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Computed diffusion weighted imaging (cDWI) and voxelwise-computed diffusion weighted imaging (vcDWI) for oncologic liver imaging: A pilot study

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A B S T R A C T

Objective: Aim of the study was to evaluate the influence of the selection of measured b-values on the precision of cDWI in the upper abdomen as well as on the lesion contrast of PET-positive liver metastases in cDWI and vcDWI.

Methods: We performed a retrospective analysis of 10 patients (4 m, 63.5 ± 12.9 y/o) with PET-positive liver metastases examined in 3 T-PET/MRI with b = 100,600,800,1000 and 1500s/mm^2. cDWI (cb1000/cb1500) and vcDWI were computed based on following combinations: i) b = 100/600 s/mm^2, ii) b = 100/800 s/mm^2, iii) b = 100/1000s/mm^2, iv) b = 100/600/1000s/mm^2 v) all measured b-values. Mean signal intensity (SI) and standard deviation (SD) in the liver, spleen, kidney, bone marrow and in liver lesions were acquired. The coefficient of variation (CV = SD/SI), the differences of SI between measured and calculated high b-value images and the lesion contrast (SI lesion/liver) were computed.

Results: With increasing upper measured b-values, the CV in cDWI and vcDWI decreased (CV in the liver in cb1500: 0.42 with b100/600 s/mm^2 and 0.28 with b100/b1000s/mm^2) while the differences of measured and calculated b-value images decreased (in the liver in cb1500: 30.7% with b = 100/600 s/mm^2, 19.7% with b100/b1000s/mm^2). In diffusion-restricted lesions, lesion contrast was at least 1.6 in cb1000 and 1.4 in cb1500, respectively, with an upper measured b-value of b = 800 s/mm^2 and 2.1 for vcDWI with an upper measured b-value of b = 1000s/mm^2. Overall, the lesion contrast was superior in cb1500 and vcDWI compared to cb1000 (15% and 11%, respectively).

Conclusion: Measuring higher upper b-values seems to lead to more precise computed high b-value images and a decrease of CV. vcDWI provides a comparable lesion contrast to b = 1500s/mm^2 and offers additionally the reduction of T2 shine-through effects. For vcDWI, measuring b = 1000s/mm^2 as upper b-value seems to be necessary to guarantee good lesion visibility in the liver based on our preliminary results.

1. Introduction

Diffusion-weighted imaging (DWI) has become one of the most widely used functional imaging techniques in magnetic resonance imaging (MRI). Within a few minutes, DWI is able to provide tissue information on a molecular scale [1]. Technical developments such as the introduction of single shot echo planar imaging (EPI) and parallel imaging improved image quality and allowed for the application of DWI in extracranial regions [2,3]. While malignant tumors usually show different tissue characteristics to the tissue they arise from (such as higher cellularity or the integrity of cell membranes), DWI nowadays plays a pivotal role in oncologic abdominal imaging [4,5]. Technically, DWI is based on a T2-weighted spin-echo EPI sequence modified by diffusion-sensitizing paired gradients [6]. The sensitivity can be varied by the time interval between the gradients, the duration and the amplitude of the applied gradients which is subsumed under the term "b-value". As DWI is based on a T2-weighted sequence, the signal intensity in b-value images does not only depend on the diffusivity of water molecules but also on the T2 relaxation properties of the investigated tissue. This is known as T2 shine-through effect and might result in misleading interpretations. It has been shown that high b-value images of up to b = 1000–1500 s/mm^2 can improve tumor detection in selected anatomic sites [7,8]. As acquiring high b-value images can time consuming and more prone to image artifacts as compared to lower b-value images, they have not been implemented in daily routine of whole-body imaging so far [9,10]. With the aim to improve image quality, Blackledge et al. proposed an approach to compute high b-value images based on lower measured b-value images: computed DWI

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(cDWI) [11]. This has mostly been evaluated in the prostate [9,10,12,13]. However, the precision of computed high b-value images and the dependence on measured lower b-value images have not been investigated yet in the upper abdomen. Recently, Gatidis et al. proposed a new voxelwise computed DWI (vcDWI) technique to further improve the visibility of diffusion restricted lesions [14]. In contrast to the method by Blackledge et al., it computes the presented b-value image for each voxel in dependence on its apparent diffusion coefficient (ADC) and calculates its respective intensity value. Thereby, voxels with low ADC are presented with signal intensity of low b-values and vice versa. This should improve the contrast of diffusion restricted lesions and reduce the T2 shine-through effect.

The aim of our study was twofold: First, to investigate the influence of the selection of measured b-value images on the precision of computed high b-value images (cDWI) in the upper abdomen. Second, to evaluate quantitative image features of cDWI and vcDWI in organs and metastatic liver lesions in dependence on the measured b-value images used for the computation.

2. Material and methods

2.1. Patient cohort

The data of 10 consecutive patients (4 male, mean age 63.5 ± 12.9 years) with PET-positive liver metastases and a PET/MRI protocol including DWI with high b-value images (up to b = 1500s/mm^2) were retrospectively evaluated. The local ethics committee waived informed consent for the retrospective evaluation of the data. The oncologic diseases were distributed as follows: Melanoma (n = 5), neuroendocrine tumor (n = 3), adenocarcinoma of the small bowel (n = 1), breast cancer (n = 1). Metastatic involvement of the liver was histology-proven in four patients. In six patients, follow-up examinations revealed progressive metastatic disease of the liver (n = 5) or response under therapy (n = 1).

