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ORIGINAL ARTICLE

Non-breath-hold high b-value diffusion-weighted MRI with parallel imaging technique: apparent diffusion coefficient determination in normal abdominal organs

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PURPOSE
To detect apparent diffusion coefficient (ADC) values in normal abdominal organs using non-breath-hold high b-value diffusion-weighted magnetic resonance imaging (DW-MRI) with a parallel imaging technique.

MATERIALS AND METHODS
A total of 50 patients with normal abdominal MRI findings were retrospectively enrolled. DW-MRI was performed with b-factors of 0, 500, and 1000 s/mm². Mean ADC measurements were calculated.

RESULTS
There were statistically significant differences ($P < 0.001$) between the ADC values of four liver segments (left lobe lateral segment: 1.77 ± 0.21 x10^{-3} mm²/s, left lobe medial segment: 1.59 ± 0.21 x 10^{-3} mm²/s, right lobe anterior segment: 1.46 ± 0.18 x 10^{-3} mm²/s, right lobe posterior segment: 1.34 ± 0.20 x 10^{-3} mm²/s). The ADC value for the left lobe lateral segment was significantly higher than the values for the other segments. The calculated ADC values for cortex and medulla of kidney were 2.08 ± 0.22 x 10^{-3} mm²/s, 1.94 ± 0.18 x 10^{-3} mm²/s, respectively; ($P < 0.001$), for pancreas tail 1.59 ± 0.38 x 10^{-3} mm²/s, for pancreas body 1.68 ± 0.26 x 10^{-3} mm²/s, pancreas head 1.65 ± 0.29 x 10^{-3} mm²/s, stomach wall 1.84 ± 0.22 x 10^{-3} mm²/s, and spleen 1.28 ± 0.38 x 10^{-3} mm²/s.

CONCLUSION
Knowledge of ADC values for normal abdominal organs will be required during quantitative evaluation of DW-MR images in diseases in accordance with the technique used. We believe that further studies investigating the effect of diseases on normal ADC values are necessary and would be helpful in quantitative DWI.

Key words: • *diffusion magnetic resonance imaging* • *abdomen*

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Diffusion is thermally induced motion of water molecules in biological tissues, which is called Brownian motion (1, 2). Diffusion-weighted magnetic resonance imaging (DW-MRI) is a technique that can be used noninvasively to quantify diffusion of water molecules in biological tissues such as white matter in the brain. This technique is widely used in neuroimaging, with its greatest use being for detection of acute cerebral stroke (3). It has been limited in use primarily to the central nervous system because the physiologic motion from respiration and cardiac movement can seriously affect the image quality in other parts of the body. With the advent of ultrafast single- and multi-shot echoplanar imaging (EPI) techniques, DWI of the abdomen has become possible (4). Also, parallel imaging techniques, which use the spatial information from a phased-array multicoil to reduce the number of signals needed for a given spatial resolution, are used to reduce readout time and scanning time, thereby improving the quality of EPI even if signal intensity and signal-to-noise ratio (SNR) on the image can be changed (5).

The purpose of this study was to detect the apparent diffusion coefficient (ADC) values in normal abdominal organs using high b-value DWI with a parallel imaging technique.

Materials and methods

This was a retrospective study conducted at a single institution. During a period of 4 months, a total of 50 patients (29 women and 21 men; mean age, 38.9 years) with normal abdominal MRI findings were enrolled in the study. Since we perform diffusion MRI of the abdomen routinely, before the imaging study we inform all patients about contrast material complications and the research protocol which we may publish, and receive their approval. The research protocol was approved by the institutional ethics committee. Written consent was obtained from all patients prior to commencement of the study.

MR imaging was performed on a 1.5 T body scanner (Avanto; Siemens, Erlangen, Germany) with a 33 mT/m maximum gradient capability using a phased-array body coil.

