

T. Satoh
M. Omi
C. Ohsako
C. Ekino

Transparent color-coded three-dimensional diffusion-weighted magnetic resonance imaging for the numerical analysis of reversible and irreversible hyperacute ischemic stroke—case report

Received: 27 August 2003
Accepted: 1 November 2004
Published online: 2 April 2005
© Springer-Verlag 2005

Abstract Although diffusion-weighted (DW) magnetic resonance (MR) imaging can detect hyperacute ischemic parenchyma with high sensitivity, the ability of DW images to reveal subtle change in abnormal diffusion may be limited by the conventional visual evaluation. To overcome the limitation, we have developed a method of transparent color-coded three-dimensional (3D) DW MR imaging for the computer-aided numerical analysis of hyperacute ischemic stroke. The 3D images were reconstructed from volume data of source DW images by using a parallel volume-rendering algorithm with transluminal imaging technique. By selecting a threshold range from a signal intensity opacity chart of volume-rendering data set, several high signal intensity areas were depicted and assigned to different colors, transparently through contours of the brain. This imaging was applied in a case of a recanalized middle cerebral artery (M2) occlusion with partially reversible ische-

mic parenchyma accompanied by partial recovery from ischemic neurological deficit. Complex and dynamic change in hyperacute ischemic parenchyma, with regression of subtle high signal intensity areas and progression of ischemic parenchyma, was depicted three-dimensionally. Transparent color-coded 3D DW MR imaging may provide computer-aided numerical analysis of hyperacute ischemic stroke appearing as a high signal intensity area on the source DW images.

Keywords Cerebral ischemia · Diffusion-weighted image · Magnetic resonance imaging · 3D reconstruction · Volume-rendering algorithm

Abbreviations ADC: apparent diffusion coefficient · DW: diffusion-weighted · MR: magnetic resonance · 3D: three-dimensional

T. Satoh (✉)
Department of Neurological Surgery,
Ryofukai Satoh Neurosurgical Hospital,
5-23-23 Matsunaga, Fukuyama,
Hiroshima 729-0104, Japan
E-mail: ucsfbtrc@urban.ne.jp
Tel.: +84-934-9911
Fax: +84-934-9910

M. Omi · C. Ohsako · C. Ekino
Department of Diagnostic Radiology,
Ryofukai Satoh Neurosurgical Hospital,
Fukuyama, Hiroshima, Japan

Introduction

Because diffusion-weighted (DW) magnetic resonance (MR) imaging detects restricted diffusion of tissue water movement related to cytotoxic edema, it can depict hyperacute ischemic parenchyma as an area of high signal intensity [1–5]. However, the ability of DW images to reveal subtle changes in abnormal diffusion may be limited by the conventional assessment based on

visual review of one or more two-dimensional source images. To overcome the visual limitation, we have developed a method of transparent color-coded three-dimensional (3D) DW MR imaging for the computer-aided numerical analysis of hyperacute ischemic stroke, by using a transluminal imaging technique with a parallel volume-rendering algorithm [6–8]. In the present report, we document the actual use of serial color-coded 3D DW MR imaging to depict the complex and

dynamic changes in the regression and progression of ischemic parenchyma in a specific case of reversible and irreversible hyperacute ischemic stroke.

Case report

Reconstruction of the transparent color-coded 3D DW MR images

MR imaging was performed with the use of echo-planar imaging sequences on a 1.0 T clinical imager (Signa HiSpeed; General Electric Medical Systems, Milwaukee, Wisc., USA). The protocol for fluid attenuated inversion recovery/DW imaging scans included single-shot, spin-echo echo-planar imaging with a slew rate of 77 mT/m/s, a b -value of 1000 s/mm², a data matrix of 128×128 pixels, a repetition time of 8000 ms per echo time of 119.1 ms, an inversion time of 1800 ms, a bandwidth of 62.50 kHz, a 1-excitation, 22-cm field of view, 32 continual sections of 3 mm thickness, and coverage of the entire brain in a total scan time of 2 min and 24 s. Diffusion weighting was applied separately in three orthogonal (x , y , z) directions, and the data were averaged together. The volume data (32 data) of DW images were transferred to a commercially available workstation with computer medical visualization software (Zio M900; AMIN Co. Ltd, Tokyo, Japan), and were interpolated every 1 mm and processed into a 3D volume-rendering data set (125 data) in 9 s.

