Dental imaging with low-field Magnetic Resonance Imaging (DentMRI)

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ABSTRACT

Magnetic Resonance Imaging (MRI) of hard biological tissues is challenging due to the fleeting lifetime and low strength of their response to resonant stimuli, especially at low magnetic fields. Here, we present three-dimensional reconstructions of ex-vivo human teeth, as well as a rabbit head and part of a cow femur, all obtained at a field strength of 260 mT. These images are the first featuring soft and hard tissues simultaneously at sub-Tesla fields, and they have been acquired in a home-made, special-purpose, pre-medical MRI scanner designed with the goal of demonstrating dental imaging at low field settings.

Keywords: magnetic resonance imaging, hard tissue imaging, tooth MRI, pulse sequence.

1. INTRODUCTION

Magnetic Resonance Imaging (MRI) is often considered the crown jewel of medical imaging. However, it is barely used in dentistry [1]. Instead, odontologists heavily use X-ray based technologies [2]. However, these come together with a number of detrimental aspects, such as the use of ionizing radiation, low soft tissue contrast, and unreliable revelation of pulp diseases [3] or tooth cracks and fractures [4]. MRI scanners are typically expensive to acquire, site, operate and maintain, mostly due to the high magnetic fields involved [5]. Low-field systems constitute a promising inexpensive alternative to standard MRI setups [5], [6], but the reduced signal-to-noise ratio (SNR) can easily lead to long acquisition times incompatible with clinical conditions. For this reason, further research on MRI of hard tissue at low magnetic field is of broad interest.

In this project we present "DentMRI-Gen I" (Fig. 1), a home-made special-purpose MRI scanner designed and fabricated with the goal of demonstrating dental imaging at low field settings. The main project achievements are:

- We demonstrate high quality combined images of soft and hard biological tissues with a low cost system.
- We show the world first images of soft and hard tissue simultaneously at sub-Tesla fields (260 mT).
- We have imaged human teeth in a scanner large enough for a rabbit head.
- We demonstrate the capabilities of Pointwise-Encoding Time reduction with Radial Acquisition (PETRA [7], [8]) pulse sequences at low fields.
- We designed a new pulse sequence specifically dedicated for hard tissue: Double Radial Non-Stop Spin Echo (DRaNSSE) [9], which we have devised to address sampling and contrast limitations we encounter with PETRA.
- We explored new reconstruction methods based on Algebraic Reconstruction Techniques (ART [10]), which perform significantly better than conventional Fourier methods.

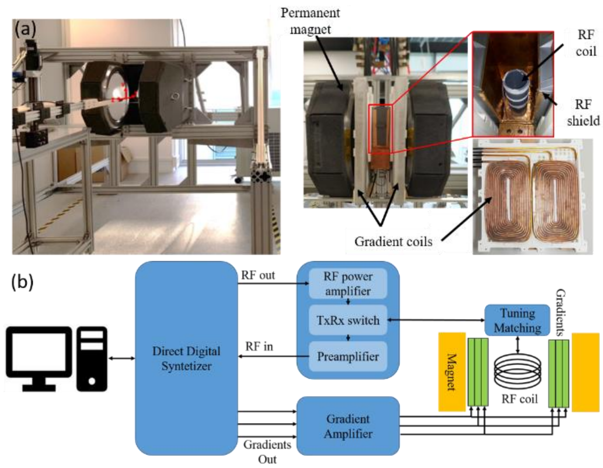

Fig 1. (a) (Left) Photograph of the main magnet installed on the support structure. (Right) Photographs of "DentMRI-Gen I", showing a general overview of the magnet and the components used for building the gradient and radio-frequency systems. (b) Block diagram of the "DentMRI-Gen I" scanner.

