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Three-Dimensional Anisotropy Contrast MRI and Functional MRI of the Human Brain: Clinical Application to Assess Pyramidal Tract in Patients with Brain Tumor and Infarction

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We describe and evaluate the findings of three-dimensional anisotropy contrast MR axonography (3DAC MRX) and functional MRI (fMRI) in brain tumor and infarction. We obtained diffusion-weighted images (DWI) in 28 patients including 23 brain tumors and 15 acute infarctions located in or near pyramidal tract. Three anisotropic DWIs were transformed into graduations color-coded as red, green or blue, and then composed to form a combined color 3DAC MRX. We also performed functional MRI in 7 of the 28 patients and compared with cortical mapping of 3DAC MRX. 3DAC MRX with 23 brain tumors showed that the ipsilateral pyramidal tract was either discontinuous due to impaired anisotropy (n=8) or compressed due to mass effect (n=15). In 10 patients of acute infarction with motor impairment, pyramidal tract involvement was visually more conspicuous on 3DAC MRX compared to standard DWI. On functional MRI, hand motor activation was observed between blue vertical directional colors of pre- and post central gyrus. In conclusion, 3DAC MRX is a new noninvasive approach for visualization of the white matter neuronal tract and provides the information concerning pyramidal tract involvement.

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Introduction

Cortical functional mapping using functional MRI (fMRI) or magnetoencephalography has been of great practical value in presurgical evaluation of patients with brain tumor in or near the eloquent areas[1－3)]. Current methods of functional mapping investigate only the cortical function, although anatomical recognition of subcortical nerve fibers is equally important.

Diffusion-weighted magnetic resonance imaging (DWI) has been used in the early diagnosis of acute stroke and most of previous approaches to evaluate nerve fibers have been based on DWI[4－6)]. Diffusion anisotropy of the rat spinal cord was visualized by Nakada et al[7)] using the three-dimensional anisotropy contrast (3DAC) technique which effectively eliminated isotropic component and highlighted anisotropic component of the diffusion of nerve fibers.

Our purpose is to describe and evaluate the findings of 3DAC MR axonography (3DAC MRX) in patients with brain tumor and acute brain infarction, and to correlate the integrity of the pyramidal tract with motor function. We also describe a clinically useful application of fiber mapping of 3DAC MRX combined with fMRI for demonstration of the sensory motor cortex and evaluate the spatial specificity of 3DAC MRX.

Materials and Methods

Twenty-three patients with brain tumors (10 females and 13 males, age 14－85 years, mean 55 years) and 15 patients with acute infarctions (2 females and 13 male, age 39－82 years, mean 68 years) were retrospectively analyzed. All patinets had the lesion located in or near pyramidal tract. Cortical mapping using fMRI was performed in 7 of these 38 patients, and was compared with 3DAC MRX. fMRI and DWI were performed with a 1.5-T whole-body MR system (Signa Horizon, GE Medical Systems, Milwaukee, WI) and a standard head coil.

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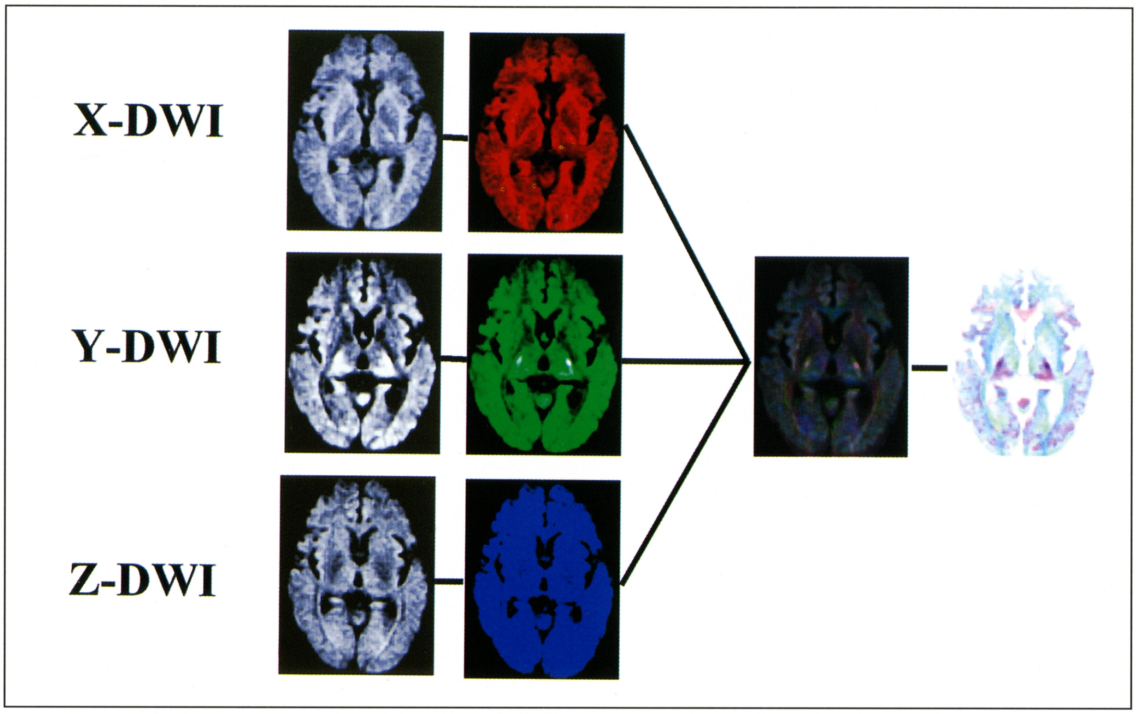