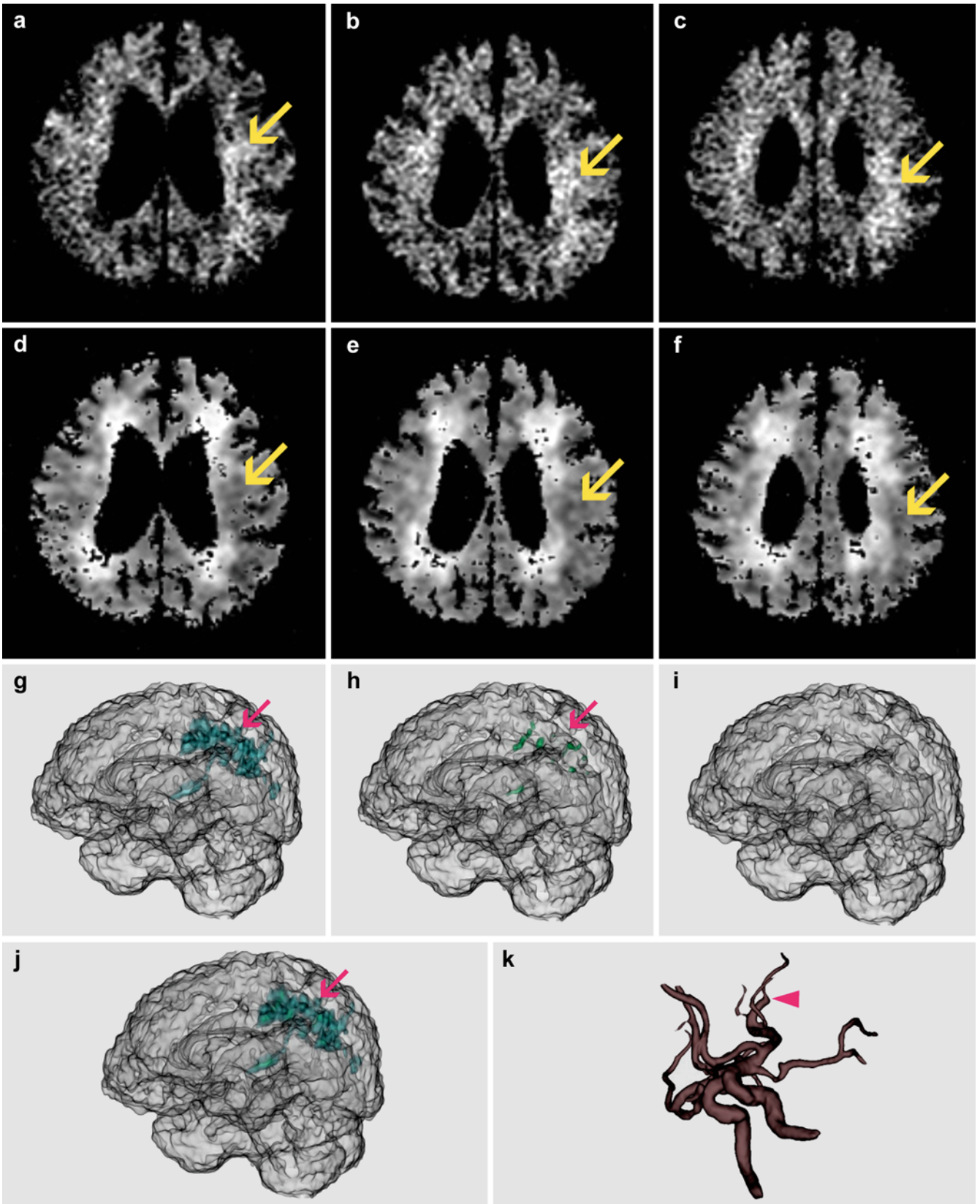
The 3D image was rendered from the data set in 11 s by a parallel volume-rendering algorithm using a transluminal imaging technique [6–8]. Based on the histogram of the signal intensity in correspondence to the margin of the brain surface and ventricles on the source images, a transparency of the borderline images for those structures was selected from the opacity chart of MR signal intensities (arbitrary unit distribution). This selection used a spiked peak curve with a threshold range of 65–75 (peak value at 70 with 20% opacity level, window width 10) and color-coded in gray. To create transparent visualization of an area with high signal intensity through the brain parenchyma, other square curves were employed to select a range of high signal intensity from the same opacity chart used for transparent borderline imaging. The areas were extracted with threshold ranges of 220–240, 240–280, and 280–500 (10% opacity level), which were then color-coded blue, green and red, respectively. The color-coded high signal intensity areas were superimposed onto the transparent borderline images, and those were shown with each color separately on several 3D images or altogether on a single 3D image. The total time required to produce a transparent color-coded 3D DW MR image was approximately 20 s from post-scanning.

