Biexponential Signal Attenuation Analysis of Diffusion-weighted Imaging of Breast

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Purpose: *In vivo*, the attenuation of diffusion-weighted imaging (DWI) signal at high b-values is sometimes nonlinear when plotted with semilogarithmic function and is fit well by a biexponential function. Previous reports have indicated that the fast and slow component fractions of the apparent diffusion coefficient (ADC) can be derived by biexponential fitting and that these fractions correspond to the actual diffusion components in the extra- and intracellular space. In this study, we investigated the clinical utility of DWI for the breast by performing DWI using multiple b-factors on healthy volunteers and clinical subjects, analyzing the signal by fitting it with a biexponential equation, and comparing the fitting parameters of breast lesions.

Patients and Methods: We investigated 8 healthy women as normal cases and 80 female patients with a total of 100 breast tumors (42 benign, 58 malignant tumors) as clinical cases. We performed DWI using 12 b-values for the healthy cases and 6 b-values for the clinical cases, up to a maximum b-value of 3500 s/mm².

Results: Decay of DWI signal of normal mammary glands, most cysts, and some fibroadenomas showed a monoeponential relationship, and conversely, that of intraductal papilloma (IDP) and malignant tumors was well fitted by a biexponential function. Comparison of parameters derived from biexponential fitting demonstrated no significant difference between benign and malignant lesions. For malignant tumor subtype, the fast component fraction of noninvasive ductal carcinoma was statistically greater than that of invasive ductal carcinoma.

Conclusions: Although the parameters from biexponential fitting may reflect the character of tumor cellularity, because pathological diagnosis was performed with an emphasis on cell configuration or shape rather than cellularity, it was difficult to distinguish malignant from benign tumors, including many IDPs, or to distinguish tissue types using DWI signal attenuation alone.

Keywords: apparent diffusion coefficient, biexponential signal attenuation, breast magnetic resonance imaging, component fraction, diffusion-weighted imaging

Introduction

Diffusion-weighted magnetic resonance imaging (DWI) was first applied clinically to examine the brain and has recently demonstrated some clinical value in examination in the body.1,2 DWI has been used to detect malignancies in the body because it has been shown that the diffusion of water molecules in malignant tumors is slower than that of the...
normal parenchyma. The breast is a popular target for DWI, and many reports demonstrate its clinical utility for breast tumors. In a meta-analysis of DWI of breast tumors performed with 1.5-tesla MR imaging, Tsushima and associates reported sensitivity of 0.89 and specificity of 0.77, comparable to results of meta-analysis of contrast-enhanced breast MR imaging. Furthermore, several studies have reported that the apparent diffusion coefficient (ADC) is useful in distinguishing malignant and benign breast tumors, but the threshold value of ADC for such discrimination can range from 1.1 to 1.6×10⁻³ mm²/s and is affected by maximum b-value.

In typical DWI using spin-echo-type echo-planar imaging (EPI) technique, 2 bipolar gradient magnetic fields are applied across the π pulse for sensitizing diffusion of water molecules. Signal attenuation from diffusion follows Equation [1], $S_b/S_0 = \exp (-bD_1) \exp (-bD_2)$ [1], in which $S_0$ represents the absence of diffusion-sensitizing gradients and $S_b$, their presence, $b$ is the b-value, and $D$ is the ADC. From this, we can obtain the ADC by plotting signal attenuation with the b-value as a semilogarithmic function. However, the application of Equation [1] for measuring diffusion in vivo is problematic. The microscopic tissue of a voxel comprises many cells and surrounding structures that create a heterogeneous environment in which water molecules diffuse, and their ability to diffuse varies locally with this heterogeneity. Consequently, the signal attenuation sometimes differs from a linear relationship when plotted semilogarithmically, thus it is difficult to calculate the ADC, appropriately.

Kärger and colleagues proved that the nonlinear signal attenuation of a microconglomerate of magnetization can be represented in 2 components (fast and slow) by superposition, and they arrived at an expansion with the biexponential equation: $S_b/S_0 = f_1 \exp (-bD_1) + f_2 \exp (-bD_2)$ [2], in which $f_1$ is the fraction of the fast component and $f_2$, the fraction of the slow component and $D_1$, is the ADC of the fast component and $D_2$, the ADC of the slow component. Using Equation [2], Niendorf’s team analyzed attenuation of signal in DWI in ischemic rat brain and observed relative changes in $f_1$, $f_2$, and cell swelling, suggesting that it is feasible to model the extra- and intracellular fraction as 2 components. However, the estimated ratios of $f_1/f_2 (9:1 \sim 7:3)$ are clearly different from the actual component fractions (1:9 \sim 3:7) determined with other physical methods. After Niendorf’s findings, many researchers have investigated this discrepancy and indicated influence from permeability or restriction of cell membrane and difference of relaxation time of intra- and extracellular space as well as other factors. However, the detailed cause of biexponential signal attenuation remains unclear.

