Apparent Diffusion Coefficient with Higher b-Value Correlates Better with Viable Cell Count Quantified from the Cavity of Brain Abscess

**BACKGROUND AND PURPOSE:** DWI by using higher b-values provides tissue diffusivity with less T2 shinethrough effect. VCD in the abscess cavity correlates with ADC values. The purpose of this study was to investigate which b-value–derived ADC correlates better with VCD.

**MATERIALS AND METHODS:** Thirty patients with brain abscess underwent conventional MR imaging and DWI with \( b = 1000, 2000, \) and \( 3000 \text{ s/mm}^2 \) on a 3T MR imaging scanner. ADC values were quantified by placing regions of interest inside the abscess cavity in all sections where the lesion was apparent on coregistered ADC maps derived from different b-values. VCD was measured on pus aspirated.

**RESULTS:** An increase in b-value was associated with a decrease in ADC values in normal parenchyma as well as in the abscess cavity. The most significant negative correlation of VCD was observed with \( b = 3000 \text{ s/mm}^2 \) (\( r = -0.98, \ P = .01 \)).

**CONCLUSIONS:** VCD in the abscess cavity can be best assessed at \( b = 3000 \text{ s/mm}^2 \) secondary to the reduction in the T2 shinethrough effect. DWI with \( b = 3000 \text{ s/mm}^2 \) is of promise value in the assessment of the therapeutic response of brain abscess.

**ABBREVIATIONS:** ADC = apparent diffusion coefficient; CNWM = contralateral normal white matter; DWI = diffusion-weighted imaging; FLAIR = fluid-attenuated inversion recovery; FWM = frontal white matter; GM = gray matter; spp = species; VCD = viable cell density; WM = white matter
ADC) have been explained on the basis of the biexponential fit model for water signal-intensity decay with different b-values.\textsuperscript{20-22} This biexponential diffusion property of water has been used in functional task-activation assessments.\textsuperscript{24}

The purpose of this study was to investigate which b-value–derived ADC correlates better with VCD. We computed a biexponential fit to understand which component is influenced by the high b-value in the abscess cavity.

Materials and Methods

Study Design
Thirty-five patients with suspected intracranial abscess (24 males and 11 females; mean age, 25 years; ranging from 9 to 47 years of age) admitted to the Department of Neurosurgery, Chhatrapati Sahuji Maharaj Medical University, Lucknow, India, from August 2009 to December 2010 and 10 healthy controls (ranging from 23 to 45 years of age) were enrolled in the study prospectively. These subjects underwent conventional MR imaging and DWI in the Department of Radiodiagnosis, Sanjay Gandhi Post Graduate Institute of Medical Sciences, Lucknow, India, on a 3T MR imaging scanner (Signa Hdx; GE Healthcare, Milwaukee, Wisconsin) with a 12-channel head coil.

Institutional ethics approval and informed consent from all patients or their nearest kin were obtained before the investigation. Diagnosis of brain abscess was suggested on the basis of diffusion imaging in 30 patients and formed the basis of inclusion for the study protocol design. The diagnosis was confirmed in all these 30 patients after surgery.

MR Imaging Protocol
The conventional MR imaging protocol included T2-weighted fast spin-echo with TE/TR/NEX = 88/4400 ms/1.2; number of sections = 42; section thickness = 3 mm; FOV = 240 mm; T2 FLAIR with TE/TR/NEX = 140/9000 ms/2; number of sections = 42; section thickness = 3 mm; FOV = 240 mm; and spin-echo T1 FLAIR with TE/TR/NEX/flip angle = 14/1300 ms/1/65°; number of sections = 42; section thickness = 3 mm; FOV = 240 mm with image matrix = 256 × 256 and no intersection gap.

All patients underwent DWI at b = 1000, 2000, and 3000 s/mm\textsuperscript{2}. DWI parameters were the following: TE = 93.2 ms; TR = 7075 ms; NEX = 2.0; number of sections = 42; section thickness = 3 mm; FOV = 240 mm; image matrix = 128 × 128 with no interslice gap. Postcontrast T1-weighted images were acquired after intravenous injection of gadadamiide dimeglamine (Omniscan, Oslo, Norway) at a dose of 0.1 mmol/kg of body weight.

