Frequently Asked Questions: Diffusion-Weighted Imaging (DWI)

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Background

MR diffusion-weighted imaging (DWI) has ceased to be used only in brain applications for several years. The utilization of whole body DWI is becoming a standard application in routine imaging. Whole body DWI has become as valuable as T2 contrast in tumor imaging and it allows to characterize tissue properties. Due to the more frequent use of DWI, questions are often asked with regard to the background, application, and interpretation of whole body DWI and its calculated Apparent Diffusion Coefficient (ADC) images.
The following will answer some of these questions.

What is diffusion?

Molecular diffusion is the random movement of molecules – in our case water (H_2O) – within tissues propelled by thermal energy. The contribution of intra- and extra-cellular (interstitial) movement to the total diffusion is still under investigation.

How is MR sensitizing the tissue for diffusion effects?

Within the spin echo preparation period of an EPI sequence, two strong gradient pulses are played out around the 180° pulse. The first pulse dephases the magnetization of moving and static spins and the second pulse rephases only static spins 100% while moving i.e. diffusing spins acquire non-zero phase dispersion, resulting in a stronger signal dampening of tissues with fast diffusion compared to tissues with slow diffusion. Free water experiences the strongest signal attenuation at higher b-values.

What does the b-value mean?

The b-value identifies the measurement's sensitivity to diffusion and determines the strength and duration of the diffusion gradients. It combines the following physical factors into one b-value and is measured in s/mm² [1].

$$b = \gamma^2 G^2 \delta^2 (\Delta - \delta/3)$$

The signal ratio diffusion-weighted to non diffusion-weighted signal is:

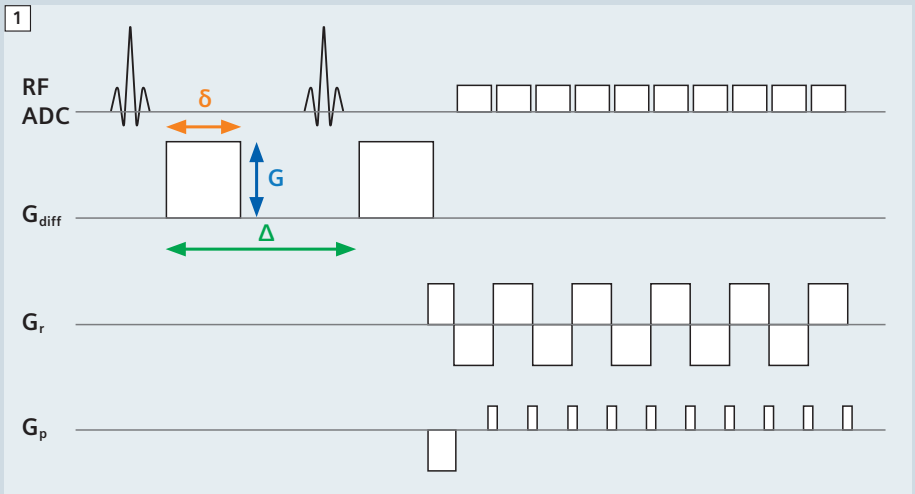
$$\frac{S}{S_0} = e^{-\gamma^2 G^2 \delta^2 (\Delta - \delta/3) D} = e^{-bD}$$

- S_0 – signal intensity without the diffusion weighting
- S – diffusion-weighted signal
- γ – gyromagnetic ratio
- G – amplitude of the two diffusion gradient pulses
- δ – duration of the pulses
- Δ – time between the two pulses
- D – diffusion coefficient is a measure of the strength (velocity) of diffusion in tissue. The stronger the diffusion, the greater the diffusion coefficient, i.e. the ADC in our in vivo case.