Fig. 1. Schematic summary of 3DAC process. Conversion of the gray scale image of each anisotropic DWI (X-, Y-, and Z-axis) into the corresponding primary color-scaled image (red, green, and blue). Three DWIs are combined into a single color image in full visible color spectrum. To ensure one to one correlation between hue axes (R, G, B) and spatial axes (X, Y, Z), this image is negatively displayed, thereby generating 3DAC image (Modified from reference 7).

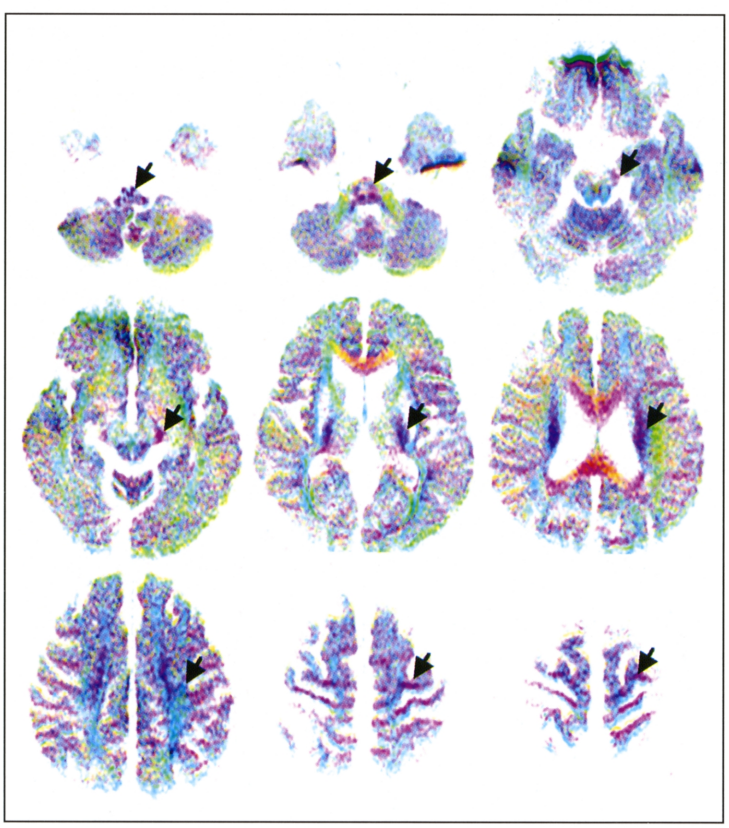

Fig. 2. Representative 3DAC MRX of a patient with small left parietal infarction. 3DAC MRX showing nerve fibers running in the left-right, anterior-posterior, or superior-inferior directions in red, green or blue, respectively. Mixed colors indicate oblique orientation of nerve fibers. The pyramidal tract appears as a distinct blue or purple colored band. The entire pyramidal tract is visualized on 3DAC images including the primary motor cortex, the corona radiata, the internal capsule, the cerebral peduncle and the ventral brain stem (arrows).

3DAC MR axonography (3DAC MRX)

Axial DWI was performed with spin-echo echo-planar imaging (TR 10000 ms, TE 100 ms, b=1000 sec/mm^2, FOV 22 -26 cm, 128 x 128 matrix, 6 mm section thickness with 2 mm intersection gap). In some cases, b value of 2000 sec/mm^2 was also obtained. Motion probing gradient (MPG) was applied in the three principal anatomic axes to obtain the anisotropic DWIs (Fig. 1). Isotropic DWI and apparent diffusion coefficient (ADC) map were obtained with b values of 0 and 1000.