Before diffusion weighted imaging was performed, breathhold, axial 3D gradient-echo T1-weighted (TR, 5.32 ms; TE, 2.58 ms; FA, 10°; matrix, 256 × 166; slice numbers, 96; slice thickness, 2.5 mm; interslice gap, 20%; FOV, 40 cm; averages, 1; acquisition time, 0:21 s; bandwith, 300 Hz/Px), 2D gradient-echo T1 in-phase and out-of-phase (TR, 128 ms; in-phase TE, 4.89 ms; out-of-phase TE, 2.38 ms; FA, 70°; matrix, 256 x 179; slice numbers, 30; slice thickness, 6 mm; interslice gap, 30%; FOV, 40 cm; averages, 1; acquisition time, 1:37 s; bandwith 1/2, 390/410 Hz/Px), axial respiratory-triggered, turbo spin-echo T2-weighted sequence with fat saturation (TR, 1900 ms; TE, 76 ms; FA, 150°; matrix, 384 x 276; slice numbers, 29;

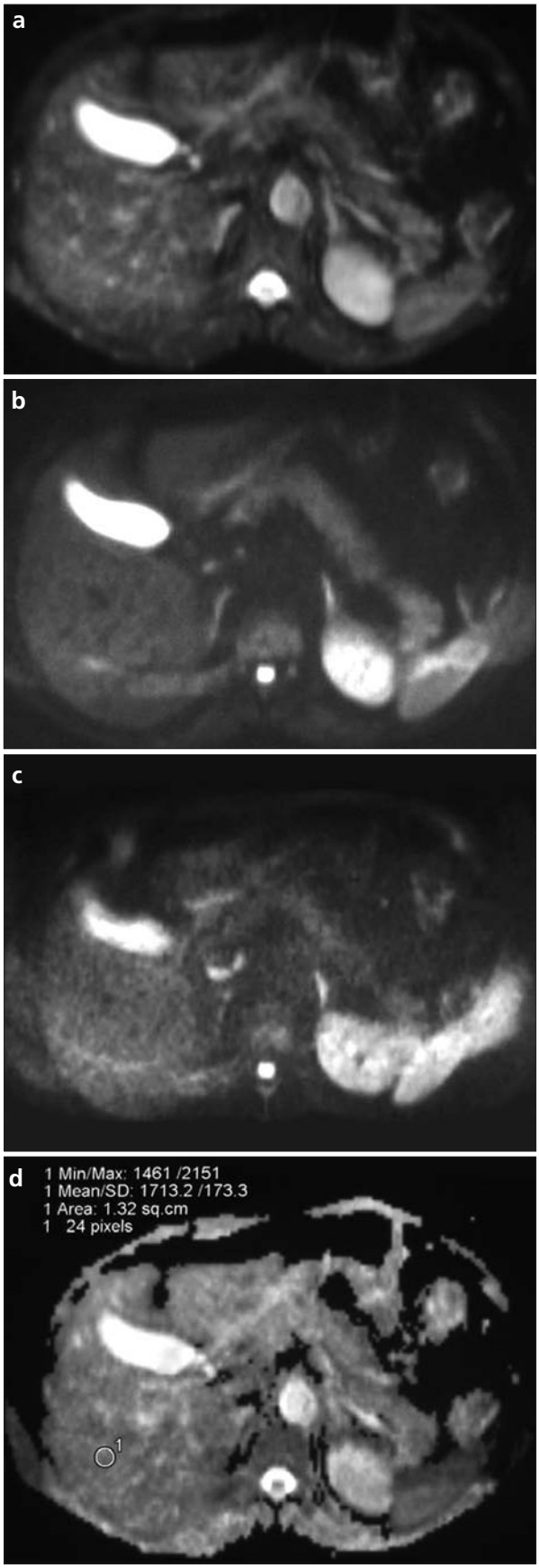

Figure 1. a-d. Diffusion-weighted imaging (DWI) of the liver with a b-factor of 0 s/mm² **(a)**, 500 s/mm² **(b)**, and 1000 s/mm² **(c)**. Apparent diffusion coefficient (ADC) map of liver **(d)**.