2. STATE OF THE ART

Despite MRI unquestionable success, imaging hard tissues (such as dentin or enamel) remains problematic [11]. This is due to the fleeting lifetime (T_2) and low strength of signals emitted by solids, as opposed to the case of soft and non-solid tissues [12]. Notwithstanding, MR images of teeth with diagnostic value have been obtained at extreme magnetic fields (> 9 T) in the University of Minnesota [13] and in collaboration between ETH Zurich and Bruker [7]. However, high field scanners incur in highly expensive acquisition and maintenance costs (~1 M€/T) and images have all been taken in pre-clinical or experimental scanners. "DentMRI-Gen I" is the first approach to low-field dental imaging that we are aware of [9].

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Tab. 1. Comparison between state of the art and project results for hard tissue MRI

	State of the art	Project Breakthrough
Magnetic field	> 4 T	260 mT
Price	~1 M€/T	~150 k€
Pulse sequence	PETRA	DRaNSSE
Reconstruction	FFT	ART

Images of hard and soft tissue simultaneously at sub-tesla fields. In our project we obtained the world first dental images in a sub-tesla system. This is a major breakthrough because the signal-to-noise ratio (SNR) decreases with magnetic field strength. Fortunately, quantum coherence times (usually referred to as T_2 times) are longer at low fields, which we exploit in our setup.

Low-cost system. The cost of the "DentMRI-Gen I" system is below 150.000 €, since we employ a permanent magnet and all parts are standard commodities, 3D-printable, or inexpensive to machine. This shall be compared with the approx. 1 M€/T of ultra-high field systems used in previous works (> 4 T).

New dedicated pulse sequence. We invented DRaNSSE to overcome time and contrast limitations we found with standard PETRA sequences. In DRaNSSE, after the first excitation radiofrequency pulse, two additional refocusing π-pulses produce two different spin echoes. In this way, we collect two images simultaneously with different T2 weighting, and we shorten acquisition times significantly.

Improved reconstruction methods. We make use of Algebraic Reconstruction Techniques (ART) for reconstruction. ART exploits explicit prior knowledge of the highly controlled physical interactions between electromagnetic fields and the sample spins in MRI systems. We demonstrated that ART can outperform the results obtained by more conventional method based on Fourier reconstruction.

4. PROJECT RESULTS

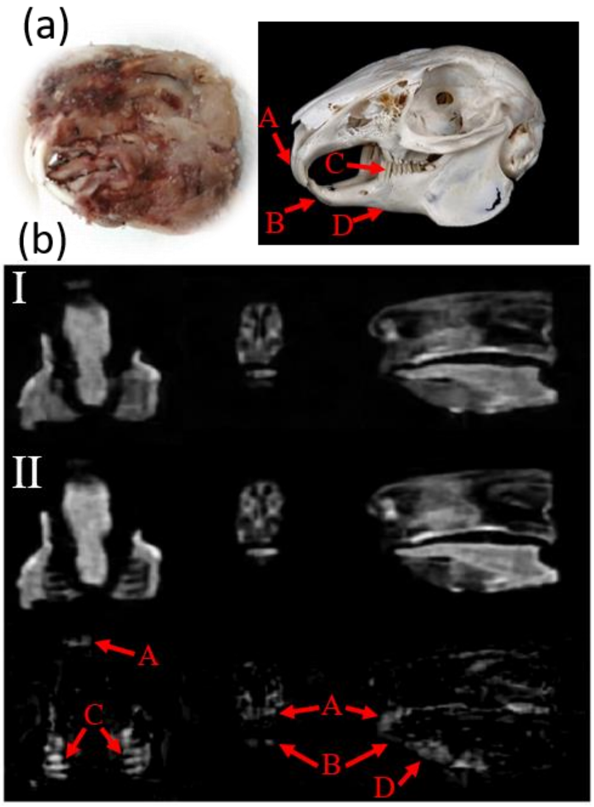

Fig 2. (a) Picture of the scanned rabbit head (left) and picture of a rabbit skull (right). (b) Images of the scanned rabbit head.

"DentMRI-Gen I" is our first-generation MRI dental scanner designed and built to demonstrate hard tissue imaging techniques in low magnetic field settings. Samples are accommodated in a cylindrical FOV of height = 100 mm and diameter = 45 mm. We enclose the sample in a Faraday cage to isolate our single radio-frequency coil from the magnetic gradient coils and electromagnetic interface noise present in the laboratory.

