Dental MRI can detect micro-cracks

Djaudat Idiyatullin[1], Michael Garwood[1], and Donald Nixdorf[2]
[1]*CMRR, Radiology Department, University of Minnesota, Minneapolis, Minneaota, United States,* [2]*Division of TMD & Orofacial Pain and Department of Neurology, University of Minnesota, Minneapolis, Minneaota, United States*

Introduction A long-standing problem in dentistry is the lack of a valid imaging method for detecting cracks in teeth[1]. Cracks in teeth are common with one being present in at least one molar tooth of 70% of randomly selected patients[2,3]. Usually cracks are detected by report of patient symptoms and by visual findings from inspection, with and without aides such as dyes, magnification, and transillumination[1]. These approaches are not able to detect cracks apical to restorations or within the root structure, both of which are considered characteristics of cracks more likely to lead to structural failure and eventual tooth loss[4]. Current X-ray based techniques, specifically cone-bean computed tomography (cbCT), does not reliably detect root fractures[5,6] and no studies assessing coronal cracks were identified, presumably because the majority of such teeth have restorations[7] that produce artifacts obscuring the coronal structures[8]. There is a critical need to develop reliable imaging technology to detect cracks in teeth, while avoiding ionizing radiation, for future clinical research purposes to explore ways of improving diagnostic certainty. We demonstrate dental SWIFT (SWeep Imaging with Fourier Transformation[9,10]) images which visualize cracks with about 20 µm thickness, which is one order of magnitude smaller than the size of the image voxel itself. To explain this phenomenon we developed and tested a digital MRI model of dental structures including cracks based on known NMR relaxation parameters of ^{1}H protons in dental tissues[11].

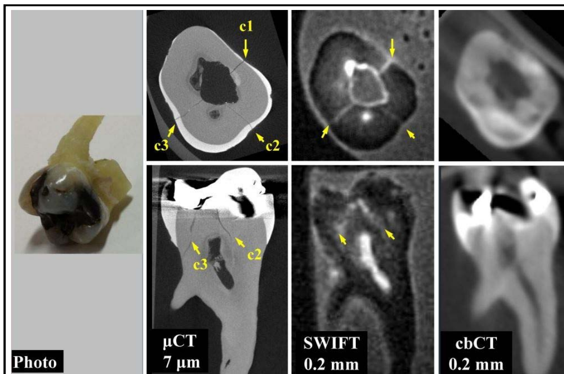

Fig.1: Photos and orthogonal slices of a molar tooth with amalgam filling, as imaged with 3D µCT, SWIFT using *in-vivo* acquisition parameters, and cbCT. The cracks c1- c3 of 50, 30 and 40 µm thicknesses respectively are marked with arrows.

Method **Samples:** Extracted teeth were harvested as waste tissue making their use exempt under current Institutional Review Board protocols. Following extraction, the teeth were stored in 10% formalin solution. For this application we chose teeth that mimic the typical clinical situation: dimensions of cracks, and presence of restorative materials. **X-ray:** The determination of crack thickness was done with µCT and a comparison with cbCT was performed to assess how a clinically available 3D imaging system performed. The µCT (XT H 225, Metris, Belgium) was obtained using 720 projections with 32 frames per projection, resulting in a resolution of 7 µm. The cbCT (17-19 iCAT, Imaging Sciences, Hatfield, PA) was obtained in one scan, with a 60 mm field of view (FOV) at 37 mA/s for 27 s and 120 kV with a resolution of 0.2 mm. **MRI experiments:** All *in vitro* MRI experiments were performed in a 4T (human) magnet equipped with Agilent console. To demonstrate the feasibility to detect cracks *in vivo* with SWIFT, we collected images under "*in vivo* conditions" by using an intraoral coil[12] and all acquisition parameters identical to *in vivo* experiments (FOV=120^3 mm^3, acquisition time = 3 min, bw=100 kHz). **Digital dental MRI model:** The simulated 3D dental image was based on data available in literature related to dental contents[13] and NMR relaxation parameters ($T_{1,2}$) of water inside different contents[11]. The size and resolution of the 3D model was adapted to the *in vivo* dental images. The intensity of each component was weighted by T_1 using the Ernst equation[14]. Blurring effect due to T_2 decay in radial images was accounted for in a modified 3D point-spread function (PSF)[15].

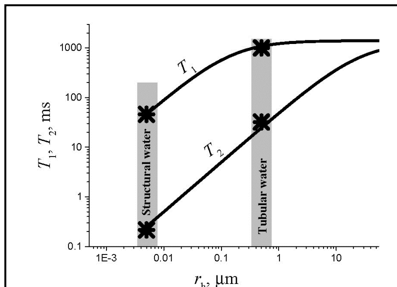

Fig.2: $T_{1,2}$ data obtained by Schreiner[11] plotted against estimated hydraulic radius and fitted with the Brownstein–Tarr equation.

