Computed diffusion-weighted MR imaging for quantitative prostate cancer diagnosis: determination of optimal b-value combinations for generating high b-value images

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Aims and objectives

Computed DWI (cDWI) is a recently proposed computational technique that produces any b-value images from DWIs acquired with at least two different b-values [1]. It is reported that cDWI at b=2000 s/mm$^2$ generated from DWIs with b=0 and 1000 s/mm$^2$ achieved a diagnostic ability for prostate cancer (PCa) comparable to a real acquired DWI at b=2000 s/mm$^2$ [2]. However, it remains unclear which combination of b-values is optimal for generating high-b-value images. We hypothesize that appropriate b value selection for cDWI can improve image quality and detection capability on cDWI as compared with actual DWI with ultra-high b value. The aim of our study was therefore to determine the appropriate b-value combination for generating cDWI at b=2000 s/mm$^2$ to improve pPCa detection, when compared with actual DWI at b=2000 s/mm$^2$ (aDWI$_{2000}$) on a 3T MR system.
Methods and materials

Study patients

A total of 45 consecutive patients with biopsy-proven prostate cancer underwent 3-T MRI examinations including DWI of the prostate followed by radical prostatectomy between June 2012 and January 2013. Fourteen patients were excluded for having received hormone and/or radiation therapy instead of surgery. The remaining 31 patients formed the study group (Table 1). Our retrospective study was approved by our institute’s ethics committee, and written informed consent was waived.

MR imaging

All patients underwent imaging with a 3-T MR unit (Achieva; Philips Medical Systems, Best, The Netherlands) using a multichannel phased-array coil (SENSE Cardiac 6ch-coil; Philips Medical Systems) for signal reception. No endorectal coil was used. T2-weighted turbo spin-echo images, covering the entire prostate gland and seminal vesicles, were acquired in two orthogonal planes, axial and coronal. The acquisition parameters for T2-weighted images and diffusion weighted images were shown in Table 2. Peristalsis was suppressed with intramuscular administration of 20 mg of scopolamine butylbromide (Buscopan; Boehringer Ingelheim, Yamagata, Japan) or 1 mg of glucagon (Glucagon-G Novo; Eisai Co. Ltd., Tokyo, Japan) #

Computed DWI

The apparent diffusion coefficient (ADC) was calculated with ADC=ln[-S_m/S_0]/(b_m-b_0), using two measured DWI signals; S_0, and S_m, based on a mono-exponential model. ADC maps were constructed according to this equation on the basis of a voxel wise calculation. Then, the computed DWI signal at b=b_c was obtained with the equation S_c=S_0 exp[-(b_c-b_0)ADC] [1,3,4]. Computed DW MR images at b=2000 s/mm^2 were generated from the following four b-value combinations: 1) between 0 and 500 s/mm^2; cDWI_{0-500}, 2) between 0 and 1000 s/mm^2; cDWI_{0-1000}, 3) between 100 and 1000 s/mm^2; cDWI_{100-1000}, and 4) between 500 and 1000 s/mm^2; cDWI_{500-1000}, respectively. MATLAB-based software, "cDWI-calculator", was used on a personal computer (Intel(R) Core(TM)2 Quad; CPU Q8400 @ 2.66GHz, 3 GB RAM) for generating all computed DWI, which takes 3 s to create one slice.

Image analyses
The acquired images were anonymised and collected in the DICOM format. Two board-certified genitourinary radiologists, one with 5 years' (Y.U.) and the other with 12 years' experience (K.K.), who had no knowledge of either the histopathological findings or the clinical data, analysed the images.

To compare the contrast resolution for each DWI, contrast ratio (CR) between PCa and non-PCa sites was calculated as following formula: 
\[
CR = \frac{(S_{ca} - S_{non-ca})}{(S_{ca} + S_{non-ca})}
\]
where \(S_{ca}\) is the average SI for the malignant lesion, \(S_{non-ca}\) is that for the normal lesion. Circular regions of interest (ROIs) were placed on real acquired DW images with \(b=2000\) s/mm\(^2\) in consensus within the malignant or normal lesions with reference to the histopathological findings of radical prostatectomy. The same ROIs were then copied onto other DW images acquired in the same axial section.