Fig. 1 An 85-year-old man with complete right hemiplegia and angular signs due to the left middle cerebral artery (M2) occlusion. The source DW images (a–c) of the initial scanning, 30 min post-ictus, showing a subtle high signal intensity area in the left posterior corona radiata along to the centrum semiovale regions (arrows), consistent with the patient's symptoms. Apparent diffusion coefficient (ADC) maps (d–f) showing an area with slight decreased diffusion constant (arrows) corresponded to those with DW images. The transparent color-coded 3D DW images selected by signal intensity threshold ranges of 220–240 (blue), 240–280 (green), and 280–500 (red), shown with each color separately (g–i) or altogether (j), above and left inferoposterolateral projection, showing the initial ischemic parenchyma (arrows) in conjunction with the contours of the brain and ventricles. The 3D volume-rendering MR angiogram (k), the same projection to 3D DW images, showing complete obliteration of M2 at the beginning of angular artery branching (arrowhead)

Case illustration

An 85-year-old man presented with sudden complete right hemiplegia and left angular signs, with NIHSS score of 19, due to acute occlusion of the left middle cerebral artery (M2). DW images (Fig. 1a–c), taken 30 min after onset, showed a subtle high signal intensity area in the left temporoparietal region, including the posterior portion of the corona radiata to the centrum semiovale; this finding was consistent with the patient's symptoms. Corresponding to this area of high signal intensity, apparent diffusion coefficient (ADC) maps (Fig. 1d–f) showed an area with a slightly decreased diffusion constant. The transparent color-coded 3D DW MR images selected by signal intensity threshold ranges of 220–240 (blue), 240–280 (green), and 280–500 (red), shown with each color separately (Fig. 1g–i) or altogether (Fig. 1j), viewed from above and left inferoposterolateral projection, depicted the spatial expansion of the initially ischemic parenchyma in conjunction with the contours of the brain. The 3D volume-rendering MR angiogram (Fig. 1k), with the coordinated projection as to the 3D DW image, revealed complete obliteration of M2 at the beginning of the angular artery branching. The informed consent to the ethical committee approved treatment option was obtained. After the intravenous administration of urokinase, the patient showed complete recovery from motor paralysis but remained still with angular signs.

At 24 h after onset, follow-up scanning with the source DW (Fig. 2a–c), ADC (Fig. 2d–f), and transparent color-coded 3D DW images with each color separately (Fig. 2g–i) or altogether (Fig. 2j) showed that the ischemic areas had progressed and extended over the left temporoparietal region with profoundly increased signal intensity. However, the initially observed ischemic parenchyma, indicated as a subtle high signal intensity area from the corona radiata to the centrum semiovale, had disappeared entirely. Correspondingly, the 3D MR