Culture of Abscess Aspirate
All patients underwent surgery within 24 hours of imaging. The pus was collected in a sterilized vial and snap-frozen in liquid nitrogen immediately after surgery/aspiration. At the same time, 1–2 mL of aspirated pus was inoculated into BACTEC Plus Aerobic/Aerobic media (Becton Dickinson, Sparks, Maryland) to isolate the aerobic, facultative anaerobic, and anaerobic bacteria for the confirmation of the diagnosis of etiologic agents. The inoculated media were incubated at 37°C and growth was monitored in BACTEC 9050 (Becton Dickinson) for 5 days. Media with positive growth were subcultured on appropriate solid media and incubated aerobically and anaerobically at 37°C. Anaerobic incubation was carried out in jars filled with a gas mixture of nitrogen gas (80%–90%), carbon dioxide (5%–10%), and deuterium (5%–10%), through an Anoxomat system (Mart Mi-
crobiology, Drachten, the Netherlands). All of the isolates were identified by standard biochemical tests as described previously.\textsuperscript{25} Cultures and smear examinations were performed for Mycobacterium tuberculosis as well as for fungi in all cases.\textsuperscript{26}

Viable Cell Count
In this study, the viability of the cells was calculated by a hemocytometer (Burker-Turk; Erma, Tokyo, Japan) after diluting pus 100- to 1000-fold in white blood cell diluting solution and expressed as cells/ milliliter as described previously.\textsuperscript{10} Inflammatory cells (leukocytes) with intact cell membranes and nuclei, as identified by 0.5% trypan blue staining, were referred to as viable cells. The method for the calculation of cell attenuation has been described elsewhere.\textsuperscript{10,27}

Data Analysis
A Java-based Image J plug-in (http://rsb.info.nih.gov/ij) was developed to generate the ADC maps from DWI datasets with different b-values.

Biexponential Fit and Its Quantification
The diffusion-weighted signal intensity in case of biexponential decay is given by

\[ S(b) = S(0) \left[ f_{\text{fast}} \exp(-b \cdot D_{\text{fast}}) + f_{\text{slow}} \exp(-b \cdot D_{\text{slow}}) \right], \]

where \( S(b) \) is the signal intensity in the presence of a diffusion gradient, \( S(0) \) is the signal intensity in the absence of a diffusion gradient, \( D_{\text{fast}} \) and \( D_{\text{slow}} \) are the fast and slow ADCs, and \( f_{\text{fast}} \) and \( f_{\text{slow}} \) represent the respective fractional contributions to the signal intensity. With \( a_{\text{fast}} = S(0) - a_{\text{slow}} = S(0) f_{\text{fast}} \), equation 1 can be written as

\[ S(b) = a_{\text{fast}}(\exp(-b \cdot D_{\text{fast}}) - \exp(-b \cdot D_{\text{slow}})) + S(0) \exp(-b \cdot D_{\text{slow}}). \]

Coregistration was done between datasets with different b-values before fitting of equation 2 to obtain the ADCs of fast and slow diffusing components. Also the conventional ADC maps were calculated by using the monoeponential diffusion equation, \( S(b) = S(0) \exp(-b \cdot D) \) from the above coregistered datasets with different b-values from patients as well as controls.\textsuperscript{28} The mean ADCs, ADC\textsubscript{fast}, and ADC\textsubscript{slow} components were calculated by placing elliptic or circular regions of interest (40–60 mm\textsuperscript{2}) on any 1 of the above maps (and applying the same region of interest on other maps) inside the abscess cavity in all sections where the lesion was present. Similarly mean ADC values were also quantified from the CNWM and GM regions of the each patient with brain abscess in each section as they were from the abscess cavity.

Statistical Analysis
Bivariate analysis of the Pearson correlation was performed to study the relationship between mean ADC values, fast and slow ADC values, and VCD quantified from the abscess cavity. An independent Student t test was also performed to see any changes in ADC values quantified from the abscess cavity, CNWM, and GM regions of patients with brain abscess as well as FWM and GM regions of healthy controls at different b-values. All statistical analyses were performed by using the Statistical Package for the Social Sciences, Version 16.0 (SPSS, Chicago, Illinois).
Results

Clinical and Laboratory Examination

The predisposing factors were recognized in 24 cases: otitis media (n = 15), congenital heart disease (n = 3), postoperative infection (n = 1), steroid therapy (n = 2), head injury (n = 1), and pulmonary tuberculosis (n = 2). In the remaining 6 patients, the source of infection could not be ascertained. Of a total of 30 brain abscesses, 18 were found to be pyogenic, 1 was fungal, and 3 were confirmed as tubercular on a culture of aspirated pus. The micro-organisms isolated on culture and confirmed by standard biochemical test were aerobic Streptococci spp (n = 10), Staphylococcus aureus (n = 1), Bacteroides spp (n = 2), Nocardia spp (n = 1), Histoplasma capsulatum (n = 1), mixed microbes (aerobic and anaerobic) (n = 4), and tubercular (n = 3). Eight cases were sterile and were considered pyogenic due to the presence of acute inflammatory cells and the absence of Mycobacterium spp and fungal growth on microscopy and culture. In the abscess cavity, the VCD varied from 6000 to 11,000 cells/mm³.