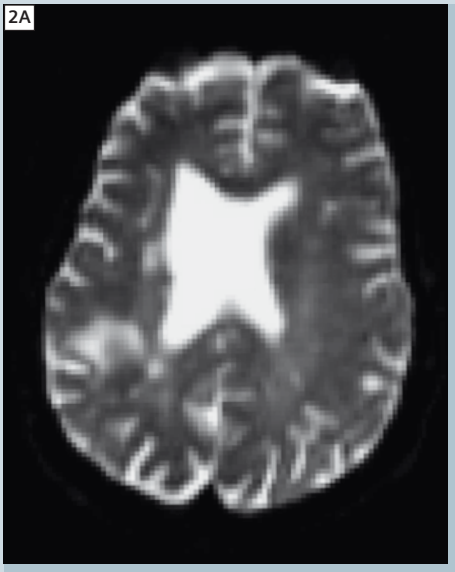
If you choose the b-value the reciprocal magnitude of the expected ADC (D) in the focus tissue you make the exponent of the exponential function being '-1'. This means your signal **S** is reduced to about 37% of its initial value $\mathbf{S_0}$.

What is the optimum b-value?

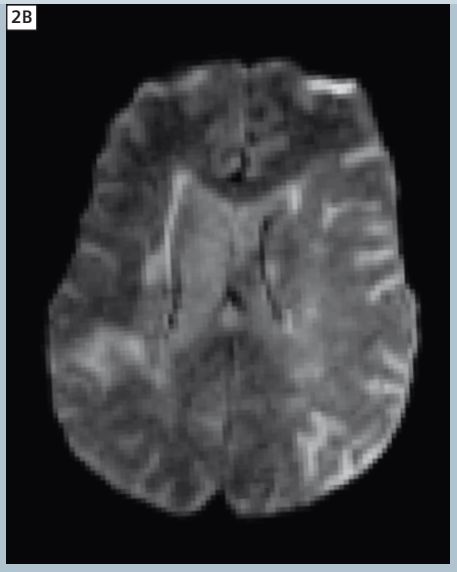
A b-value of zero delivers a T2-weighted EPI image for anatomical reference. The b-values should attenuate the healthy background tissue more than the lesion at a level so that the intensity differences are about a factor of two at a comfortable signal-to-noise ratio (SNR) level i.e. there is signal left in the highest b-value image.
In the range of clinically-relevant b-values (up to approximately 1,000), then the greater the b-value, the stronger the diffusion weighting and the higher



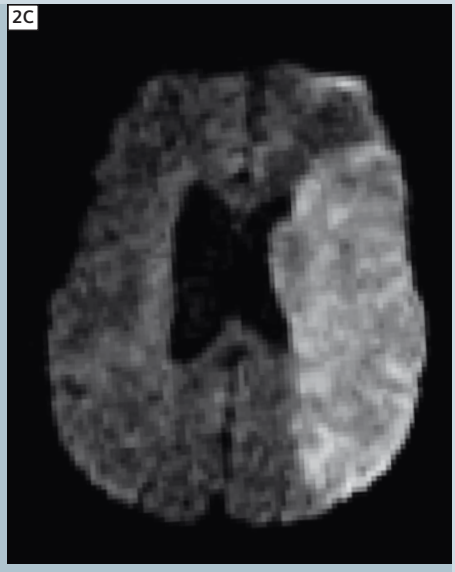
1 Sequence diagram of an EPI diffusion-weighted sequence illustrating the physical quantities of the b-value.



2A b = 0. No diffusion weighting, low-resolution T2 image.



2B b = 500. Intermediately diffusion-weighted image.



2C b = 1000. Strongly diffusion-weighted image.

