ADC mapping of the dentin-pulp complex response to caries

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Purpose

Several feasibility studies showed that MRI can be suited to dental applications enabling assessment of dental pulp vitality with high sensitivity and specificity (1,2). However, no MRI study employing diffusion-weighted imaging (DWI) was used to assess the dentin-pulp complex response to caries. DWI is sensitive to microscopic incoherent motion of water and allows quantification of the apparent diffusion coefficient (ADC) of water in the tissue, which is susceptible to several cellular changes and tissue abnormalities (3). The application of DWI was extensively investigated in certain pathologies; i.e., cerebrovascular stroke and demyelinating disease, where ADC reductions were found to be more or less pronounced depending on stages of ischemia (4,5). Caries also induces dental pulp tissue ischemia so that DWI is an appropriate tool for detection of the dentin-pulp complex response. It may be expected that diffusion is faster in regions with less intensive dentin-pulp complex response, characterized as hypo-intense regions in DWI, and slower in regions with more intensive dentin-pulp complex response, characterized as hyper-intense regions in DWI.

In present study high-resolution 3D $T_1$-weighted MRI was used to visualize and quantify caries lesions of which dentin-pulp complex response was then assessed by ADC mapping. The results were compared with the standard International Caries Detection and Assessment System (ICDAS) to evaluate a prognostic potential of ADC mapping.
Methods and Materials

Human Teeth Ex Vivo

In the study, 26 extracted human teeth were used: 15 molars, 6 premolars and 5 canines. Reasons for tooth extraction were orthodontic or surgical. The teeth were immersed in physiological solution immediately after extraction and stored in a cold incubation box at 8°C. MR imaging was started no later than twelve hours after the extraction to avoid autolysis in the dental pulp that may affect MRI results. In order to prevent dental pulp desiccation during the experiment as well as to visualize tooth surface along with prompt MRI, the teeth were coated by the silicone dental impression material.

ICDAS Severity Scores

Detection of caries lesions was interpreted by two independent clinical observers using ICDAS severity scores. Each of individual observers had extensive clinical experience in restorative dentistry and was denied access to all other significant information, such as patient identity, clinical history and results of histopathological evaluations. 7-grade ICDAS severity scale (score 0, sound dental surface; score 1, first visual change in enamel; score 2, distinct visual changes in enamel; score 3, localized enamel breakdown; score 4, underlying discolored dentin with or without localized enamel breakdown, score 5, distinct cavity with visible dentin; score 6, extensive distinct cavity with visible dentin) was assessed by conventional probing, radiography and fibre-optic transillumination.

Magnetic Resonance Imaging

The imaging was performed on a MRI scanner consisting of a 2.35 T (Oxford Instruments) equipped with accessories for MR microscopy (Bruker) with a maximum imaging gradients of 300 mT/m and a TecMag spectrometer (Houston). Dental pulp anatomy was imaged by high-resolution 3D $T_1$-weighted MRI using the 3D spin-echo imaging sequence. Imaging parameters were the following: echo time 2.3 ms, repetition time 400 ms, imaging matrix 256 × 128 × 128, field of view 30 mm × 15 mm × 15 mm; spatial resolution of 120 µm per pixel was isotropic. Signal-to-noise ratio was improved by acquiring eight signal averages so that the total scan time was 15 hours.

Each tooth was imaged also by the 3D DWI method using similar resolution parameters: field of view 30 mm × 15 mm × 10 mm and imaging matrix 256 × 128 × 8; in-plane resolution was identical to that of 3D $T_1$-weighted MRI, while the slice thickness was 1.9 mm. The DWI method was based on the pulsed-field gradient spin-echo (PGSE) technique (22) with two 11 ms gradient pulses positioned symmetrically with respect to the refocusing RF pulse ($\delta = 11$ ms, $\gamma = 18$ ms). The repetition time and the echo time of the 3D DWI method were 1300 ms and 34 ms, respectively. The DWI method was
performed with four different diffusion gradient amplitudes with \( b \) values of 0 s/mm\(^2\), 132 s/mm\(^2\), 317 s/mm\(^2\) and 635 s/mm\(^2\); the scan time of the DWI method was 90 minutes. The corresponding ADC map was calculated from the four DW images using the MRI Analysis Calculator plug-in of the ImageJ (National Institute of Health) image-processing software.