For initial demonstration purposes, we first show ex-vivo images of a rabbit head (Fig. 2(a)). Fig. 2(b) contains selected slices from the full 3D reconstruction employing a PETRA sequence. We acquired two independent images: one with a short dead time to read in the combined signal from hard and soft tissues (Fig. 2(b) top) with a total scan time of 61 minutes; and one with a long dead time to remove the short-lived contribution of teeth and skull tissues (Fig. 2(b) middle) in 33 minutes. Both images are reconstructed with ART and denoised with

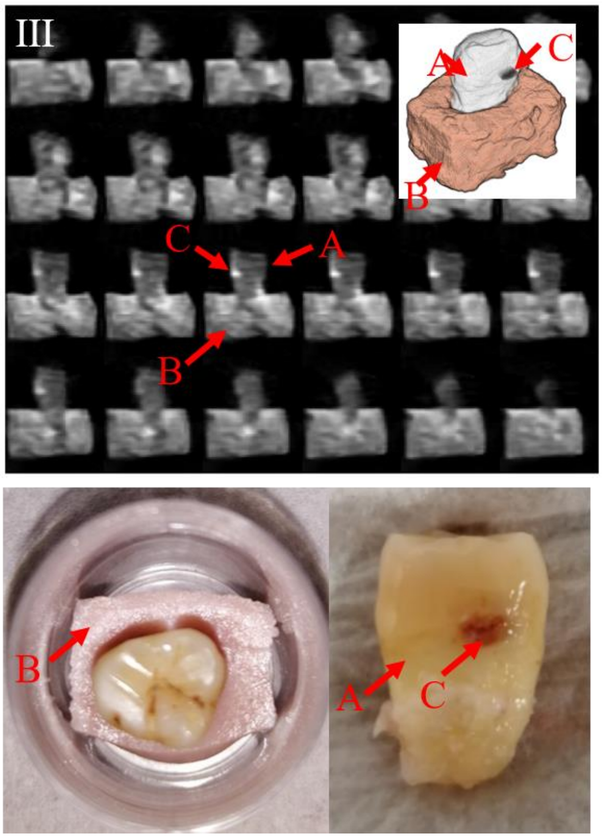

Fig 4. (a) 2D slices of human tooth embedded in a piece of pork ham. Inset: 3D reconstruction. (b) Photographs of the sample.

Block-Matched filters. Finally, we subtract one of the above scans from the other to produce the bottom image in Fig. 2(b), where only hard tissues are highlighted.

Fig. 2 demonstrates the capabilities of "Dent-MRI-Gen I" for imaging of soft and hard tissues simultaneously at sub-Tesla fields. Below we demonstrate our scanner's performance for a sample consisting of a human tooth inserted into a piece of ham emulating the gum (Fig. 3(b)). Fig. 3(a) shows 2 dimensional slices obtained from a PETRA scan in 144 minutes (sequence parameters in Table 2). The image is reconstructed with ART and denoised with a Block-Matched filter. In Fig. 3(a) we identify the tooth (A), ham (B) and caries (C), also visible in the photographs in Fig. 3(b). Also shown in the Fig. is a segmented, 3 dimensional rendering of the sample. In this case, we acquired a second image with the same parameters as for image III, but using a dead time of 1 ms and acquiring for 4 ms, for a total scan time of 40 minutes.