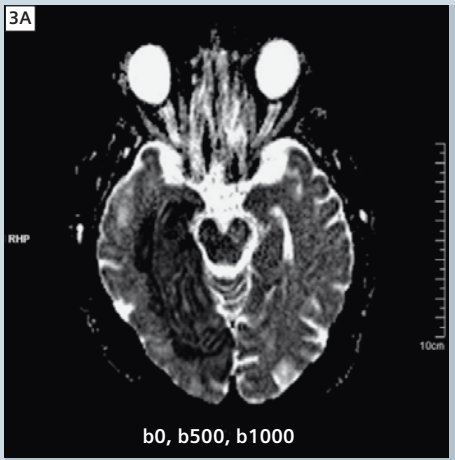
the contrast in pathogenic regions. Shown below are examples of three b-values: b 0, b 500, and b 1000 s/mm^2. The proper b-value has approximately 80% of the reciprocal ADC value of normal background tissue. Keep in mind that higher b-values may pronounce lesions even more at the price of poor SNR due to longer TEs and increased susceptibility. This can be compensated by increasing averages, which result in longer scan times. Changing the b-value immediately influences other parameters like minimal TE, slice thickness and FOV as well as maximum matrix at a given optimal bandwidth. Furthermore anisotropy of tissues, like white matter, also influences the choice [2].

Why are a minimum of three directions measured for each high b-value?
Diffusion may be different in all three dimensions, like in white matter. Fibers exhibit longer free path in the longitudinal direction than perpendicular to it. The ADC images are therefore different depending on the sensitizing direction. This information is collected by applying diffusion gradients in all three dimensions. For example, in the case of commissures, diffusion is severely limited perpendicular to the fibers due to the surrounding myelin layer. In contrast, there are few or no limitations along the fibers. Anisotropy may have a strong effect on measurement results. To measure the diffusion strength independent of anisotropy, diffusion images of different orientation are measured and averaged.

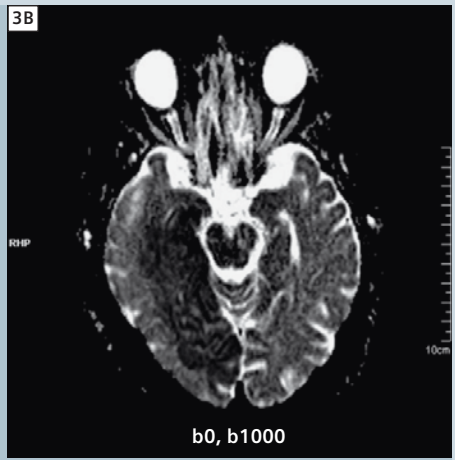
Why should I measure three b-values for a DWI protocol when two would be enough for calculating ADC?
While two b-values are sufficient for creating an ADC image, the selection of three b-values (b 0, b 500, b 1000) delivers a more accurate calculation of the ADC values. The lower SNR of the b 1000 images introduces a higher standard deviation of the ADC which is partially compensated by the median value of b500.
Here is an example of two ADC images, the first acquired with three b-values and the second with two b-values.

What is a trace image?
The 'trace image' displays the geometric averaging of all three directional measurements, resulting in trace-weighted images. It suppresses to some extent anisotropy information and focuses on differences in signal attenuation. Like the ADC map, the trace-weighted map shows the strength of the diffusion and not its orientation.

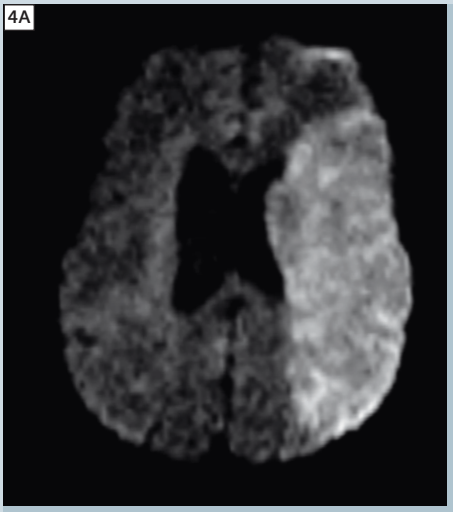
Why do we need ADC images, and what does the 'A' in ADC stand for?
In addition to diffusion contrast, diffu-