2.2. PET/MRI protocol

All patients were examined in a simultaneous 3 T PET/MRI-scanner (Biograph mMR, Siemens Healthcare GmbH, Erlangen, Germany). A 2D single-shot spin-echo EPI sequence in 3-scan-trace mode with monopolar diffusion gradients and five different b-values (b = 100, 600, 800, 1000 and 1500s/mm^2) was applied in the upper abdomen of each patient. Sequence parameters are given in Table 1. Additionally, a navigator-triggered T2-weighted 3D fast-spin-echo sequence (T2-TSE) was performed. Other sequences were chosen depending on clinical indication. Depending on the disease, ^{18}F-FDG (melanoma, adenocarcinoma, breast cancer) or ^{68}Ga-DOMITATE (neuroendocrine tumor) was used as PET-tracer.

Table 1
Sequence parameters of DWI. Examinations were performed in free breathing.

	DWI
Echo Time	65 ms
Repetition Time	7300 ms
Matrix Size	168 × 192
Pixel Size	2.2 x 2.2 mm
Slice Thickness	5 mm
Number of slices	34
Pixel Bandwidth	1736 Hz/pixel
Acquisition Time	2.5 min
Field of view	350 × 400
Number of averages	5
Acquisition plane	axial
b-values (s/mm^2)	100, 600, 800, 1000, 1500
Fat suppression method	Spectral attenuated inversion recovery fat suppression

2.3. The computation of cDWI/vcDWI

While in the cDWI method the signal intensity of each image voxel is calculated for a predefined constant b-value [11], in the vcDWI method the chosen b-value for each voxel varies dependent on its ADC-value: $S_b(x) = S_0(x) * \exp(-ADC(x) * (k*ADC(x)-b_0)$, where $S_b(x)$ is the calculated signal intensity of voxel x for a b-value (k*ADC(x)), S0(x) its measured signal intensity with b-value = 0 s/mm^2 (b_0), ADC(x) is its ADC value and k = 10^6 s^2/mm^4. The ADC-dependent choice of the voxelwise-computed b-value can thus increase the contrast between diffusion-restricted and unrestricted tissues because signal intensities of voxels with low ADC are computed at lower b-values while voxels with high ADC at higher b-values [14].

VcDWI as well as cDWI images for b = 1000 and b = 1500s/mm^2 (cb1000 and cb1500, respectively) were calculated based on a mono-exponential model from five different combinations of b-value images: i) b = 100 and 600 s/mm^2 (b100/600), ii) b = 100 and 800 s/mm^2 (b100/800), iii) b = 100 and 1000s/mm^2 (b100/1000), iv) b = 100, 600 and 1000s/mm^2 (b100/600/1000) v) all measured b-value images (b_all). The calculation of cDWI and vcDWI was carried out as described in Blackledge et al. [11] and the recently published work by Gatidis et al. [14] using MATLAB (The MathWorks Inc, Natick, MA).

2.4. Image analysis

To avoid partial volume effects, only lesions with a diameter of > 1 cm were included to the quantitative evaluation. Lesions were rated as PET-positive if the focal tracer uptake exceeded the regional uptake of physiological liver tissue. For anatomical correlation, the T2-TSE images were rigidly registered to the b = 800 images. Regions of interest (ROIs) were drawn freehand in the b = 800 images in up to three PET-positive lesions of the liver by F.S. (6 years of experience in MRI, 4 years of experience in hybrid imaging). Furthermore, circular ROIs were set in visually not affected parenchyma of the right and left liver lobe, the spleen, the right or left kidney, the psoas muscle, the second lumbar vertebra (bone marrow) and the image background. Care was taken to avoid image artifacts and borders of organs and lesions. ROIs in physiological tissue and background had a target diameter of 1.5 cm in the liver and 1 cm in other organs. The ROIs were copied to the different measured and computed b-value images. Those steps were performed using PMod (PMOD Technologies Ltd, Zurich, Switzerland). Mean signal intensities (SI) were measured in each ROI. Standard deviations (SD) were acquired in tissue ROIs in cDWI and vcDWI. SI of the liver was defined as the mean value of SI in the right and left liver lobe. Measured b = 1000s/mm^2 and b = 1500s/mm^2 images are abbreviated as “mb1000” or “mb1500” in the following, respectively.

The following parameters were calculated:

The relative signal difference of physiological tissue ROIs between the measured and calculated (cDWI) b-value images:

Relative differences = abs (SI calculated b-value image – SI measured b-value image) / SI measured b-value image * 100.

The contrast (signal intensity ratio) of the lesion ROIs to the surrounding liver tissue (liver ROI) for the different measured b-value images as well as for cDWI and vcDWI:

Lesion contrast = lesion SI / liver SI.

The coefficient of variation within the different physiological tissue ROIs for the different measured b-value images as well as for cDWI and vcDWI as an indicator of the image noise:

CV = SD / SI.