# A Comparison of Mean Displacement Values Using High b-Value Q-Space Diffusion-weighted MRI with Conventional Apparent Diffusion Coefficients in Patients with Stroke

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**Rationale and Objectives:** Q-space analysis using high b-value diffusion-weighted magnetic resonance (MR) data provides information on tissue microstructure in contrast to conventional MR imaging (MRI) based on low b-value diffusion-weighted imaging (DWI). The purpose of this study was to evaluate the use of mean displacement (MDP) map in stroke patients using q-space diffusion-weighted MRI (QSI).

**Materials and Methods:** Twenty-one patients presenting with a total of 22 acute or subacute cerebral infarctions were included. MR protocol consisted of conventional MR sequences, DWI (b-value; 1000 s/mm$^2$) and QSI (b-value; maximum 12,000 s/mm$^2$). Apparent diffusion coefficient (ADC) maps of conventional DWI and MDP maps of QSI data were obtained and compared in the ischemic lesions and corresponding normal tissues.

**Results:** Decreased ADC values were present in all lesions. There was no correlation between ADC and MDP values in the lesions ($r$ = 0.21). MDP values of the lesions were 8.60 $\pm$ 1.26 $\mu$m (mean $\pm$ SD). Most of the lesions (16/22) had higher MDP values than normal brain tissue. Three lesions showed lower MDP values and three showed mixed MDP values.

**Conclusions:** The MDP maps using QSI data provides additional information for stroke patients compared to conventional DWI.

**Key Words:** q-space; apparent diffusion coefficient; stroke; mean displacement; diffusion-weighted image; ADC maps; MRI.



Diffusion-weighted imaging (DWI) is widely applied as a noninvasive magnetic resonance (MR) technique for assessing brain development and pathological conditions. Clinically, single-shot echo-planar imaging (EPI) with low b-values (800–1000 s/mm$^2$) is the most common technique because of its short acquisition time (<1 minute) to complete whole brain imaging, relatively high signal-to-noise ratio (SNR), and high sensitivity and specificity for detecting acute stroke lesions (1). Apparent diffusion coefficient (ADC) is a DWI-derived parameter used to estimate stroke lesions.

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However, ADC is not a reliable predictor of brain tissue damage because even severely decreased ADC values may normalize in human stroke (2). Moreover, brain tissue with initially decreased ADC values may include "tissue at risk" for stroke (3). For the reasons ADC values derived from conventional DWI of limited use in the evaluation of brain tissue damage in stroke patients.

One explanation for the poor predict value of ADC is that conventional DWI analysis is based on an assumption of a Gaussian shape for the underlying probability density function (PDF) of diffusion of water molecules. However, neuronal tissue is a complex environment, and the decay of diffusion signal is affected by many factors such as water restriction and intra- and extracellular water exchange and variation in tissue compartment sizes. Therefore, different approaches not relying on the previously mentioned assumption are required to address all the factors affecting the signal in diffusion-weighted sequences.

By q-space analysis (4–15) using multiple high b-value diffusion-weighted MR data, extraction of structural information is possible because assumption of Gaussian shape is not needed in estimation of PDF for water molecules in this technique and the signal decay is related to displacement space through the q value yielding displacement maps (6–8,10,12–15). This is in contrast to conventional DWI, which yields ADC maps through the b value, in which the signal is usually a mono-exponential change. Therefore, we hypothesized that the true movement of water molecules in any brain structures, including intra- and extracellular spaces, can be demonstrated using q-space analysis in vivo.

The purpose of this study was to evaluate the mean displacement (MDP) values of the ischemic lesions in patients with stroke using high b-value q-space diffusion-weighted MRI (QSI), compared with corresponding ADC values of conventional low b-value DWI.

## MATERIALS AND METHODS

A total of 21 patients (12 men and 9 women, mean age 65.5 years) diagnosed with acute or subacute cerebral infarctions participated in the study. There was not acute stroke unit equipped in our hospital; stroke-onset time was extremely inhomogeneous. Patients' age, time after stroke onset, previous history of cerebral infarction, and presence of leukoaraiosis are summarized in Table 1. Informed consent was obtained from each patient. The local ethical committee approved this study.