Recently, the parameters $f_1$, $f_2$ and $D_1$, $D_2$ have been used to characterize tissue properties in a clinical context, and the parameters derived from the biexponential fitting of signal decay in DWI in human brain have been reported to be different in ischemia, edema, and tumor and after radiation. Biexponential signal attenuation in the prostate has also been reported, and the feasibility of employing this model for clinical use has been suggested.

In this study, we investigated the clinical utility of DWI for breast evaluation by performing DWI using multiple b-factors on healthy volunteers and clinical subjects, analyzing the signal by fitting it with a biexponential equation, and comparing the fitting parameters of normal tissue, benign and malignant lesions, and various disease subtypes.

**Materials and Methods**

**Subjects**

We performed DWI imaging of 8 healthy female volunteers (aged 39 to 60 years, mean age, 49 years) with normal breast tissue and 80 female clinical subjects (aged 15 to 84 years, mean age, 58 years) with a total of 100 breast tumors. There were 42 benign lesions (mean size 1.83 ± 1.64 cm) in 37 patients, including 5 fibroadenomas (FA), 7 intraductal papillomas (IDP), one complex sclerosing lesion, 17 simple cysts, and 12 condensed cysts (conc. cyst). Fifty-eight malignant lesions (mean size 2.29 ± 1.38 cm) were categorized by general rules for clinical and pathological recording of breast cancer by the Japanese Breast Cancer Society and included 9 noninvasive ductal carcinomas (NIDC), 6 papillotubular carcinomas (pap-tub), 11 solid tubular carcinomas (sol-tub), 24 scirrhous carcinomas (sci), 4 invasive lobular carcinomas, 2 invasive micro papillary carcinomas, one mucinous carcinoma, and one medullary carcinoma. Final diagnosis was established on the basis of results of histopathological examination of surgically excised specimens in 55 lesions (53 malignant lesions, one FA, one complex sclerosing lesion); needle biopsy specimens in 26 lesions (5 malignant, 21 benign); and breast ultrasonography and contrast-enhanced dynamic MR imaging in 19 cysts. All diagnostic evaluations except the MR imagings were performed at the Hiroshima University Hospital. The study was approved by our center’s institutional review board, and all patients and volunteers gave informed consent.
MR imaging

All MR imaging was performed with a 1.5T superconducting magnet (Gyrosan Achieva 2.6; Philips Medical Systems, Best, The Netherlands) using a 7-channel SENSE breast coil. In prone position, patients underwent diffusion-weighted axial imaging using spin-echo-type single-shot EPI technique. We used the tetrahedral diffusion gradient technique\(^3\) to suppress prolongation of echo time (TE)\(^3\) and obtain 4 image series, from which isotropic diffusion-weighted images were generated. The 12 diffusion b-values for healthy volunteers and six for clinical subjects ranged from 0 to a maximum of 3500 $s/mm^2$ with an interval of 318 $s/mm^2$ for volunteers and 700 $s/mm^2$ for clinical subjects. Diffusion gradient duration ($\delta$) was 37 ms with an interval ($\Delta$) of 48.5 ms; both were fixed at every b-value, with only the diffusion-sensitizing gradient strength ($G$) changed with each change of b-value. Thus, diffusion duration ($\Delta - \delta/3$) was constant at 36 ms. The EPI sequence incorporated spectral spatial-selective inversion recovery (SPAIR) radio-frequency (RF) pulses to provide effective fat suppression. The k-space order was sequential, and other parameters used for the DWI sequence were: repetition time (TR), 5600 ms; TE, 99 ms; matrix, $128 \times 114$ (256 reconstruction); field of view (FOV), 280 mm; thickness, 4 mm; interslice gap, 0.4 mm; half scan factor, 0.6; SENSE factor, 2.0; and number of excitations (NEX), 3. Scan times were 11 min 21 s for the 12 b-values used for volunteers and 4 min 40 s for the 6 b-values used for clinical subjects.