**Image analysis**

Caries lesions were assessed from \( T_1 \)-weighted MR images. The images were converted to the 8-bit grey scale with scaling to the signal of the intact dental pulp to which the intensity of 100 was assigned. This was followed by separation of caries lesions from the remaining intact dental pulp, which was done by the thresholding operation. The cut off value between signals of the caries lesions and the intact dental pulp \( S_{co} \) was determined using the relation

\[
S_{co} = S_{caries} - 0.6 \cdot (S_{caries} - S_{pulp})
\]

where \( S_{caries} \) and \( S_{pulp} \) denote average signal of caries and dental pulp regions respectively. The relation for the cut off value was determined, based on the expertise of two independent observers who agreed that such obtained cut off values do enable optimal visual discrimination between the intact and impaired regions of the dentin-pulp complex. Determination of caries lesions was followed by the assessment of the demineralization depth measured as a distance from the occlusal side of teeth to the caries pit.

Teeth of all seven ICDAS scores were analyzed by ADC mapping to obtain the corresponding average ADC values of dentin-pulp complex responses. In addition to that, the ADC maps of dentin-pulp complexes of all seven ICDAS scores were analyzed by histograms of normalized ADC distributions. The histograms were calculated as relative proportions of pixels of increasing ADC values in bins of \#ADC = 0.1 \times 10^{-9} \text{ m}^2/\text{s}. The proportions were calculated for the entire dentin-pulp complex, i.e., for all slices within the complex.
Results

High-resolution 3D $T_1$-weighted MRI enabled non-invasive visualization of dentin-pulp complex anatomy in an arbitrary orientation. Signal raise in demineralized hard dental tissues enabled detection and tracking of affected dental pulp along with discrimination among caries lesions and intact dentin-pulp complex of non-carious tooth over the whole range of ICDAS scores (Table 1). The signal rise in demineralized hard dental tissues can be seen in $T_1$-weighted MR images of representative teeth specimens (molars and premolars) with different ICDAS scores (Fig. 1a). The MR images have different ratios between the average signal of affected dental-pulp complex and the average signal of the intact dental pulp of non-carious tooth. The ratios are increasing with an increasing ICDAS scores (Table 2). No significant differences in the signal ratios between canines, premolars and molars of an identical ICDAS score were found. As can be seen from Table 2 ICDAS scores correlate also with the average demineralization depth, i.e., the higher the ICDAS score, the deeper the caries lesion.

Figure 1b shows ADC maps of the same teeth specimens as shown in Fig. 1a in the same field of view, slice orientation and slice position. DW images clearly show the destruction of dental pulp tissue as well as the progression of water from the enamel surface into the demineralized hard dental tissues. The regions of water progression correspond to the regions with the fastest diffusion (yellow). In addition to a detection of the free water regions (yellow, ADC # $2 \cdot 10^{-9}$ m$^2$/s) ADC enabled a reliable discrimination between regions of intact (red, ADC # $1.3 \cdot 10^{-9}$ m$^2$/s) and decayed (blue, ADC # $0.5 \cdot 10^{-9}$ m$^2$/s) tissues. Average ADC values of dentin-pulp complexes with different ICDAS scores are presented in Table 2.

Normalized ADC distributions of dentin-pulp complexes of the representative teeth from Fig. 1 are shown in Fig. 2. In the initial ADC distribution (intact dentin-pulp complex, ICDAS 0) ADC was in the range $0.5-1.7 \cdot 10^{-9}$ m$^2$/s with a peak at $1.24 \cdot 10^{-9}$ m$^2$/s. The position of the peak is unchanged until ICDAS 3, which corresponds to a visible enamel breakdown. The ADC distribution then progressively shifts towards lower ADC values with increasing ICDAS scores ending with the range $0.3-1.0 \cdot 10^{-9}$ m$^2$/s and the peak at $0.6 \cdot 10^{-9}$ m$^2$/s (severe destruction) at ICDAS score 6. The ADC distribution at ICDAS score 6 has also relatively narrow peak in comparison to other distributions due to higher compaction of the severely affected dental pulp, i.e., reduced extracellular water content in the pulp.