**TABLE 1. Summary of Stroke Patients Clinical Information**

| Patient | Age (y) | Time After Stroke Onset | Previous History of Cerebral Infarction | Leukoaraiosis |
|---|---|---|---|---|
| 1 | 61 | 120 | + | – |
| 2 | 63 | 72 | + | + |
| 3 | 80 | 3 | + | + |
| 4 | 64 | 3 | + | + |
| 5 | 57 | 21 | + | + |
| 6 | 48 | 28 | – | – |
| 7 | 76 | 6 | – | + |
| 8 | 80 | 268 | + | – |
| 9 | 58 | 24 | + | – |
| 10 | 57 | 312 | – | – |
| 11 | 53 | 48 | – | + |
| 12 | 93 | 192 | + | + |
| 13 | 52 | 16 | – | + |
| 14 | 72 | 3 | + | + |
| 15 | 67 | 168 | + | + |
| 16 | 37 | 18 | – | – |
| 17 | 78 | 312 | + | + |
| 18 | 63 | 48 | + | + |
| 19 | 63 | 216 | + | + |
| 20 | 69 | 96 | + | + |
| 21 | 74 | 48 | + | + |

All MR imaging was performed on a 1.5 Tesla MR imager (Signa HD, GE Medical Systems, Milwaukee, WI) with an eight-channel head coil. After conventional imaging sequences including T2-, T2*-, and T1-weighted imaging and fluid attenuated inversion recovery imaging in transverse plane, conventional DWI and QSI were performed 3–312 hours after the onset of symptoms. Imaging parameters of conventional DWI were as follows: repetition time (TR)/echo time (TE) = 8000/70 ms, matrix 128 × 128, bandwidth = 250 kHz, field of view (FOV) = 240 × 240 mm, slice thickness/gap = 5/1.5 mm and b value of 0 and 1000 s/mm$^2$ with the maximum b value applied in three directions in 20 slices. Imaging parameters of QSI were as follows: TR/TE = 10,000/147.6 ms, bandwidth = 250 kHz with the q values of 242.1–838.5 cm$^{-1}$ by 13 steps for each axis. These values were from 1000, 2000, 3000, and up to 12,000 s/mm$^2$, converted as b values. Q values were applied in three directions (x, y, z). Motion probing gradient (MPG) duration time ($\delta$) and MPG separation time ($\Delta$) were kept at 55.8 and 62.0 ms, respectively.

As stated above, FOV, spatial resolution, slice thickness, and slice gap of QSI were the same as in conventional DWI. Total scan time is approximately 40 seconds and 6 minutes 30 seconds for conventional DWI and QSI, respectively.

B0 distortion correction was applied to all diffusion data on a workstation (Advantage Workstation, GE Medical Systems, Milwaukee, WI). All conventional DWI images were transferred to an independent workstation and ADC maps were obtained. All QSI data were transferred to another independent PC, and MDP maps were obtained in each MPG axis by using software (QSI-analyzer; 2, 15) based on theory of q-space analysis (14,16). In short, the main principle in q-space analysis is that a Fourier transformation of the signal intensity with respect to q $E_{tdif}(q)$ provides the PDF $P_s(R, t_{dif})$for the water diffusion,

$$P_s(R,\ t_{dif}) = FT\{E_{tdif}(q)\}$$

Where $t_{dif} = \Delta - \delta/3$, the effective diffusion time.

Moreover, the shape of the PDF curvature is characterized by the full width at the half maximum (FWHM) and MDP value at each MPG axis can be calculated using the equation (16):

$$\text{MDP value} = 0.425 \times \text{FWHM}$$

Regions of interest (ROIs) of at least 9 pixels were placed on 22 high-signal ischemic lesions on conventional DWI and calculated ADC values on corresponding ADC maps. Moreover, ROIs were also placed on the corresponding region on the contralateral normal brain. Particular care was taken to avoid contamination by old infarction or leukoaraiosis close to the normal brain as possible. On MDP maps, the ROIs were placed on the same location as described previously and calculated MDPs. Additional ROIs were placed on MDP map under the condition that the values in the lesion seemed to be heterogeneous. The average of MDP values in three axes (X, Y, Z) in the ischemic lesions were compared to corresponding ADC values.