Imaging Findings

Brain abscesses were located in the frontal lobe (n = 3), parietal lobe (n = 4), temporal lobe (n = 10), parietotemporal lobe (n = 4), and cerebellum (n = 9). The brain abscess appeared hyperintense on T2-weighted images with a peripheral hypointense rim (Fig 1A) and iso- to hypointense on T1-weighted images (Fig 1B). Postcontrast study showed rim enhancement (Fig 1C). A few brain abscesses showed homogeneous hyperintensity on DWI (Fig 1D–F), with corresponding homogeneous hypointensity on ADC images (Fig 1G–I). However, most brain abscesses showed heterogeneity on DWI and corresponding ADC images.

Quantification of ADC

The mean ADC values of the abscess cavity, CNWM, and GM regions quantified by placing regions of interest on ADC maps obtained from different b-values are summarized in Table 1. On independent Student t tests, a significant decrease in mean ADC values was observed in the abscess cavity at different b-values. In CNWM, there was no significant difference among mean ADC values obtained from different b-values. In GM regions, there was a significant difference only between mean ADC values of b = 1000 and b = 3000 s/mm² (Table 1). In healthy controls, we observed significant differences in mean ADC values quantified from FWM and GM regions at different b-values (Table 1).

Table 1: ADC values quantified from the abscess cavity, CNWM, and GM of patients with brain abscess and the WM and GM of healthy controls at different b-values

| Regions          | $A (b=1000)$ | $B (b=2000)$ | $C (b=3000)$ | P Value |
|------------------|--------------|--------------|--------------|---------|
|                   | Mean ± SD    | Mean ± SD    | Mean ± SD    |         |
| Abscess cavity   | 0.59 ± 0.20  | 0.48 ± 0.13  | 0.39 ± 0.11  | A vs B = .05; A vs C = .01; B vs C = .05 |
| CNWM             | 0.64 ± 0.04  | 0.63 ± 0.11  | 0.62 ± 0.14  | A vs B = .86; A vs C = .80; B vs C = .93 |
| GM               | 0.74 ± 0.04  | 0.71 ± 0.12  | 0.71 ± 0.02  | A vs B = .37; A vs C = .01; B vs C = .97 |
| Healthy controls |             |              |              |         |
| WM               | 0.82 ± 0.02  | 0.68 ± 0.02  | 0.58 ± 0.02  | A vs B = .01; A vs C = .01; B vs C = .01 |
| GM               | 0.78 ± 0.03  | 0.71 ± 0.01  | 0.64 ± 0.02  | A vs B = .01; A vs C = .01; B vs C = .01 |

*Mean ± SD* × 10⁻³ s/mm².
On independent Student \( t \) tests, no significant difference was observed between ADC\(_{\text{fast}}\) of brain abscess lesions, CNWM, and GM regions of patients with brain abscess. ADC\(_{\text{slow}}\) of the abscess cavity was found to be significantly lower than the ADC\(_{\text{slow}}\) of the GM of patients with brain abscess (Table 2).

On bivariate analysis by using the Pearson correlation, a significant negative correlation was observed between the VCD and mean ADC values from different \( b \)-values (\( b=1000 \) s/mm\(^2\), \( r=-0.76, P=.01 \); \( b=2000 \) s/mm\(^2\), \( r=-0.86, P=.01 \); and \( b=3000 \) s/mm\(^2\), \( r=-0.98, P=.01 \)) (Fig 2). No significant correlation was observed between VCD and fast and slow ADC components computed through biexponential fit (ADC\(_{\text{fast}}\) \( [r=-0.17, P=.56] \) and ADC\(_{\text{slow}}\) \( [r=-0.15, P=.58] \)).

The biexponential fit of combined and fast components revealed a decrease in signal intensity with increasing \( b \)-values in the WM and GM regions and abscess cavity (Fig 3A–C). However, there was a gradient in decrease in the signal intensity of the slow component moving from GM to WM regions with not much change in the abscess cavity as a function of \( b \)-values (Fig 3A–C).

**Discussion**

In this study, significantly low mean ADC values were observed in the abscess cavity at different \( b \)-values. With increasing \( b \)-values, ADC values decreased in the abscess cavity, GM, and CNWM regions of brain. The decrease in ADC values between \( b=1000 \) and \( b=3000 \) s/mm\(^2\) was significant in the GM of patients and controls, while it also showed only a significant decrease from FWM in healthy controls. Although there was a significant negative correlation of VCD with all 3 \( b \)-values, the correlation at \( b=3000 \) s/mm\(^2\) was found to be close to 1. The quantification of fast and slow components of ADC by using a biexponential fit in the abscess cavity did not correlate with VCD.