As shown in Figs. 2 and 3, T_2 contrast is possible by image subtraction. This is a lengthy procedure, however, which can be significantly improved with DRaNSSE. Here we compare one approach against the other. For these tests we use a piece of cow femur (Fig. 4(a)), which is mostly composed of only two tissues (bone, with $T_2 \sim 1$ ms, and marrow, with $T_2 > 50$ ms). In Fig. 4(b), images labelled as

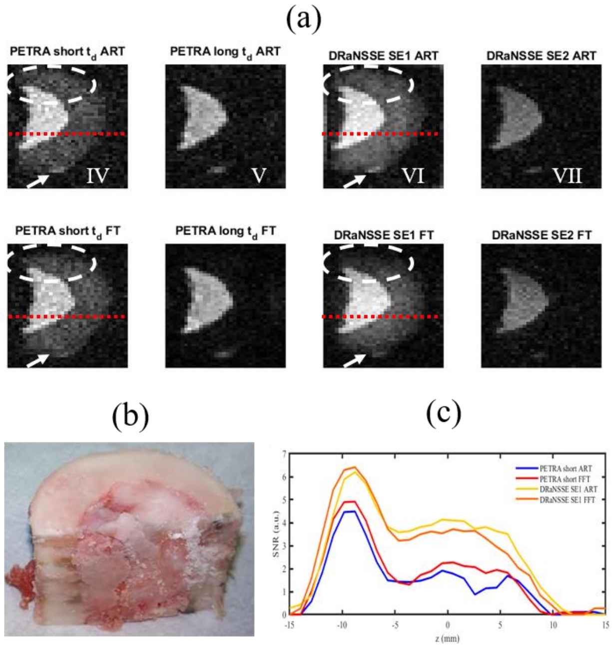

Fig 3. SNR for different reconstruction methods. (a) Raw image slices from 3 dimensional acquisition with PETRA and DRaNSSE, reconstructed with ART (top row) and FT (bottom); (b) Photograph of cow bone sample. (c) Signal to noise ratio along the red dotted lines in (b). White dashed lines highlight differences between ART and FT reconstructions.

"PETRA long (short) t_d" correspond to an individual PETRA scan with long (short) dead times, where marrow (and bone) appear visible. For DRaNSSE we run a single scan, which can be used to reconstruct marrow (and bone) from the second (first) acquisition in the sequence, corresponding to images with the label "DRaNSSE SE2 (SE1)". Sequence parameters can be found in Table 2. Importantly, the total scan times for this study are kept the same, i.e. the sum of both PETRA scan durations is very close to the single DRaNSSE scan time (~ 65 minutes). It is apparent from a qualitative comparison between the raw (unfiltered) image sets IV and VI in Fig. 4(b), that DRaNSSE reconstructions feature a higher SNR than with PETRA. Fig. 4(c) shows the SNR along the red dotted lines in Fig. 4(b) for four different cases, quantitatively reinforcing this observation. Voxels corresponding to bone and marrow tissue both feature a stronger SNR for DRaNSSE when reconstructed with ART. All in all, the SNR is a factor ~ 1.4 higher with DRaNSSE than with PETRA for soft tissues and ~2.2 for hard tissues. Not shown in this manuscript, comparison between SNR maps of images reconstructed with ART and Fourier transforms demonstrate that ART can strongly outperform the image quality of images reconstructed with Fourier.

A detailed description of the results can be found in the manuscript "Simultaneous imaging of hard and soft biological tissues in a low-field dental MRI scanner" uploaded to the arXiv as a preprint and recently accepted by Nature Scientific Reports [9].

5. FUTURE PROJECT VISION

5.1. Technology Scaling

In the first phase of the ATTRACT project we have reached a Technology Readiness Level (TRL) 4 with “Gen I”. To get closer to market, a prospective “Gen II” scanner must fulfil a number of specifications:

- Adapted to human physiognomy
- Low weight, small footprint
- Advanced pulse sequences (bssfp)
- Dynamical decoupling schemes
- Slice selection
- Advanced reconstruction methods
- 3D image of 1 mm resolution in < 10 min
- 2D image of 500 um resolution in < 1 min
- Certifiable prototype
- Low cost: < 100 k€

First and foremost, scan times must be reduced. To that end, we plan three major upgrades for “Gen II”: i) we will make use of balanced steady-state free precession protocols, which yield optimal SNR values and can be safely used at low magnetic fields [6], [16]; ii) we will use quantum dynamical decoupling techniques such as WAHUHA [17] or CHASE [18] sequences, which can prolong the lifetime of the magnetic resonance signal of hard tissues; and iii) we will perform dual species MRI on protons and ^{31}P nuclei, since the latter are more abundant in hard biological tissues and they provide complementary information [19]. Additionally, we are investigating slice selection with zero-echo time sequences for fast 2D imaging.