3DAC MRX was obtained from each anisotropic DWI using Advantage Windows (GE Medical Systems, Milwaukee, WI) (Fig. 2). The involvement of pyramidal tract on 3DAC MRX were categorized as follows; 1) Discontinuous tract showing increase in density of all colors with loss of anisotropy, 2) Compressed tract showing deviation of the fiber without change of the color.

Functional MRI (fMRI)

Functional MRI was obtained with multislice gradient echo-planar image (TR 2000 ms, TE 40 ms, FA 90 deg, FOV 24cm, 128x128 matrix, 6 mm section thickness). The patients performed a motor task of hand sponge squeezing. Activation maps were calculated by commercial analysis software (Functool 1.0, GE Medical Systems, Milwaukee, WI). The correlation coefficient algorithm was used with the confidence level of 0.001 (0.1% probability). Recognition of central gyrus with fMRI or 3DAC MRX was evaluated as follows; good: easy recognition of central sulcus, fair: faint activated pixels on sensory motor area on fMRI, and visualisation of the white matter of precentral gyrus or post central gyrus on 3DAC MRX, poor: impossible to recognise sensory motor area.

Results

3DAC MRX findings in brain tumor and acute infarction

3DAC MRX demonstrated the pyramidal tracts continuously from the presumed motor cortex to the brain stem. However, 3DAC MRX could not differentiate the pyramidal tract from the thalamocortical fibers or other nerve fibers running along the pyramidal tract (Fig. 1).

Displacement of the pyramidal tract and direction of the fiber were easily recognised in cases of brain tumor (Fig. 3, 4). 3DAC MRX with 23 brain tumors showed that the ipsilateral pyramidal tract was either discontinuous due to impaired anisotropy (n=8) or compressed due to mass effect (n=15). The patients with discontinuous fiber tract showed more severe motor dysfunction compared to those with compressed fiber tract. Isotropic high ADC component such as intratumoral necrosis or perifocal edema showed whitish color due to cancellation with sum of three primary colors. Contrast enhancing portion of brain tumor tended to be colored variously.

Ten patients of acute infarction with motor impairment showed discontinuous pyramidal tract due to decreased anisotropic diffusion (Fig. 5). In remaining 5 patients without motor impairment, there was no change of the color in pyramidal tract.

Low ADC areas of 15 acute infarctions appeared dark color on 3DAC MRX. The pyramidal tract involvement of acute infarction was visually more conspicuous on 3DAC MRX compared to isotropic DWI.

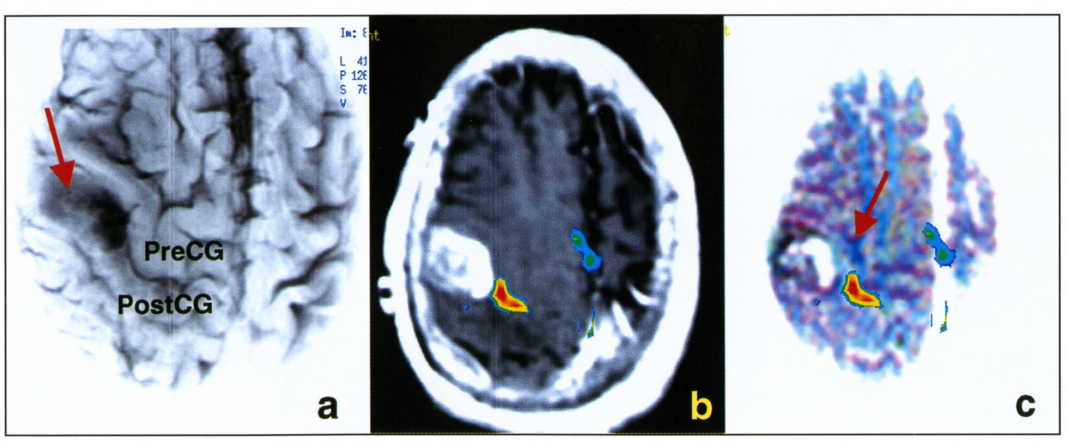

Fig. 3. A 85-year-old male with right parietal glioblastoma.
a. Surface anatomy scanning image shows a tumor subjacent to the left postcentral gyrus (arrow). PreCG: precentral gyrus, PostCG: postcentral gyrus. **b.** fMRI demonstrates activated pixels in the central sulcus. **c.** fMRI superimposed on 3DAC. White matter of the precentral gyrus is shown in blue color (arrow).