slice thickness, 6 mm; interslice gap, 30%; FOV, 36 cm; averages, 1; acquisition time, 1:37 s; bandwith, 260 Hz/Px), coronal T2-weighted half-Fourier single-shot turbo spin-echo (HASTE) (TR, 1100 ms; TE, 116 ms; FA, 150°; matrix, 256 x 204; slice numbers, 25; slice thickness, 6 mm; interslice gap, 30%; FOV, 35 cm; averages, 1; acquisition time, 0:28 s; bandwith, 488 Hz/Px) sequences and then diffusion weighted single-shot spin-echo echo-planar sequence with the chemical shift selective fat-suppression technique (TR/TE, 4900/93; matrix, 192 × 192; slice numbers, 30; slice thickness, 6 mm; interslice gap, 35%; FOV, 45 cm; averages, 5; acquisition time, approximately 3 min, PAT factor, 2; PAT mode, parallel imaging with modified sensitivity encoding [m SENSE]) were carried out. DW-MRI was performed with b-factors of 0, 500, and 1000 s/mm².

Following DWI, contrast enhanced dynamic imaging was performed with an axial 3D gradient-echo T1-weighted MR sequence during and after administration of gadopentetate dimeglumine in a dose of 0.1 mmol/kg of body weight as a bolus injection with 20 s between each breath-hold acquisition (each breath hold lasted between 20–24 s). We routinely perform these sequences with freebreathing diffusion MRI in upper abdominal MRI examinations.

Image interpretation

The DWI datasets were transferred to an independent Workstation (Leonardo console, software version 2.0; Siemens AG Medical Solutions, Forchheim, Germany) for postprocessing, and the ADC maps were reconstructed.

To measure ADC values, we established round regions of interest (ROI) on each anatomical site. Care was taken to exclude vessels and motion artifacts from the ROIs. For each ADC value measurement we applied 5 ROI measurements and accepted the average of the closest 3 measurements (Figs. 1, 2).

Statistical analysis

All statistical analyses were performed using SPSS (Statistical Package for Social Sciences) version 10.0 for Windows. The ADC values of cases are reported as the mean ± standard deviation. Also, variance analysis and paired samples test for comparison of