Signal analysis

We displayed and analyzed DWI images using “ImageJ” freely available DICOM viewer software (http://rsbweb.nih.gov/ij/). We placed a region of interest (ROI) in a target lesion and in normal breast on DWI, and to verify lesion positions, we compared DWI with a fat-saturated T$_2$-weighted fast spin-echo image and with contrast-enhanced 3D-dynamic turbo field-echo images acquired after DWI in the same orientation. In tumors, ROIs were smaller than the mass size and excluded the area of normal tissue; in normal tissue, ROIs were 10 pixels in diameter. In every b-value image, we checked for misregistration from patient motion and excluded those cases with excessive motion from further analysis.

We plotted the DWI signal using in-house software developed in a commercial analysis package (Matlab v.7.8, MathWorks Inc., Natick, MA, USA) and fitted to data using the Levenberg-Marquardt algorithm\(^3\) as follows: $S_b/S_0 = f_1 \exp(-bD_1) + (1-f_1) \exp(-bD_2) + BG$ [3]. Equation [3] is a slight modification of Equation [2], altering $f_2 = 1-f_1$ and adding background (BG). When high b-values are applied, the BG term is important because the DWI signals are reduced to a noise level. We compared the variables ($f_1$, $D_1$, $D_2$) obtained for the breast tissues with each other using Wilcoxon-Mann-Whitney test in a commercial program (KaleidaGraph v.4.0, Synergy Software, Reading, PA, USA). $P<0.05$ was considered significant.

In this study, FA, IDP, and complex sclerosing lesions were classified as benign. Cysts were not included in this grouping but categorized separately as either simple or condensed.

Results

Figure 1 shows the DWI signal attenuations of normal mammary glands of volunteers and cysts of clinical subjects. All normal mammary glands could be best fitted by a monoexponential function ($f_1$ was fixed at 1.0, $D_1 = 2.67 \pm 0.11 \times 10^{-3} \text{ mm}^2/\text{s}$), and the signal declined until it reached the background noise level at b-values over 1000 $\text{mm}^2/\text{s}$ (Fig. 1a). Most simple cysts were fitted by a monoexponential function ($f_1 = 0.95 \pm 0.03$, $D_1 = 2.54 \pm 0.71 \times 10^{-3} \text{ mm}^2/\text{s}$), though final attenuation levels and b-values varied (Figs. 1b, 2). The signal of condensed cysts gradually declined until the highest b-value (Figs. 1c, 2), where the fast component fraction was estimated to be minor ($f_1 = 0.36 \pm 0.23$, $D_1 = 1.96 \pm 0.59 \times 10^{-3} \text{ mm}^2/\text{s}$).

Most benign tumors were well fitted by a biexponential function ($f_1 = 0.93$, $D_1 = 2.25 \times 10^{-3} \text{ mm}^2/\text{s}$) than those of the other three ($f_1 = 0.70$, $D_1 = 1.85 \times 10^{-3} \text{ mm}^2/\text{s}$); thus, the signal decay was similar to that of a monoexponential function (Fig. 3a). Consequently, the average of each parameter of FA was $f_1 = 0.79 \pm 0.14$, $D_1 = 2.01 \pm 0.68 \times 10^{-3} \text{ mm}^2/\text{s}$, and $D_2 = 0.10 \pm 0.10 \times 10^{-3} \text{ mm}^2/\text{s}$ (Fig. 3a). The fast component fraction of IDP ($f_1 = 0.66 \pm 0.13$, $D_1 = 2.27 \pm 0.36 \times 10^{-3} \text{ mm}^2/\text{s}$) was slightly smaller than the averaged value of FA (Figs. 3b, 4).

All malignant tumors showed biexponential signal attenuation (Figs. 5, 6). Comparing the shape of the curves of the common carcinoma types (NIDC, pap-tub, sol-tub, and sci), it was impossible to find a characteristic difference for each tumor subtype. The averaged ADC value of the fast components ($D_1 = 2.10 \pm 0.68 \times 10^{-3} \text{ mm}^2/\text{s}$) of all malignant tumors was nearly equal to that of the benign tumors ($D_1 = 2.12 \pm 0.38 \times 10^{-3} \text{ mm}^2/\text{s}$), but the fast component fraction was slightly different.
Fig. 1. Diffusion-weighted imaging (DWI) signal attenuation of (a) normal mammary glands, (b) simple cysts, and (c) condensed cysts.

\((f_1 = 0.72\) for the malignant and \(0.67\) for the benign). Among special-type carcinomas, a mucinous carcinoma showed the greatest fast component fraction \((f_1 = 0.94, D_1 = 2.23 \times 10^{-3}\, \text{mm}^2/\text{s})\).