5.2. Project Synergies and Outreach

Our next major goal is to construct and obtained medical certification for our new “DentMRI - Gen II” system. To that end, we collaborate with the prestigious Llobell-Cortell dental clinic in Valencia (Spain) and with the first technology transfer fund created by a public university in Spain. Meanwhile, Tesoro Imaging S.L. has engaged business angels in Spain, and we see in ATTRACT a great opportunity to network with international investors.

From a technical perspective, a key aspect where we need external input is in image reconstruction, where Deep Learning can have an important impact with respect to our current iterative algorithms. We have already initiated a partnership with the Leiden University Medical Center and Philips, and look forward to conversations with spokespeople of other ATTRACT Phase funded projects with expertise in the fields of Machine Learning and Artificial Intelligence.

Regarding dissemination, we have recently received news that all these results will be published in Scietific Reports, an open-access journal from the Nature Publishing Group. We have also produced a dissemination video (accessible in Youtube) which is to appear as a featured story in the ATTRACT website, and we have prepared material for an ATTRACT featured story, which is also already online. We will continue with all these activities, and we expect that the first dental images with clinical value obtained with “Gen II” will be published in a top scientific journal.

5.3. Technology application and demonstration cases

During ATTRACT Phase 2, we will prepare for CE and FDA medical certifications, so we will demonstrate our technology in several dental clinics in Europe and USA. This will bring concrete benefit to: Scientific Research, since our technology opens the door to an MRI regime thus far unexplored; Industry, since Tesoro Imaging will commercialize affordable dental MRI scanners; and Societal Challenges, specifically in the health sector, since dentists will be able to access better information without requiring harmful X-ray technologies.

5.4. Technology commercialization

Tesoro Imaging S.L. has already initiated the path towards commercialization of this project’s results. We are currently closing a second round of 0.75 M€ with strategic stakeholders (including highly reputed dentists). At the end of 2020 we plan a third round of about 1 M€ to build “Gen II” and to reach the certification phase. A fourth round is foreseen at the end of 2021 in order to obtain the CE and FDA certifications. Once the system is certified we may either bring in an industrial partner with a commercial network or increase the capital to develop the market. Our plans further include securing public funding, notably from ATTRACT phase 2 and other EC calls including FET Innovation Launchpads or the EIC Pathfinder program.

Our device can replace X-rays and traditional image-based scans with a current market over 7 billion euro a year and increasing at a two digit pace.

5.5. Envisioned risks

Dental MRI at low fields is an extremely challenging goal which has never been achieved before. The associated risk is therefore high. However, during ATTRACT Phase 1 we have demonstrated all of the main technological milestones required for a successful system (see Sections 1-4), and the only remaining issue is scan time. In the last weeks we have been able to take 2D images of hard tissues in “Gen I”, based on a slice selection technique for ZTE sequences. This was thought not to be possible, so we have filed a new patent at i3M, which we have licensed to Tesoro for the dental health sector. 2D scans can be performed exceptionally fast, so we are now confident that we can meet the specifications detailed in Section 5.1.

The commercial risks may be different, though, and a possible issue is the practitioners' ability to interpret the images delivered by our scanner. To mitigate this risk, Tesoro will offer a training service for their customers.

5.6. Liaison with Student Teams and Socio-Economic Study

We have not collaborated with student teams outside our own students at i3M, and we look forward to doing so during ATTRACT Phase 2. Being in a university, we are constantly engaged in teaching and dissemination activities, and can easily facilitate MSc. level explanation materials of our technology. Likewise, we would be delighted to contribute to socio-economic studies carried out in the scope of Phase 2 in whichever way may be useful, with interviews, scientific impact studies, technical information, etc.

6. ACKNOWLEDGEMENT

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