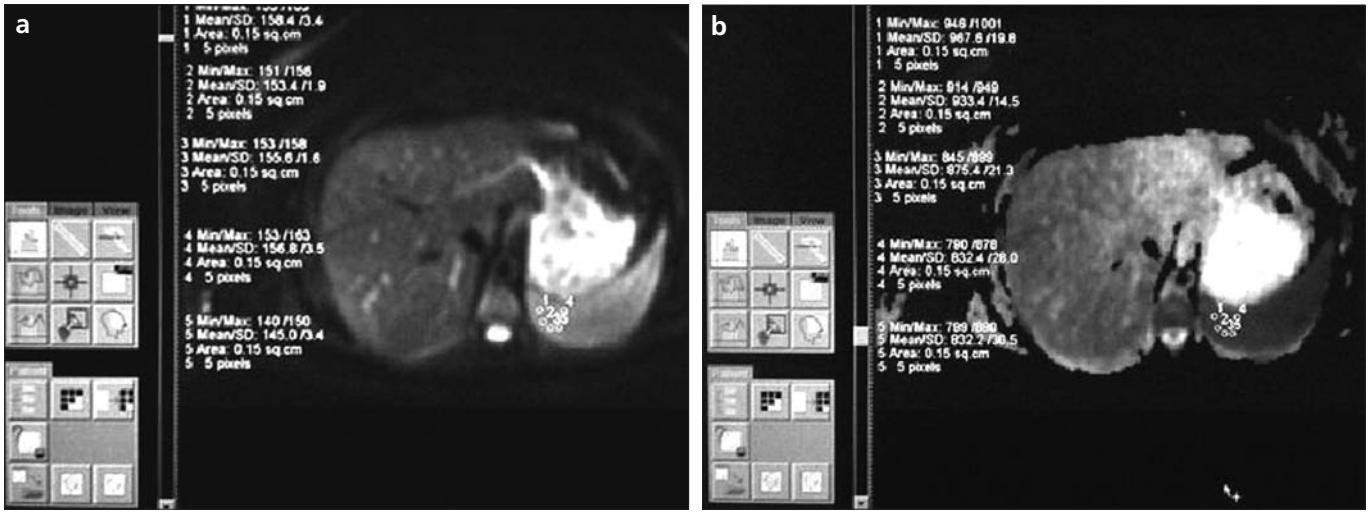

Figure 2. a, b. To measure apparent diffusion coefficients (ADCs), 5 circular regions of interest were placed over areas of homogeneous parenchyma, taking care not to include vessels or artifacts on b-factor 0 s/mm^2 **(a)** and then transported on the corresponding slices of the ADC map **(b)** with a copy-paste operation. ADC then automatically appeared on the images. ADC of the parenchyma was obtained by averaging the closest 3 of 5 measurements for each subject.

abdominal organ segments were performed. A P value of less than 0.05 was considered to indicate a statistically significant difference.

Results

ADC values for all patients who underwent conventional and DW-MRI examinations are listed in Table.

There were statistically significant differences among ADC values for 4 liver segments ($P < 0.01$) (left lobe lateral segment [LL]:1.77 ± 0.21 x 10^{-3} mm^2/s, left lobe medial segment [LM]: 1.59 ± 0.21 x 10^{-3} mm^2/s, right lobe anterior segment [RA]: 1.46 ± 0.18 x 10^{-3} mm^2/s, right lobe posterior segment [RP]: 1.34 ± 0.20 x 10^{-3} mm^2/s). The ADC value for the LL was significantly higher than that for the LM ($P < 0.05$), probably due to degraded image quality. There was a significant statistical difference ($P < 0.01$) between ADC values for LL and RP, LL and RA, and RP and RA. The difference between the calculated ADC values for the medulla and cortex of kidney was statistically significant ($P < 0.001$). Differences in ADC values among the pancreatic head, body, and tail were not statistically significant ($P > 0.05$).

Table. ADC values of normal abdominal organs

Location	Mean ADC (mm^2/s)
Liver[a]	
Left lobe lateral seg	1.77 ± 0.21 x10^{-3}
Left lobe medial seg	1.59 ± 0.21 x10^{-3}
Right lobe anterior seg	1.46 ± 0.18 x10^{-3}
Right lobe posterior seg	1.34 ± 0.20 x10^{-3}
Kidney[a]	
Cortex	2.08 ± 0.22 x10^{-3}
Medulla	1.94 ± 0.18 x10^{-3}
Pancreas[b]	
Head	1.65 ± 0.29 x10^{-3}
Body	1.68 ± 0.26 x10^{-3}
Tail	1.59 ± 0.38 x10^{-3}
Stomach	1.84 ± 0.22 x10^{-3}
Spleen	1.28 ± 0.38 x10^{-3}

ADC, apparent diffusion coefficient; seg, segment.
[a]The differences of the ADC values among the segments/parts are statistically significant.
[b]There is no statistically significant difference between parts of the organ.

Discussion

Diffusion imaging is a MRI technique that can be used to quantify diffusion of water molecules noninvasively in biological tissues such as white matter in the brain. The random motion of water molecules outside of the body is uninhibited and called free diffusion. However, in vivo, the diffusion is restricted because of macromolecules and intact cell membranes. Diffusion restriction increases in highly cellular tissues. In contrast, it decreases in low cellular tissues with large extracellular space or with broken down cellular membranes (6). DW images may be evaluated both qualitatively and quantitatively. Visual assesment is possible by evaluation of the hyperintensity observed in DW images. However, this includes both restricted diffusion and the effect of tissues with high T2 relaxation times, which is called the T2 shine through effect. To overcome this effect ADC maps are interpreted. Areas of restricted diffusion show low ADC values and appear as a low signal area (opposite to DW images). The quantitative analysis of the diffusion may be

calculated on a workstation by applying a ROI on the image.