The table summarizes the estimated parameters for normal tissue, cysts, benign tumors, and malignant tumors, including their subtypes.

Subsequently, we performed a meta-analysis of these data. Figure 7 shows the comparison with the parameters of simple cysts, condensed cysts, benign tumors, and malignant tumors. All \(D_1\) of these tumors had statistically significantly lower values than that of normal tissue. The fast component fraction of simple cysts was significantly greater \((f_1 = 0.95 \pm 0.03)\) than that of condensed cysts and tumors \((P < 0.0001)\) (Fig. 7a), and the \(D_2\) of simple cysts was significantly lower \((0.02 \pm 0.03 \times 10^{-3}\, \text{mm}^2/\text{s})\) than that of the other lesions \((P < 0.0001)\) (Fig. 7c). The \(f_1\) of condensed cysts \((0.36 \pm 0.23)\) was statistically smaller than that of the other lesions \((P < 0.0003)\) (Fig. 7a). Conversely, there were no significant differences for any parameter between benign and malignant tumors.

In comparing the parameters among the subtypes of benign tumors (FA and IDP), only the \(D_2\) value was statistically significant \((P < 0.05)\) (Fig. 8). In malignant tumors, comparison of the parameters of NIDC and IDC showed that only the \(f_1\) value of NIDC was significantly greater than that of IDC \((P = 0.016)\) (Fig. 9). There was no significant difference in any of the parameters among the common types of IDC (pap-tub, sol-tub, and sci), but when they were compared with parameters of NIDC, the \(f_1\) of NIDC was significantly greater than that of sol-tub or sci \((P < 0.05)\) (Fig. 10).

**Discussion**

In previous studies of DWI for breast tumors, ADCs were calculated by monoexponential analysis of signal decay by Equation [1] up to a b-value of 1500 s/mm², and an inverse correlation between
Fig. 2. A 41-year-old woman with simple cyst and condensed cyst
A–G: Diffusion-weighted images with b-values of 0 (A); 700 (B); 1400 (C); 2100 (D); 2800 (E); and 3500 (F) s/mm² and illustrated position of region of interest (ROI) (G). H: Signal attenuation of simple cyst (ROI1) and condensed cyst (ROI2). The signal of the simple cyst declined until it reached the background noise level and was well fitted by the monoexponential function, and that of the condensed cyst, which consists mostly of the slow component, declined gradually.

Fig. 3. Diffusion-weighted imaging (DWI) signal attenuation of (a) fibroadenoma (FA), complex sclerosing lesion, and (b) IDP.
A 40-year-old woman with intraductal papilloma of the left breast. 

**Fig. 4.** A 40-year-old woman with intraductal papilloma of the left breast. 

**A–G:** Diffusion-weighted images (DWI) with b-value of 0 (A); 700 (B); 1400 (C); 2100 (D); 2800 (E); and 3500 (F) s/mm² and illustrated position of region of interest (ROI) (G). 

**H:** Axial 3-dimensional (3D) contrast-enhanced fat-suppressed magnetic resonance (MR) image (repetition time [TR]/echo time [TE]/flip angle [FA], 7.6/3.8/12) at 90 seconds after contrast administration shows enhancing mass. 

**I:** DWI signal of intraductal papilloma indicated biexponential attenuation, and derived parameters were fraction of the fast component ($f_1$) = 0.80; apparent diffusion coefficient (ADC) value of the fast component ($D_1$) = $2.25 \times 10^{-3}$ mm²/s; and ADC value of the slow component ($D_2$) = $0.32 \times 10^{-3}$ mm²/s.

The decrease in ADC mainly results from increased cellularity, but some tumors show other changes, such as fluid viscosity and cell permeability, as well.

In this respect, biexponential signal analysis will provide more precise information about tissue character.

Thus, we performed DWI with high b-values up to 3500 s/mm² and examined the character of biexponential signal attenuation using Equation [3], in which fast and slow components are postulated. More data at various b-values are required to estimate the parameters more accurately, but limited examination time permitted application of only 6 b-values in clinical subjects. The 3 parameters ($f_1$, $D_1$, $D_2$) obtained were used for statistical discrimination among normal tissue, cysts, and tumor organization types.