To compare the diagnostic capability among all DWIs, five combinations of images: protocol (T2WI+cDWI\(_{0-500}\)), (T2WI+cDWI\(_{0-1000}\)), (T2WI+cDWI\(_{100-1000}\)), (T2WI+cDWI\(_{500-1000}\)), and (T2WI+aDWI\(_{2000}\)) were independently evaluated by the two genitourinary radiologists (Y.U. and K.K.) for the likelihood of the presence of cancer by prostatic region on a five-point scale (5, definitely present; 4, probably present; 3, equivocal; 2, probably absent; 1, definitely absent). For region-specific comparisons among the protocols, the prostate was divided into eight regions: the bilateral peripheral zones (PZ), comprising the base, midgland and apex, and the bilateral transition zones (TZ).

**Statistical analyses**

CRs were compared by using Tukey's HSD test. ROC analyses were performed and sensitivity, specificity and accuracy of each DWI were compared by using McNemar's test.
## Table 1: Characteristics of the study subjects

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<table>
<thead>
<tr>
<th></th>
<th>T2WI</th>
<th>DWI</th>
</tr>
</thead>
<tbody>
<tr>
<td>sequence</td>
<td>Turbo spin echo</td>
<td>Single shot spin echo EPI</td>
</tr>
<tr>
<td>TR/TE (msec)</td>
<td>4000/130</td>
<td>4000/65</td>
</tr>
<tr>
<td>Parallel imaging</td>
<td></td>
<td>SENSE</td>
</tr>
<tr>
<td>Slice thickness/gap (mm)</td>
<td>3 / 0</td>
<td>3 / 0</td>
</tr>
<tr>
<td>FOV (mm)</td>
<td>240 × 240</td>
<td>450 × 450</td>
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<tr>
<td>matrix</td>
<td>320 × 224</td>
<td>128 × 102</td>
</tr>
<tr>
<td>NEX</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>MPG</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>b-value (s/mm²)</td>
<td>-</td>
<td>0, 100, 500, 1000, and 2000</td>
</tr>
<tr>
<td>Scan time</td>
<td>3 min 40 sec</td>
<td>7 min 20 sec</td>
</tr>
</tbody>
</table>

TSE: turbo spin-echo, TR: repetition time, TE: echo time, ETL: echo train length, EPI: echo-planar imaging, SENSE: sensitivity encoding, FOV: field of view

**Table 2: MR imaging parameters**

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Results

Details of patient characteristics are shown in Table 1. Histopathological examinations identified 121 regions out of a total of 248 regions were found to be cancer-positive (PZ: 94, TZ: 27).

CRs of each cDWI (cDWI\(_{0-500}\): 0.53±0.2; cDWI\(_{0-1000}\): 0.45±0.2; cDWI\(_{100-1000}\): 0.47±0.2; and cDWI\(_{500-1000}\): 0.49±0.1) were significantly higher than that of aDWI\(_{2000}\) (0.32±0.1, p<0.05).

Area under the curve (Az) of cDWI\(_{0-500}\) (Az=0.66) were significantly smaller than that of others (cDWI\(_{0-1000}\): Az=0.72, cDWI\(_{100-1000}\): Az=0.73, cDWI\(_{500-1000}\): Az=0.79, aDWI\(_{2000}\): Az=0.75, p<0.05). (Fig.1.) When applied each feasible threshold value, accuracy (71.3 [177/248] %) of cDWI\(_{500-1000}\) was significantly higher than that of cDWI\(_{0-500}\) (64.1 [159/248] %, p<0.05) and aDWI\(_{2000}\) (69.0 [171/248] %, p<0.05). (Table 3.) A representative case is shown in Fig. 2.
Fig. 1: ROC curves of five protocols for PCa diagnosis: Az of cDWI 0-500 was significantly lower than that of other DWIs (p<0.05).