The ADC, as a quantitive parameter calculated from DWI, combines the effects of capillary perfusion and water diffusion in the extracellular extravascular space (4). Thus, DWI provides information on perfusion and diffusion simultaneously in any organ. It can be used to better differentiate normal from abnormal structures of tissues, and it might help in the characterization of various abnormalities (7). However, for a correct interpretation, the normal ADC values for biological tissues should be known in accordance with the diffusion technique used.

Due to the random organization of the capillary network at the level of the voxel, even the microcirculation of blood has effects on the ADC. Therefore, the ADC includes the effects of both real diffusion and perfusion (pseudodiffusion). The effect of perfusion on the ADC is most pronounced with low b values (e.g., b=50–100 s/mm^2). By contrast, high b values mostly overcome this effect (e.g., b=1000 s/mm^2) (6, 8). We preferred to study high b value DWI, to supress normal tissues as much as possible, and to easily detect highly cellular lesions.

Most of the abdominal DW-MRI studies in the literature are based on the single-shot breathhold technique (9, 10). In our study, DW-MRI was performed without breath holding, thus allowing examination of severely ill, old, or obese patients who were unable to hold their breath for a long time. Our preliminary results suggest that DW imaging combined with parallel imaging makes the usage of abdominal DW-MRI possible without breathholding in daily practice. Hence, even though there were ghost and motion artifacts degrading the image quality, they were not severe enough to affect the diagnosis. It has been suggested that a parallel imaging technique may help to reduce artifacts and improve the reliability of the measured values (5).

Geometric distortions and poor image quality are the shortcomings of single-shot imaging, however, it remains the preferred technique due to its reduced sensitivity to bulk motion (11). This imaging technique allows a target volume such as liver or kidney to be rapidly assessed. Non-breathhold imaging allows the imaging of a greater volume, even the whole body. Thin sections and multiplanar reformats are possible. Multi-shot interleaved EPI with parallel imaging may diminish distortions and enhance spatial resolutions. It is an easy way to apply parallel imaging techniques to single-shot imaging. The disadvantage of multi-shot imaging is motion-related phase error that varies from shot to shot and interferes with sensitivity encoding. Direct phase subtraction methods are used but are insufficient for removing all motion artifacts

A conjugate-gradient algorithm has been used in which the phase error has been treated as an image encoding function (12).

A propeller multi-shot (blade sequence) DW-MRI has been proposed. It has been acclaimed that high resolution images may be obtained with the blade sequence because it improves image quality by reducing geometric distortions and artifacts. It has been reported that the ADC values of phantoms and abdominal organs measured by DW-propeller were generally greater than those measured by single-shot DW-SE-EPI (13).

Compared with our results, lower as well as higher ADC values have been reported by other investigators. These discrepancies may be due to differences in patient population, imaging sequence used, TE, b value, or special techniques that were applied, such as peripheral pulse gating and longer acquisition time (7, 14).

When interpreting a space-occupying lesion in the abdomen with DW-MRI and ADC values, it is important to know that the ADC values of organs differ and, moreover, that there are differences among the segments of liver and between kidney cortex and medulla. In our study it was important to know the differences of the ADC values.

Appreciation of the normal ADC values of the abdominal organs is important when interpreting DW images, particularly in cases affecting all of the target organ, when a normal region of the organ may not be available for comparison. DWI may be added to routine abdominal imaging protocols, and visual assesment of DW images has been shown to add confidence to lesion detection and characterization. The additional benefit of DWI is the ability to detect quantitative indices, which may be important in the assessment of disease response to treatment methods. Conventional assessment by measuring lesion size is insensitive to early treatment-related changes (15).

Knowledge of the ADC values of normal abdominal organs will be required during quantitative evaluation of DW-MR images of diseases in accordance with the technique used. There are many studies concerning normal ADC values of the abdominal organs, however, we aimed to determine these values with a freebreathing and parallel imaging technique. We believe that further studies investigating the effect of diseases on normal ADC values are necessary and would be helpful in quantitative DWI. During the evaluation of abdominal DW images and ADC maps it should be kept in mind that the ADC values of normal and pathological tissues may differ according to the DWI techniques that are used.

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