Attenuation of DWI signal in the mammary gland of healthy volunteers was monoexponential and had no detectable slow component (Fig. 1a). In the light of histopathology, it is unlikely that normal mammary gland has no cell component, so we speculate that a threshold is required to detect the slow component. The ADC value ($D_1$) = $2.67 \pm 0.11 \times 10^{-3}$ mm²/s was higher than those reported (1.51 to $2.09 \times 10^{-3}$ mm²/s), which were calculated from data using b-values up to 1000 s/mm². If we calculated ADC from the data of $b = 0$, 636 s/mm² or $b = 0$, 954 s/mm² with monoexponential...
Equation [1], the mean ADC ($2.03 \pm 0.25 \times 10^{-3}$ mm$^2$/s or $1.83 \pm 0.02 \times 10^{-3}$ mm$^2$/s) agrees well with the reported value. Generally, ADC calculated from the data of 2 b-values is estimated to be lower when using a higher b-value because the signal at a high b-value approaches the noise level. In the present study, we can estimate a higher ADC value because we consider the background term ($BG$) in Equation [3].

Signal attenuation of simple cysts was almost monoexponential by the predominance of a fast component ($f_1 = 0.95 \pm 0.03, D_1 = 2.54 \pm 0.71 \times 10^{-3}$ mm$^2$/s), but that of condensed cysts was analyzed to have a greater fraction of slow component ($f_2 = 1 - f_1 = 0.64$) (Figs. 1b, 1c, 2, 7). This result indicates that simple cysts consist mainly of a fluidic component, and condensed cysts consist of a viscous high-protein component, as expected from their pathological features. The greater $f_1$ and lower $D_2$ are characteristic of simple cysts, and the smaller $f_1$ is characteristic of condensed cysts.

There was no significant difference in any parameter between benign and malignant tumors (Fig. 7), though previous reports have indicated significantly different ADC between benign and malignant tumors as calculated by monoexponential analysis. In this study, lesions categorized benign included many IDPs (7/13), which have similar ADCs to those of malignant tumors. We supposed this to be the main reason for the weak difference in each parameter between benign and malignant tumors.

In comparing the subtypes of benign tumors (FA and IDP), FA tended to have a greater fast component ($f_1 = 0.79 \pm 0.14$) and lower ADC ($D_1 = 2.01 \pm 0.34 \times 10^{-3}$ mm$^2$/s, $D_2 = 0.10 \pm 0.10 \times 10^{-3}$ mm$^2$/s) than those of IDP ($f_1 = 0.66 \pm 0.13, D_1 = 2.12 \pm 0.73 \times 10^{-3}, D_2 = 0.28 \pm 0.77 \times 10^{-3}$ mm$^2$/s), though the difference was not statistically significant, except for $D_2$ (Fig. 8). This tendency may represent...
Fig. 6. A 71-year-old woman with scirrhous carcinoma of the left breast
A–G: Diffusion-weighted images (DWI) with b-value of 0 (A); 700 (B); 1400 (C); 2100 (D); 2800 (E); and 3500 (F) s/mm² and illustrated position of region of interest (ROI) (G). H: Axial 3-dimensional (3D) contrast-enhanced fat-suppressed magnetic resonance (MR) image (repetition time [TR]/echo time [TE]/flip angle [FA], 7.6/3.8/12) at 90 seconds after contrast administration shows enhancing mass. I: DWI signal attenuation of scirrhous carcinoma fitted the biexponential function and the derived parameters were a fraction of the fast component ($f_1$) = 0.83; apparent diffusion coefficient (ADC) value of the fast component ($D_1$) = $2.09 \times 10^{-3}$ mm²/s; and ADC value of the slow component ($D_2$) = $0.29 \times 10^{-3}$ mm²/s.

an increase of collagen fibers in FA rather than an increase of cellular components. IDPs are benign tumors that are difficult to distinguish from malignant tumors in routine MRI. Our results also showed that IDPs exhibit biexponential decay similar to that of malignant tumors (Figs. 3b, 4) that was difficult to distinguish by DWI biexponential analysis only. Tozaki and associates reported that the mean ADC value of IDP, which is a proliferative benign lesion, was the same as that of mass-forming NIDC, which agrees with our results. This finding may be explained by the possible similarity of tumor cellularity of IDP and malignant tumors and that DWI signal attenuation is more affected by tumor cellularity regardless of histological benignity or malignancy.