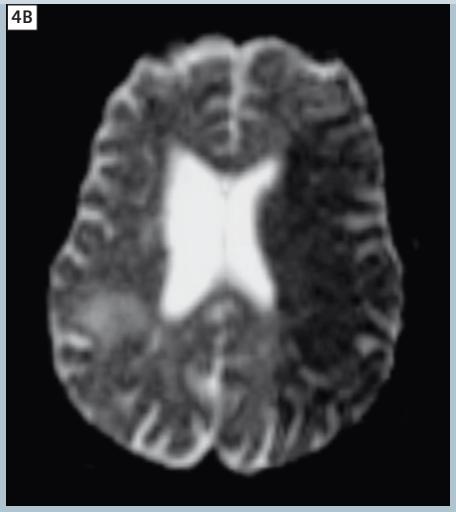
3A ADC calculated from 3 b-values (0, 500, 1000).



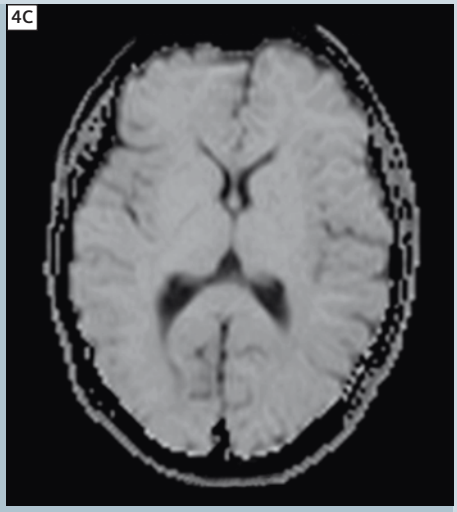
3B ADC calculated from 2 b-values (0, 1000).



4A b1000 image; infarct is brighter than normal tissue.



4B ADC Image; infarct appears darker than normal tissue.



4C Exponential-Map

sion images also have an overlaying T2 contrast. In regions with long T2, this can simulate reduced diffusion ('T2 Shine-Through'). These portions of the signal can be eliminated by calculating a pure diffusion coefficient.
The 'A' stands for apparent because we do not measure the pure diffusion coefficient (D or DC). In living tissue the diffusion process is superimposed by capillary pseudo diffusion and gross motion to which the MR measurement is also very sensitive.

How is the ADC calculated?
Having measured a set of at least 2 different b-value images (e.g., b 0 and b 1000 s/mm²) the system calculates pixel by pixel the ADC by linear regression. The ADC pixel values together form the ADC map. On a half logarithmic scale, the signal decay delivers a straight tilted line whose slope provides the ADC. The faster the signal decay the steeper the slope and the higher the ADC.
The Diffusion image (b 1000) below displays reduced diffusion as hyperintense (brighter pixels); in contrast the ADC map displays it as hypointense (darker pixels).

Why are some lesions typically brighter than the background brain tissue on the higher b-value image and darker on the ADC map?
Due to the nature of certain lesions and their missing perfusion, the cells swell and hinder a normal diffusion; i.e., the mean free path is shorter. Water molecules cannot move as far in the damaged tissue as in normal tissue. As a result, the ADC is lower and appears darker than the surrounding normal tissue.

Which benefit does the calculation of an exponential map deliver?
The exponential map or image is calculated by dividing the maximal b-value diffusion-weighted image by the b_0 image. Mathematically the exponential map displays the negative exponential of the ADC; it is a synthetic diffusion-weighted image without T2 'shine-through' effect.
The contrast behaviour is similar to the high b-value image [3].

How do I get the ADC value out of my ADC image and what is the right unit?
Place a region of interest (ROI) on the ADC map and record the mean value in that ROI. A value of 850 intensity points is to be interpreted as 0.85 10^{-3} mm²/s. This is valid for software versions since *syngo* MR B13. Systems with A-level software (e.g., *syngo* MR A30) and *syngo* MR B11, a mean value of 85 delivers the result above.