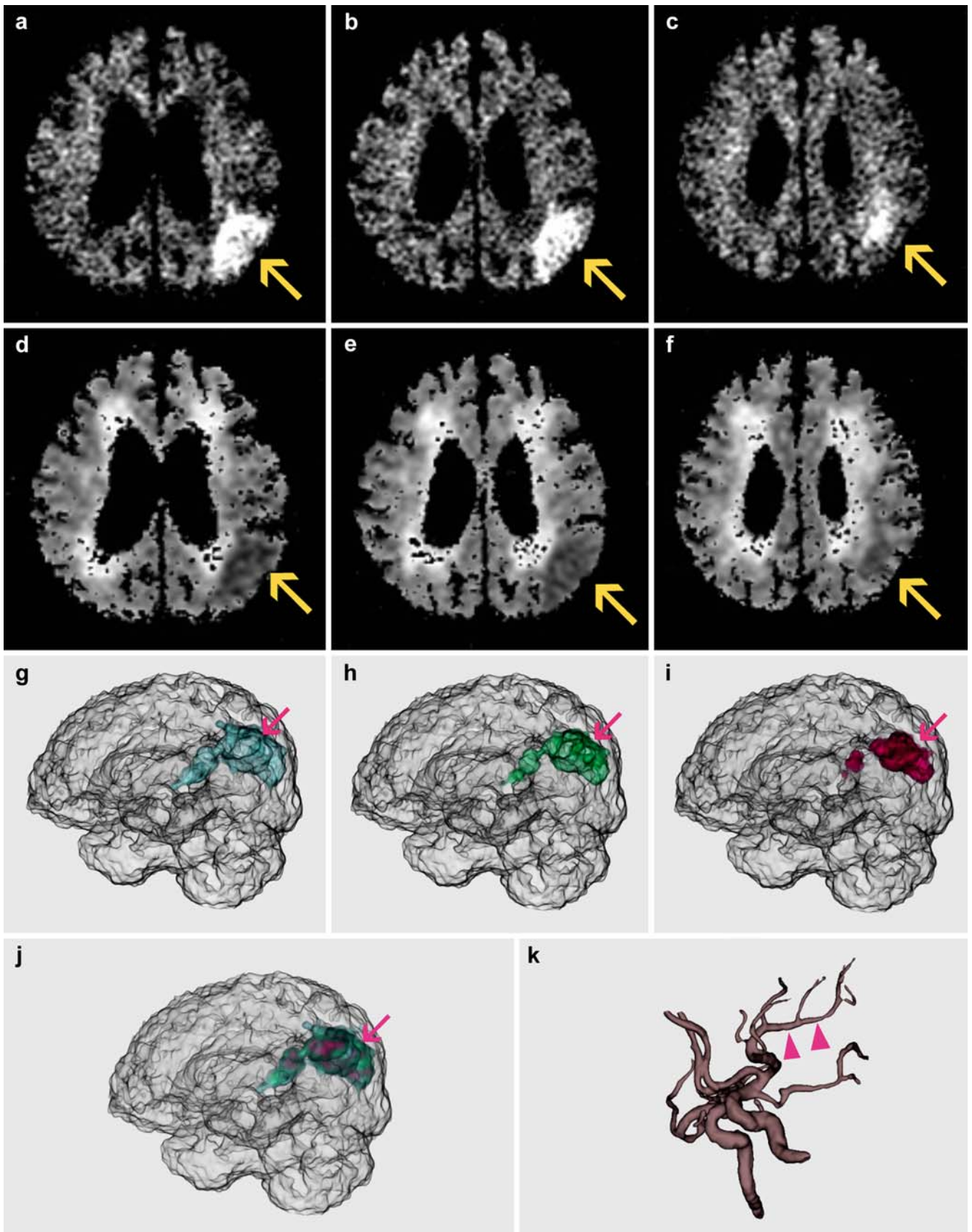




Fig. 2 An 85-year-old man with complete right hemiplegia and angular signs due to the left middle cerebral artery (M2) occlusion. Serial follow-up scanning with source DW (a–c), ADC (d–f), and color-coded 3D DW images with each color separately (g–i) or altogether (j), at 24 h post-ictus, showing the progression of the ischemic parenchyma (arrows), but the regression of a subtle high signal intensity area in the corona radiata to the centrum semiovale. Follow-up 3D MR angiogram (k), showing the complete recanalization of the previously occluded angular artery (arrowheads)

angiogram (Fig. 2k) confirmed the complete recanalization of the previously occluded angular artery. The patient was discharged in 3 weeks without motor and sensory disturbances but with the left angular signs and sensory aphasia.

Discussion

Although detection of acute ischemic parenchyma by DW imaging appears to be impeccable, the initial DW imaging may fail to depict lesions at hyperacute ischemic time point [1–5]. The majority of cases of ischemic parenchyma with initially negative findings on DW images can develop into infarct tissue later with positive diffusion abnormality [9, 10]. Diffusion abnormality noted on the initial DW imaging with subtle elevated signal intensity might be salvaged in specific cases, if reperfusion occurs early enough [11–13].

Because the area of abnormal diffusion has been assessed by visually reviewing one or more source DW images in comparison with slice-matched anatomic images, it may be difficult to appreciate the degrees of signal intensity and the heterogeneity of the contents within the hyperacute ischemic parenchyma. It is also difficult to use two-dimensional images to evaluate the spatial spread and change in ischemic parenchyma with time course. For the evaluation of a dynamic and complex change in diffusion abnormalities involving hyperacute ischemic stroke, we have developed a

method of computer-aided medical visualization technique.

The computer-generated 3D image can provide numerical analysis of the volume data obtained from the source DW images. Consequently, the hyperacute ischemic lesions defined as a high signal intensity area can be depicted not by the visual assessment but the numerical threshold range applied to the signal intensity opacity chart of the volume-rendering data set. With the transparent color-coded 3D DW imaging, the restricted diffusion corresponded to the ischemic parenchyma that could be selected from the data set and depicted three-dimensionally from various projections with specific colors. The computer-aided numerical analysis of diffusion abnormality can provide a patient-specific assessment of the 3D spread of a hyperacute ischemic stroke. Additionally, temporal change in the degree and heterogeneity of signal intensity distribution within ischemic parenchyma can be visualized with different colors, and then be evaluated with serial color-coded 3D DW images.