It has been shown by in vivo and ex vivo experiments that the increase in cell attenuation in brain abscesses negatively correlates with mean ADC values.\(^10\) The mean ADC values measured from the abscess cavity showed trends similar to those exhibited by cellular tumors in humans\(^26\) and animal tumor models.\(^27\) It has been reported that \( b \)-value is inversely proportional to ADC.\(^29\) DeLano et al\(^14\) have reported that when \( b \)-values increase from 1000 to 3000 s/mm\(^2\), ADC values decrease from 30% to 35% for the same regions of interest. The authors related it to the biexponential decay in signal intensity. The signal-intensity decay observed in their study as a function of \( b \)-factor is in close agreement with our results from a biexponential model in the abscess cavity of these patients (Fig 3A–C).

It has been reported that the ADC of viable tissue is a result of independent contributions from the intracellular and extracellular compartments.\(^30,31\) Therefore, at least 2 factors contribute to a decrease in ADC values with increasing cell attenuation. The first is that tissues with high cell attenuation have a large fraction of intracellular water compared with tissues with low cell attenuation. The intracellular water has presumably lower ADC than the extracellular water due to a higher content of diffusion barriers in the intracellular compartment.\(^30\) Second, tissues with high cell attenuation have small extracellular compartments compared with tissues with low cell attenuation. The mobility and mean ADC decrease in tissues with high cellularity results in low ADC because of small extracellular water content. The influence of this factor is strengthened because the ADC is biased toward the diffusion coefficient of the compartment with the longest T2 (ie, the extracellular compartment).\(^31\)

On the biexponential fit model, we observed a decrease in signal intensity of the fast component as we moved from low to high \( b \)-values. The strongest correlation of VCD with ADC values at \( b=3000 \) s/mm\(^2\) can be attributed to the fact that on increasing diffusion weighting, there is a decrease in T2 shinethrough effect, resulting in removal of fast components, which in turn is responsible for more precise measurements of ADC values of the intact inflammatory cells inside the abscess cavity. The absence of any change in signal intensity of the slow component inside the abscess cavity further suggests that mainly the fast component is probably responsible for the T2 shinethrough effect, which is removed on increasing the diffusion-weighting.

On the basis of biexponential fit, the fast and slow diffusion components of water have been described in human brain and interpreted as from extracellular and intracellular compartments, respectively.\(^32,33\) Le Bihan\(^34\) has suggested that fast and slow components of the water diffusion correspond to 2 differently structured water pools, rather than specific water compartments. He proposed a model where both the slow and fast components of water diffusion originate partly in the in-
In the current study, we used b-values up to 3000 s/mm², which we did not observe any correlation of fast and slow components of the ADC with the actual cell count, suggesting that these 2 components may not represent the extra- and intracellular water compartments, respectively. Our results further confirm that these 2 components of water diffusion originate from the 2 different pools rather than from the 2 different compartments of water.

The viable inflammatory cells in the abscess cavity are the result of active inflammation, and a decrease in inflammatory cells is considered a marker for the response to therapy. This has been shown by serial ADC measures in which an increase in ADC indicates a response, while a decrease in its value suggests reactivation of the disease. Similar results have been shown by serial fractional anisotropy measurements in brain abscess, in which an increase in fractional anisotropy is associated with upregulation of inflammatory cytokines and increased inflammatory cells, while the reverse is true when there is a positive response. Usinsk et al16 have also used serial high b-values (up to $b = 3000 \text{s/mm}^2$) to assess the response to highly active antiretroviral therapy in a case of progressive multifocal leukoencephalopathy. Our data suggest that ADC maps derived from $b = 3000 \text{s/mm}^2$ may be ideal for quantification of intact inflammatory cells in the abscess cavity and may be able to predict therapeutic response much better than ones obtained from $b = 1000 \text{s/mm}^2$.

Various authors have used b-values up to 5000 s/mm² to demonstrate the biexponential fit in human brain.22,23,29 In the current study, we used b-values up to 3000 s/mm², which may be suboptimal to demonstrate the biexponential fit and may be considered a limitation.

Conclusions
The viability of cells, a measure of disease activity, can be best quantified by ADC values derived by using $b = 3000 \text{s/mm}^2$ DWI. This may be used in the future to assess the therapeutic response to antibiotics in patients with brain abscess. The fast and slow components of diffusivity may not truly represent the extracellular and intracellular compartments and may simply represent the free and bound water present in the tissue.
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