Figure 3 shows a relation between the ICDAS score and the demineralization depth (a) as well as a relation between the average ADC value of the dentin-pulp complex and the demineralization depth (b). From the graph in Fig. 3a it can be seen that the ICDAS score is in a positive correlation with the demineralization depth $x$. Linear regression analysis
between the two yielded \( ICDAS = a \times + b \), where \( a = 1.19 \text{ mm}^{-1} (1 \pm 0.19) \) and \( b = -0.22 (1 \pm 0.30) \); the fit quality was \( R^2 = 0.93 \). Similarly, negative correlation was obtained between the average ADC value of the dentin-pulp complex and the demineralization depth, which is shown in Fig. 3b. The corresponding linear regression analysis yielded the regression line \( ADC = c \times + d \), where \( c = -0.07 \cdot 10^{-9} \text{ m}^2 \text{s}^{-1} \text{mm}^{-1} (1 \pm 0.14) \) and \( d = 1.24 \cdot 10^{-9} \text{ m}^2 \text{s}^{-1} (1 \pm 0.03) \) with \( R^2 = 0.77 \). The results can be interpreted that the demineralization depth increase of one millimeter results in ICDAS increase for 1.2 grades and in a 5.6 % decrease of the average ADC of the affected dentin-pulp complex. Both linear regression line results can be combined yielding a linear regression relation between the ICDAS score and the average ADC value of the affected dentin-pulp complex: \( ICDAS = e \times ADC + f \), where \( e = a/c = -1.7 \cdot 10^{-10} \text{ s/m}^2 \ (1 \pm 0.33) \) and \( f = b - (a \cdot d)/c = 20.8 (1 \pm 0.37) \). From the relation follows that decreasing ADC values correspond to increasing ICDAS scores; ICDAS score 0 corresponds to ADC of \( 1.22 \cdot 10^{-9} \text{ m}^2 \text{s}^{-1} \), while ICDAS score 6 corresponds to ADC of \( 0.87 \cdot 10^{-9} \text{ m}^2 \text{s}^{-1} \).
Table 1: Distribution of teeth according to their types (molars, premolars and canines) and ICDAS scores.

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<th>ICDAS score</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Σ</th>
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<td>2</td>
<td>2</td>
<td>2</td>
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<td>5</td>
<td>4</td>
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Fig. 1: Images of intact and decayed teeth specimens of all ICDAS scores: (a) high-resolution T1-w MR images and (b) ADC maps. T1-w MRI clearly shows morphology of the dentin-pulp complex along with localization of caries lesion (arrows) while ADC map provide an efficient discrimination between intact and decayed regions of the dentin-pulp complex. The demineralization depth was determined as a distance from the surface of the tooth to the deepest part of caries lesion (dashed lines).

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<table>
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<th>$ICDAS$ score</th>
<th>0</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>$S_{caries}/S_{pulp}$</td>
<td>/</td>
<td>0.76 ±</td>
<td>0.85 ±</td>
<td>0.96 ±</td>
<td>1.16 ±</td>
<td>1.31 ±</td>
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<td></td>
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<td>0.05</td>
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<td>0.02</td>
<td>0.03</td>
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<td>0.03</td>
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<tr>
<td>Average demineralization depth [mm]</td>
<td>/</td>
<td>1.35 ±</td>
<td>1.74 ±</td>
<td>2.30 ±</td>
<td>3.36 ±</td>
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<td>0.33</td>
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<td>ADC [$10^{-9}$ m$^2$/s]</td>
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<td>1.06 ±</td>
<td>1.04 ±</td>
<td>0.98 ±</td>
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**Table 2:** Ratios of signals between caries and intact pulp regions of dentin-pulp complexes (as obtained from image analysis of T1-w images), their demineralization depths and corresponding ADC values for different $ICDAS$ scores.

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Fig. 2: Normalized ADC distributions of dentin-pulp complexes of representative teeth having different ICDAS scores. The threshold ADC value of $1.0 \times 10^{-9}$ m$^2$/s (dashed line) can be considered as a boundary between the intact and decayed dentin-pulp complex. With increasing ICDAS scores the distributions have an increasing proportion of ADC values below the threshold, which corresponds to the increasing proportion of decayed tissues.

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Fig. 3: Correlations between the ICDAS score and the demineralization depth (a) and between the average ADC value of the dentin-pulp complex and the demineralization depth (b). Each of 26 teeth is shown in both graphs using a symbol corresponding to its ICDAS score. Linear regression lines (dashed lines) show that the ICDAS score as well as the average ADC value correlates with the demineralization depth, i.e., the demineralization depth increase of one millimeter results in ICDAS increase for 1.2 scores and in a 5.6 % decrease of the average ADC of the affected dentin-pulp complex.

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Conclusion

Feasibility of quantitative dental caries assessment by two complementary MRI methods, 3D $T_1$-weighted MRI and ADC mapping, was studied. The first provides high-resolution information that was used to locate a caries lesion and to determine the demineralization depth, while the second provides water mobility information, which was used to quantify the severity of tooth decay comparable to that of ICDAS scoring. This feasibility *in vitro* study has prospects to become a standard method for caries assessment *in vivo* with future development of modern clinical MRI scanners.
References