There are many publications on DWI and ADC. But why are there so many different unit and digits used for ADCs?
Currently, there is no consensus about applied units in DWI. You will find all of the following units which are equal (*syngo* MR B13).

A mean intensity of 1000 is equal to:
1.0*µm²/ms or intensity times 10^{-3}
1.0*10^{-3} mm²/s or intensity times 10^{-6}
1.0*10^{-5} cm²/s or intensity times 10^{-8}
1.0*10^{-9} m²/s or intensity times 10^{-12}
Also found:
1000*10^{-6} mm²/s
1000*µm²/s

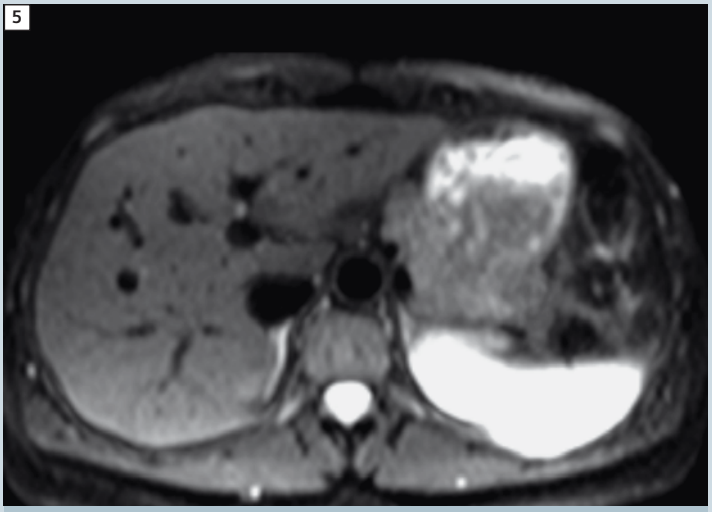
Why does the ADC have a unit of an area/time although diffusion occurs in all three dimensions?
By definition, the diffusion coefficient is defined as the product of 1/3 times medial velocity times mean free path:

$$D = 1/3 * v' * l$$

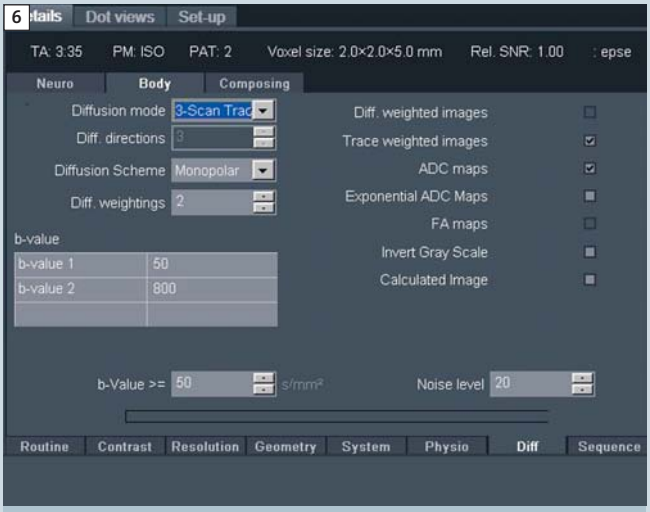
The unit is an area per time.

Why is there a lack of standardization for the choice of b-values in whole body DWI?
As a relatively new application body DWI is on its way to become a technique with recommended b-values and measurement conditions. See cited reference [4] for further information.

Why do most body and liver DWI protocols start with b-value 50 s/mm²?
The selection of a low b-value larger than zero provides suppression of large vessels which makes lesions more con-



5 b50 image of normal liver at 3T.