The DWI signal attenuations of all malignant tumors were biexponential (Fig. 5). When comparing the fitting parameters of NIDC and IDC, the $f_1$ of NIDC was significantly greater than that of IDC ($P = 0.016$), and there was no significant difference in the ADCs ($D_1, D_2$) (Fig. 9). Previous reports suggested that the ADC values calculated by monoexponential analysis were statistically significantly higher in NIDC than IDC. Thus, we calculated the ADCs by 2-point method ($b = 0, 700$ s/...
Table. Each derived parameter of breast tumors by biexponential signal analysis of diffusion-weighted imaging

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>$f_1$</th>
<th>$D_1$</th>
<th>$D_2$</th>
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<tbody>
<tr>
<td>Normal</td>
<td>16</td>
<td>1.00</td>
<td>2.67 ± 0.11</td>
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<td>Simple cyst</td>
<td>17</td>
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<td>2.54 ± 0.71</td>
<td>0.02 ± 0.03</td>
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<td>Benign</td>
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<td>0.79 ± 0.14</td>
<td>2.01 ± 0.34</td>
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<tr>
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<td>0.09</td>
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<td>Malignant tumor</td>
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$f_1$: fraction of the fast component; $D_1$, $D_2$: apparent diffusion coefficient (ADC) of the fast or slow component ($\times 10^{-3}$ mm$^2$/s); IDC: invasive ductal carcinoma; IDP: intraductal papilloma; NIDC: noninvasive ductal carcinoma; pap-tub: papillotubular carcinoma; sci: scirrhous carcinoma; sol-tub: solid-tubular carcinoma.

Fig. 7. Comparisons of each derived parameter by diffusion-weighted imaging (DWI) biexponential signal analysis of cysts and benign and malignant tumors of the breast. (a) $f_1$: fraction of the fast component; (b) $D_1$: apparent diffusion coefficient (ADC) value of the fast component; (c) $D_2$: ADC value of the slow component; Con. cyst: condensed cyst.
Fig. 8. Comparisons of each derived parameter by diffusion-weighted imaging (DWI) biexponential signal analysis of fibroadenoma (FA) and intraductal papilloma (IDP). (a) $f_1$: fraction of the fast component; (b) $D_1$: apparent diffusion coefficient (ADC) value of the fast component; and (c) $D_2$: ADC value of the slow component.

Fig. 9. Comparisons of each derived parameter by diffusion-weighted imaging (DWI) biexponential signal analysis of benign, noninvasive ductal carcinoma (NIDC) and invasive ductal carcinoma (IDC). (a) $f_1$: fraction of the fast component; (b) $D_1$: apparent diffusion coefficient (ADC) value of the fast component; and (c) $D_2$: ADC value of the slow component.
Fig. 10. Comparisons of each derived parameter by diffusion-weighted imaging (DWI) biexponential signal analysis of malignant tumor subtype (common type). (a) $f_1$: fraction of the fast component; (b) $D_1$: apparent diffusion coefficient (ADC) value of the fast component; and (c) $D_2$: ADC value of the slow component; NIDC: noninvasive ductal carcinoma; pap-tub: papillotubular carcinoma; sci: scirrhous carcinoma; and sol-tub: solid-tubular carcinoma.

From the results of our biexponential analysis of breast DWI, we found that a smaller fast component fraction ($f_1$), which corresponds to a lower conventional ADC, will result from higher cellularity of tumor tissues. As well, although some lesions can be distinguished by the $f_1$, clear discrimination of malignant from benign tumors is difficult. Similar to the $f_1$, $D_1$ and $D_2$ directly affect the conventional ADC, but the cause of the difference between $D_1$ and $D_2$ remains unclear.

Our previous phantom experiments on biexponential DWI signal attenuation showed that the ADC of the fast component ($D_1$) can be calculated correctly, though that of the slow component is calculated lower. Furthermore, the calculated component fraction is reliable when the initial signal intensities ($S_0$) of fast and slow components are approximately equal. Consequently, one should note that the parameters estimated by biexponential signal analysis do not always represent the actual condition of tissues.

Future studies may help determine how to correct the fast and slow component fractions calculated by biexponential analysis in vivo and elucidate the influence of perfusion, membrane permeability,
Conclusions

We performed biexponential analysis of signal attenuation of normal mammary gland tissue and breast tumors in DWI and found monoexponential signal decay in all normal tissue, most cysts, and some FAs and, conversely, biexponential attenuation in all IDPs and malignant tumors. The parameters ($f_1, D_1, D_2$) derived from biexponential fitting may reflect the character of the underlying tumor cellularity, but their use is still limited in distinguishing malignant tumors from IDPs and determining tumor types because pathological diagnosis emphasizes cell configuration or shape rather than cellularity.

References