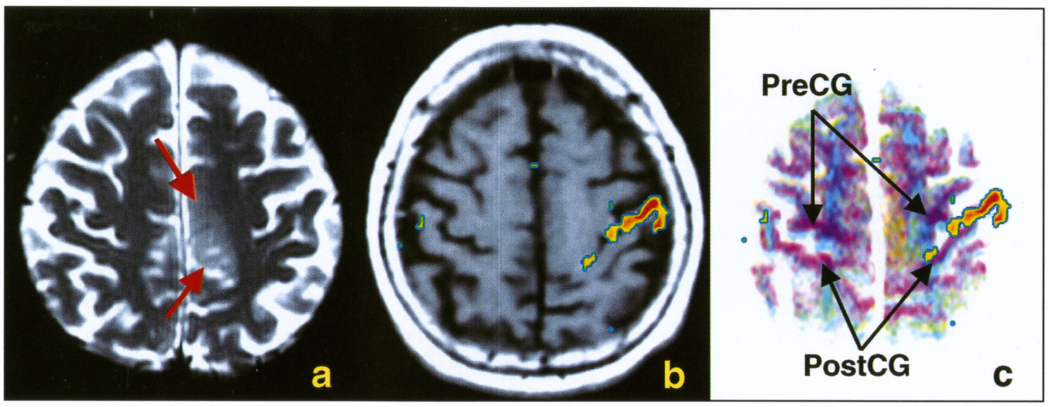

Fig. 4. A 56-year-old female with left frontal astrocytoma.
a. T2WI demonstrates tumor located in the left paracentral lobule (arrows). **b.** fMRI demonstrates activated pixels in the central sulcus. **c.** fMRI superimposed on 3DAC. White matters of the pre-and postcentral gyri are shown in purple color. PreCG: precentral gyrus, PostCG: post central gyrus.

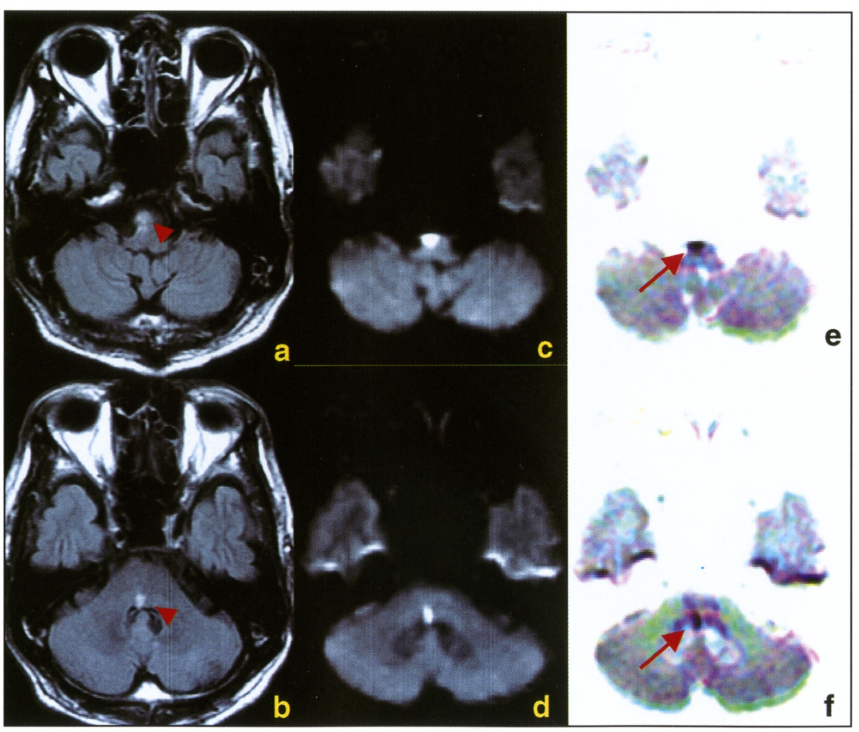

Fig. 5. A 65-year-old male with acute brain stem infarction, manifesting as left hemiparesis and MLF syndrome.
a, b. FLAIR images 5 days after ictus demonstrate high signal intensities in the medulla and the pons (arrowheads). **c, d.** Isotropic DWI. **e, f.** 3DAC MRX demonstrates the dense mixture of the three colors in right ventral aspect of the medulla and dorsal aspect of the pons (arrows).

3DAC MRX - fMRI correlation (Table 1)

fMRI demonstrated task activation of sensorimotor cortex in all 7 patients. The precentral and postcentral gyri were fully visible on 3DAC MRX in 5 of the 7 patients and equivocally in the remaining 2 (Fig. 3, 4). In these 2 patients, MR images showed a deformity of the precentral or post central gyrus caused by tumor. The activated pixels of fMRI superimposed on 3DAC MRX were found to lie between blue (or purple) vertical directional colors of white matter in pre-and postcentral gyrus.