There are several limitations to evaluate the abnormal diffusion by the transparent color-coded 3D DW images. With the use of numerical imaging analysis, abnormal diffusion areas with high signal intensities other than ischemic parenchyma, including magnetic susceptibility artifacts from pyramidal bone and posterior fossa, could be visualized simultaneously according to the signal intensity threshold range selected from the volume data set. Additionally, because the signal intensity of abnormal diffusion may vary slightly among individuals and conditions of examination, direct comparison of the change in the degree and extent of abnormal diffusion may be inconsistent with the initial and follow-up scanning. Careful judgment is necessary to evaluate the ischemic lesions depicted by color-coded signal intensity distribution on 3D DW images. More work is required to validate the technique and to evaluate the significance of being able to visualize color-coded signal intensity distribution of 3D DW images in patients with hyperacute ischemic stroke.

References

1. Lovblad K-O, Baird AE, Schlaug G, Benfield A, Siewert B, Voetsch B, Connor A, Burzynski C, Edelman RR, Warch S (1997) Ischemic lesion volumes in acute stroke by diffusion-weighted magnetic resonance imaging correlate with clinical outcome. *Ann Neurol* 42:164–170
2. Yuh WTC, Ueda T, White M, Schuster ME, Taoka T (1999) The need for objective assessment of the new imaging techniques and understanding the expanding roles of stroke imaging. *Am J Neuroradiol* 20:1779–1784
3. Fiebich JB, Jansen O, Schellinger PD, Heiland S, Hacke W, Sartor K (2002) Serial analysis of the apparent diffusion coefficient time course in human stroke. *Neuroradiology* 44:294–298
4. Kamal AJ, Segal AZ, Ulug AM (2002) Quantitative diffusion-weighted MR imaging in transient ischemic attacks. *Am J Neuroradiol* 23:1533–1538
5. Ahlhelm F, Schneider G, Backens M, Reith W, Hagen T (2002) Time course of the apparent diffusion coefficient after cerebral infarction. *Eur Radiol* 12:2322–2329

6. Satoh T (2001) Transluminal imaging with perspective volume rendering of computed tomographic angiography for the delineation of cerebral aneurysms. *Neurol Med Chir (Tokyo)* 41:425–430
7. Satoh T, Onoda K, Tsuchimoto S (2003) Visualization of intraaneurysmal flow patterns with transluminal flow imaging of three-dimensional MR angiograms in conjunction with aneurysmal configurations. *Am J Neuroradiol* 24:1436–1445
8. Satoh T, Ekino C, Ohsako C (2004) Transluminal color-coded three-dimensional magnetic resonance angiography for visualization of signal intensity distribution pattern within an unruptured cerebral aneurysm: preliminary assessment with anterior communicating artery aneurysms. *Neuroradiology* 46:628–634
9. Lefkowitz D, LaBenz M, Nudo SR, Steg RE, Bertoni JH (1999) Hyperacute ischemic stroke missed by diffusion-weighted imaging. *Am J Neuroradiol* 20:1871–1875
10. Oppenheim C, Stanescu R, Dormont D, Crozier S, Marro B, Samson Y, Rancurel G, Marsault C (2000) False-negative diffusion-weighted MR findings in acute ischemic stroke. *Am J Neuroradiol* 21:1434–1440
11. Minematsu K, Li L, Sotak CH, Davis MA, Fisher M (1992) Reversible focal ischemic injury demonstrated by diffusion-weighted magnetic resonance imaging in rats. *Stroke* 23:1304–1310
12. Kidwell CS, Saver JL, Mattiello J, Starkman S, Vinuela F, Duckwiler G, Goblin YP, Jahan R, Vespa P, Kalafut M, Alger JR (2000) Thrombolytic reversal of acute human cerebral ischemic injury shown by diffusion/perfusion magnetic resonance imaging. *Ann Neurol* 47:462–469
13. Krueger K, Kugel H, Grond M, Thiel A, Maintz D, Lackner K (2000) Late resolution of diffusion-weighted MRI changes in a patient with prolonged reversible ischemic neurological deficit after thrombolytic therapy. *Stroke* 31:2715–2718