6 *syngo* body-diffusion card in software version *syngo* MR D11A.

spicuous. The calculation of the tissue ADC can be more accurate when starting with even higher b-values like 100 or 200 to omit the contribution of flow and micro vascular effects. Low b-values more often serve as anatomical reference. In software level *syngo* MR D11A and above you can delimit the b-values for ADC calculation on the body diffusion application card of the protocol.

Why do liver diffusion-weighted images look darker on 3T than 1.5T?

The T2 and T2* relaxations times for liver tissue, and other tissues as well, are considerably shorter as the field strength increases The overall signal is therefore diminished at 3T, even at lower b-values, due to the relatively long echo times (TE) used in DWI [5].

Which new DWI features are introduced with software version *syngo* MR D11A for MAGNETOM Aera and Skyra?

There is a new 'body diffusion' application card with many new applications:

- diffusion scheme monopolar/bipolar
- start ADC calculation for b > = ...
- exponential ADC; no T2 shine-through
- invert gray scale ("PET-like" image)
- calculated image of artificial b-values plus
- choice of dynamic field correction
- improved fat saturation schemes

What should I know when scanning liquids in phantoms with DWI sequences?

Firstly, the liquids should not move in the phantom bottle. Flowing liquid in the phantom would cause artificially strong diffusion and results in low intensity DWI images with inaccurately long ADC values.

Secondly, the diffusion coefficient is also strongly temperature dependent. Pure water has a diffusion coefficient of about 3 *10^{-3} mm²/s (exactly: 2.96) at body temperature of 37 °C (98.6 °F). Water of 0 °C (32 °F) has a diffusion coefficient of 1.12 * 10^{-3} mm²/s. This could serve as a standard for different machines.

Additional reading

In addition to the comprehensive Siemens applications guide, "Diffusion/Perfusion Imaging", there is literature [6] available which covers neuro and body diffusion. (Listed according to year of publication):

Derek K. Jones: Diffusion MRI: Theory, Methods, and Applications; Oxford University Press

Bachir Taouli: Extra-Cranial Applications of Diffusion-Weighted MRI; Cambridge University Press

Dow-Mu Koh: Diffusion-Weighted MR Imaging: Applications in the Body; Springer

Heidi Johansen-Berg: Diffusion MRI: From Quantitative Measurement to In-Vivo Neuroanatomy; Academic Press

References

1 Le Bihan D, Breton E, Lallemand D, Grenier P, Cabanis E, Laval-Jeantet M (1986). MR imaging of intravoxel incoherent motions; application to diffusion and Perfusion in neurologic disorders. Radiology. 161: 401-407.
2 Kingsley PB, Monahan WG (2004) Selection of the Optimum b Factor for Diffusion-Weighted Magnetic Resonance Imaging Assessment of Ischemic Stroke. MRM 51: 996-1001.
3 Provenzale JM, Engelter ST, Petrella JR, Smith JS, MacFall JA (1998). Use of MR Exponential Diffusion-Weighted Images to eradicate T2 "Shine-Through" Effect. AJR. 172:537-539.
4 Padhani AR, Liu G, Mu-Koh D, Chenevert TL, Thoeny HC, Takahara T, Dzik-Jurasz A, Ross BD, Van Cauteren M, Collins D, Hammoud DA, Rustin GJS, Taouli B, Choyke PL (2009). Diffusion-Weighted Magnetic Resonance Imaging as a Cancer Biomarker: Consensus and Recommendations. NEOPLASIA.11 (2): 102-125.
5 de Bazelaire CMJ, Duhamel GD, Rofsky NM, Alsop DC (2004).MR Imaging Relaxation Times of Abdominal and Pelvic Tissues in Vivo at 3.0 T. Radiology 230: 652-659.
6 Hagmann P, Jonasson L, Maeder P, Thiran JP, Van Wedeen J, Meuli R (2006). Understanding Diffusion MR Imaging Techniques: From Scalar Diffusion-weighted Imaging to Diffusion Tensor Imaging and Beyond. Radiographics 26: 205-223.

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