Table 1. Result of functional MRI combined with 3DAC MR axonography

case #	age/ gender	diagnosis	location	fMRI		3DAC	
				right	left	right	left
1	67M	cerebral infarction	rt & lt. parietal	fair	good	good	good
2	49M	cerebral infarction	rt. parietal	fair	good	good	good
3	78M	cerebral infarction	lt. frontal	good	good	good	good
4	85M	glioblastoma	rt. parietal	good	n.d.	fair	n.d.
5	44M	meningioma	rt. frontal	fair	n.d.	fair	good
6	56F	astrocytoma	lt. frontal	n.d.	good	n.d.	good
7	64M	astrocytoma	rt. parietal	good	n.d.	good	n.d.

rt; right, lt; left, n.d.; not done

Discussion

The utility of DWI for the diagnosis of acute cerebral infarction has now been thoroughly established[4, 5]. Recently, investigators have used the diffusion anisotropy characteristics of white matter to study normal myelination patterns and pathological conditions that alter microstructure such as axonal integrity[5-7]. Nakada et al recently introduced a new algorithm for the preparation of apparent diffusion tensor, 3DAC MR imaging[8, 9]. The images produced are color pictures allowing the unprecedented opportunity for visualizing axonal direction.

Inoue et al[10] represented the entire pyramidal tract from the primary motor subcortex to the ventral brain stem with oblique coronal 3DAC MRX. Although 3DAC MRX in our present study was made with a oblique axial images, which could not differentiate the exact location of pyramidal tract from the thalamocortical fibers or other nerve fibers running along the pyramidal tract, fine anatomical fiber directions were visible and displacement of these fiber tract was easily recognised in cases of brain tumor. Using 3DAC MRX, acute infarction with low ADC areas appeared dark color and was more conspicuous in evaluating these fiber tract involvement compared to isotropic DWI.

We used echo-planar imaging (EPI) sequence for 3DAC MRX which differs from previous reports using spin-echo sequence[9, 11]. There are the advantages that 3DAC MRX using EPI sequence is less sensitive to phase error due to patient's motion and takes shorter scan time. However, there are the disadvantages that EPI sequence is more sensitive to inhomogeneity of magnetic field which induces geometrical distortion of the images, and shows lesser spatial resolution compared to spin-echo based 3DAC MRX[10]. In our study, 3DAC MRX demonstrated incomplete mixture in the periphery of the image, but the appearance of the pyramidal tract involvement had good correlation with impairment of motor function.

In tumors or arteriovenous malformations of central and precentral regions of the brain, it is important to localize the areas important for function before open surgery or minimal invasive therapy to prevent damage of functionally active tissue and persistent neurological deficits[1-3]. Functional MRI has been used extensively to evaluate hemodynamic changes in the human cortex during physiological activation including motor, somatosensory, visual, and language tasks. But during neurosurgical interventions, preservation of subcortical axons is as important as that of cortical neurons. We therefore evaluated the combination of 3DAC MRX and fMRI to detect cortical motor areas with their corresponding pyramidal tracts.

In our study, the precentral and postcentral gyri were fully visible with blue vertical directional colors of white matter on 3DAC MRX in 5 of the 7 patients. And furthermore, our results represented a good spatial relationship in cortical mapping of primary sensorimotor cortex between 3DAC MRX and fMRI. In the remaining 2 patients, 3DAC MRX failed to demonstrate the pre- and postcentral gyri. We presumed a deformity of the precentral or postcentral gyrus induced by tumor infiltration or perifocal edema may decrease an anisotropy of the nerve fiber. Functional MRI has same problem in pathological condition such as brain edema

which may cause reduction of signal intensity change in fMRI because of the relative paucity of blood flow and lower metabolic demand[12]. In our clinical setting of fMRI, localization of sensorimotor cortex can obtained in all 7 patients, and we believe that combination of 3DAC MRX and fMRI is useful in identifying a primary motor cortex and a pyramidal tract and can provide indications for determining surgical strategy.

In conclusion, 3DAC MRX is a new effective approach for visualization of apparent diffusion tensor using the three primary colors and provides high contrast resolution of full color spectrum compared to gray scale isotropic DWI. 3DAC MRX can visualize anatomical details of fiber tracts and provide the information of disease process affecting specific neural fibers such as pyramidal tract.

Acknowledgement

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