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Table 3: Diagnostic ability for PCa of each DWI

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<table>
<thead>
<tr>
<th></th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Accuracy</th>
<th>PPV</th>
<th>NPV</th>
<th>Az</th>
</tr>
</thead>
<tbody>
<tr>
<td>cDWI₀,5₀₀</td>
<td>49.5%</td>
<td>78.0%</td>
<td>64.1%</td>
<td>68.2%</td>
<td>61.9%</td>
<td>0.66*</td>
</tr>
<tr>
<td></td>
<td>(60/121)</td>
<td>(99/127)</td>
<td>(159/248)</td>
<td>(60/88)</td>
<td>(99/160)</td>
<td></td>
</tr>
<tr>
<td>cDWI₀,1₀₀₀</td>
<td>78.5%*</td>
<td>61.4%*</td>
<td>69.8%*</td>
<td>66.00%</td>
<td>75.00%</td>
<td>0.72*</td>
</tr>
<tr>
<td></td>
<td>(95/121)</td>
<td>(78/127)</td>
<td>(173/248)</td>
<td>(95/144)</td>
<td>(78/104)</td>
<td></td>
</tr>
<tr>
<td>cDWI₀,1₀₀₀₀</td>
<td>80.2%*</td>
<td>58.3%*</td>
<td>69.0%*</td>
<td>65.00%</td>
<td>75.60%</td>
<td>0.73*</td>
</tr>
<tr>
<td></td>
<td>(97/121)</td>
<td>(74/127)</td>
<td>(171/248)</td>
<td>(97/150)</td>
<td>(74/98)</td>
<td></td>
</tr>
<tr>
<td>cDWI₀,5₀₀₀₀</td>
<td>77.7%*</td>
<td>65.3%*</td>
<td>71.3%<em>,</em>**</td>
<td>68.10%</td>
<td>75.40%</td>
<td>0.79*,***</td>
</tr>
<tr>
<td></td>
<td>(94/121)</td>
<td>(83/127)</td>
<td>(177/248)</td>
<td>(94/138)</td>
<td>(83/110)</td>
<td></td>
</tr>
<tr>
<td>cDWI₂₀₀</td>
<td>84.3%<em>,</em>**</td>
<td>54.3%<em>,</em>**</td>
<td>69.0%<em>,</em>***</td>
<td>63.80%</td>
<td>78.40%</td>
<td>0.75*</td>
</tr>
<tr>
<td></td>
<td>(102/121)</td>
<td>(69/127)</td>
<td>(171/248)</td>
<td>(102/160)</td>
<td>(69/88)</td>
<td></td>
</tr>
</tbody>
</table>

*: Significant difference with cDWI₀,5₀₀ (p<0.05), **: Significant difference with cDWI₀,1₀₀₀ (p<0.05), ***: Significant difference with cDWI₀,1₀₀₀₀ (p<0.05), ****: Significant difference with cDWI₀,5₀₀₀₀ (p<0.05).

Fig. 2: 68-year-old PCa patient with Gleason score of 3+4=7 PCa, pT2a, initial PSA of 4.5ng/ml: Abnormal signal intensity was shown in the right lobe of PZ on aDWI, cDWI₀-5₀₀, cDWI₀-1₀₀₀, cDWI₁₀₀-1₀₀₀₀ and cDWI₅₀₀₀-1₀₀₀₀.

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Conclusion

cDWI_{500-1000} had better diagnostic specificity and accuracy than cDWI_{0-500} and aDWI_{2000}, and demonstrated high image quality and contrast resolution.

In theory, however, for computing high b-value DWI, excluding low b-values may be relatively insensitive to perfusion insensitive, and achieve to obtain cDWI with more accurate diffusion-weighted information.
Personal information

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