures that a dentist is not traditionally trained to interpret, such as skull base and brainstem. It is worth noting that factor ii is responsible for minimizing motion artifacts (radial streaking) originating from the intense signals (cheeks, lips, and tongue) that would be included with other coil configurations.

The reduced intensity in the front teeth position, which is noticeable in Figures 4a and 5a is related to the 2 mm gap between the ends of the copper loop. This deficiency could be circumvented by decreasing the gap or even partly overlapping the coil’s ends in a future coil design.

Here, we have used a single channel coil in transmit-receive mode, although this orthogonal coil can also be as a receive-only coil in combination with another transmitting volume coil. At this point is not obvious how the proposed approach could effectively be used with a parallel imaging technique to accelerate teeth imaging. However, for whole mandibular imaging (20), for example, we believe the orthogonal coil in occlusal position could be used in combination with an array of “conventionally designed” extra or intra oral coils for parallel acquisition.

The Biot Savart calculation, despite its simplicity, is in good agreement with our phantom experiments. This is due to the limited diameter of the coil (5 cm), which in this case is about 40 times smaller than the wavelength in vacuum and about 4 times smaller than the wavelength in high-water-content media (37). However, future research will benefit from full-wave electromagnetic field calculations in complicated dental tissues including air, dentin, enamel, teeth supporting tissues, and saliva, especially in the presence of different restorative materials, such as endosseous implants.

FIG. 5. Three selected orthogonal slices (a) and selected panoramic slices (b) of a 3D SWIFT image obtained using the transverse components of the $B_1$ field.
To the best of our knowledge, Figure 5b presents the first MRI panoramic images at such high nominal resolution (0.3 mm³). The actual spatial resolution is lower due to the effects of residual motion and off-resonance blurring, which for radial acquisition could be compensated at the postprocessing stage and are in the scope of future research.

CONCLUSIONS

The transverse components of the $B_1$ field of a surface coil in the occlusal position can be effectively used for imaging of teeth and associated structures.

REFERENCES