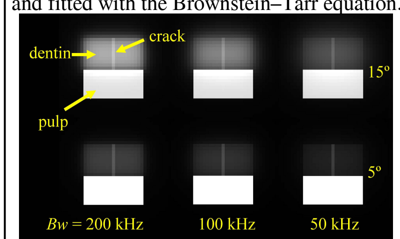

Fig.3: Digital model of cracked tooth at different bandwidth and flip angles.

Result and Discussions On the slices presented in **Fig.1**, three cracks are clearly identifiable, labelled c1- c3, which were measured by µCT to have 50, 30 and 40 micron thicknesses, respectively. We found that cracks of 20 µm thickness and larger are identifiable with SWIFT MRI and have a contrast to noise ratio (CNR=SNR$_{crack}$-SNR$_{dentin}$) of about 5. This is encouraging because it demonstrates that cracks in teeth can be detected using SWIFT MRI even though the physical thickness is about 10 times less than the size of the image voxel. At the same time the presence of cracks in the cbCT are obscured due to artifacts originating from the metallic restoration, which is a known problem for cbCT methodology[16]. Even without such artifacts, the CNR in cbCT is poor and therefore contributes to the difficulty in detecting such small cracks reliably[17]. The graph in **Fig.2** used the $T_{1,2}$ data obtained by Schreiner[11] for water located in two different environmental porosities, called "structural water" and "tubular water". To see that the relaxation of water mostly depends on porosity we plotted these data against the approximate hydraulic radius ($h_d = V/S$ –volume- surface ratio) of pores[18]. In the main bulk of the dentin the tubule is 1-2 µm in diameter[19] giving $h_d \approx 1.5/4 \approx 0.4$ µm for a cylindrical structure. The structural water associated with the spaces between the collagen and the crystallites of the mineral apatite in the order of 10 nm[20], gives $h_d \approx 10/2 \approx 5$ nm for planar structures. The excellent fit of the curves leads to the conclusion that water relaxation in dentin is well described by the Brownstein–Tarr equation[21]: $1/T_{1,2} = 1/T_{1,2}^B + \rho_{1,2}/h_d$, where $T_{1,2}^B$- relaxation of bulk water and $\rho_{1,2}$- surface relaxivities. This approximation allows the rough estimation of $T_{1,2}$ parameters of water in cracks of any size. **Fig.3** presents the results of simulations of the dental MRI model with a crack of 20 µm thickness for different excitation bandwidth and flip angles. As expected dentin's signal increases at increased bandwidths and flip angles. At the same time we noticed that increasing bandwidth does not improve the detectability cracks of this size.

Conclusions In the case of MRI the presence of water in cracks creates a positive contrast enhanced by two mechanisms. First, the concentration of water inside a crack is at least 5x higher than in dentin[13]. Second, the T_2 of mobile water in cracks is much larger than that of water located in motion restricted dentin pores, which makes the signal from the water located in cracks less blurred and more localized inside of the same voxel. Our findings suggest that crack sizes on the order of tens of microns could be detected with regular MRI methods; however the high deviation of local magnetic field in dental tissues results in off-resonance artifacts and for this reason we suggest using pulse sequences that capture fast decaying T_2 signal, such as UTE, ZTE and SWIFT. The digital dental MRI model helped in understanding the contrast mechanism in dental MRI images and was useful for optimization the study imaging protocols. The similarity between dentin and cortical bone suggests that our findings may be relevant to identifying other bone pathologies.

Acknowledgements This research is supported by National Institutes of Health grant P41 EB015894, S10 RR023730 and S10 RR027290 and WM KECK Foundation.

References [1]Lubisich JERD 22,2010 [2]HILTON *IADR/AADR GenSessExhib* 2011 [3]PRECEDENT NIDCR2013 [4]Berman JOE 36,2010 [5]Costa JOE 38,2012 [6]Brady,Int End J,2013 [7]Seo JOE 38,2012 [8]Scarfe Int JofDent 2009,2009 [9]Idiyatullin JMR 181,2006 [10]Idiyatullin JOE 37,2011 [11]Schreiner BiophJ 59,1991 [12]Idiyatullin MRM 72,2014 [13]Pasteris ELEMENTS 4,2008 [14]Ernst RevSciIns 37,1966 [15]Rahmer MRM 55,2006 [16]Barrett Radiogr 24,2004 [17]Tsesis JOE 36,2010 [18]Brunauer JColl InterfSci 24,1967 [19]Mjor BrazDentJ 20,2009 [20]Cowin JofBiomech 32,1999 [21]Brownstein JMR 26,1977.