Differentiating Tumor Progression from Pseudoprogression in Patients with Glioblastomas Using Diffusion Tensor Imaging and Dynamic Susceptibility Contrast MRI


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ABSTRACT

BACKGROUND AND PURPOSE: Early assessment of treatment response is critical in patients with glioblastomas. A combination of DTI and DSC perfusion imaging parameters was evaluated to distinguish glioblastomas with true progression from mixed response and pseudoprogression.

MATERIALS AND METHODS: Forty-one patients with glioblastomas exhibiting enhancing lesions within 6 months after completion of chemoradiation therapy were retrospectively studied. All patients underwent surgery after MR imaging and were histologically classified as having true progression (>75% tumor), mixed response (25%–75% tumor), or pseudoprogression (<25% tumor). Mean diffusivity, fractional anisotropy, linear anisotropy coefficient, planar anisotropy coefficient, spheric anisotropy coefficient, and maximum relative cerebral blood volume values were measured from the enhancing tissue. A multivariate logistic regression analysis was used to determine the best model for classification of true progression from mixed response or pseudoprogression.

RESULTS: Significantly elevated maximum relative cerebral blood volume, fractional anisotropy, linear anisotropy coefficient, and planar anisotropy coefficient and decreased spheric anisotropy coefficient were observed in true progression compared with pseudoprogression (P < .05). There were also significant differences in maximum relative cerebral blood volume, fractional anisotropy, planar anisotropy coefficient, and spheric anisotropy coefficient measurements between mixed response and true progression groups. The best model to distinguish true progression from non–true progression (pseudoprogression and mixed) consisted of fractional anisotropy, linear anisotropy coefficient, and maximum relative cerebral blood volume, resulting in an area under the curve of 0.905. This model also differentiated true progression from mixed response with an area under the curve of 0.901. A combination of fractional anisotropy and maximum relative cerebral blood volume differentiated pseudoprogression from nonpseudoprogression (true progression and mixed) with an area under the curve of 0.807.

CONCLUSIONS: DTI and DSC perfusion imaging can improve accuracy in assessing treatment response and may aid in individualized treatment of patients with glioblastomas.

ABBREVIATIONS: AUC = area under the curve; CL = linear anisotropy coefficient; CP = planar anisotropy coefficient; CS = spheric anisotropy coefficient; FA = fractional anisotropy; LRM = logistic regression model; max = maximum; MD = mean diffusivity; PsP = pseudoprogression; rCBV = relative cerebral blood volume; TP = true progression
tion of PsP and TP is critical because patients with TP may require a change in therapeutic strategy while those with PsP may not. While published reports have attempted to differentiate PsP from TP, these studies did not account for the common finding of a mixture of treatment-related changes and recurrent tumor. Management of these partial responders may be challenging, with short-interval imaging studies often required to determine clinical course. If identified early, these patients may benefit from novel therapeutics.

Mean diffusivity (MD), measured from diffusion imaging, has been used to diagnose and monitor treatment response in brain tumors. Both mean and minimum MD values have been used in differentiating PsP from TP. However, due to the heterogeneity of treatment response, MD may have a limited role because reduced diffusion could represent not only highly cellular tumor areas but also inflammatory processes. DTI is increasingly being used in the characterization of glioblastomas; anisotropy measures, including fractional anisotropy (FA), linear anisotropy (CL), planar anisotropy (CP), and spheric anisotropy (CS), have been used to differentiate glioblastomas from metastasis and primary cerebral lymphomas. However, only 1 study has used DTI for differentiation of PsP and TP.

Relative cerebral blood volume (rCBV) obtained from DSC perfusion imaging has been widely used for tumor grading, distinguishing recurrent tumor from radiation necrosis, and differentiating PsP from TP. Some studies have suggested that median rCBV and histogram analysis of rCBV can help differentiate PsP from TP. However, rCBV has not been used to identify a mixed or partial response.

The clinical management of patients with recurrent glioblastoma is rapidly changing because several alternative therapeutic options are being investigated, including bevacizumab, tumor treating fields, and immunotherapy. Increased incidence of PsP poses a dilemma for the treating physicians because determining the optimal therapeutic approach relies on a definitive diagnosis of TP, PsP, or mixed response. We hypothesize that DTI and DSC parameters have added value in making this differentiation and thus evaluated them for differentiating these 3 categories of treatment response.

MATERIALS AND METHODS

Patients

This study was approved by the institutional review board and was compliant with the Health Insurance Portability and Accountability Act. MR imaging data from 41 patients with glioblastomas (14 women/27 men; 55.71 ± 11.83 years of age; age range, 23–80 years), who had initially undergone gross total resection of the tumor followed by standard radiation therapy and temozolomide chemotherapy and exhibited new enhancing lesions on follow-up MR imaging within 6 months after completion of radiation therapy, were retrieved from the University of Pennsylvania database base from May 2011 to May 2014 and retrospectively analyzed. All patients underwent repeat surgery within 2 weeks after the MR imaging study in which the new enhancing lesions were first observed.

MR Imaging Data Acquisition

MR imaging studies were performed on a Tim Trio 3T whole-body scanner (Siemens, Erlangen, Germany) by using a 12-channel phased array head coil. Routine sequences included axial T1-weighted 3D MPRAGE (TR/TE/TI = 1760/3.1/950 ms, 192 × 256 matrix size, 1-mm section thickness) and axial FLAIR (TR/TE/TI = 9420/141/2500 ms, 3-mm section thickness). DTI data were acquired by using a single-shot spin-echo EPI sequence with parallel imaging by using generalized autocalibrating partially parallel acquisition and an acceleration factor of 2. Diffusion weighting was applied in 30 isotropically distributed directions by using a b-value of 1000 s/mm², with a total acquisition time of 8 minutes. For DSC imaging, a bolus of gadobenate dimeglumine (MultiHance; Bracco Diagnostics, Princeton, New Jersey) was injected with a preloading dose of 0.07 mmol/kg, which was used to reduce the effect of contrast agent leakage on CBV measurements. DSC imaging was performed by using a gradient-echo echo-planar imaging sequence during a second 0.07-mmol/kg bolus of contrast agent (TR/TE = 2000/45 ms, FOV = 22 × 22 cm², resolution = 1.72 × 1.72 × 3 mm³, 20 sections, 45 measurements with at least 10 image volumes before bolus arrival, acquisition time = 1 minute 38 seconds). The injection rate was 5 mL/s for all patients and was immediately followed by a bolus injection of saline (total of 20 mL at the same rate). Postcontrast T1-weighted 3D MPRAGE images were acquired after completion of the DSC sequence.

Image Processing

The diffusion tensor datasets were coregistered to the b = 0 s/mm² images by using a 3D affine transformation estimated by maximizing the mutual information between the images. The corrected raw images were combined to estimate the DTI parametric maps by using in-house software (IDL; ITT Visual Information Solutions, Boulder, Colorado). Diffusion tensor images were computed by using the methods described earlier. Leakage-corrected CBV maps using the γ variate function were generated by using NordicICE software (NordicNeuroLab, Bergen, Norway).

The DTI, CBV maps, and FLAIR images were coregistered to contrast-enhanced T1-weighted images. The CBV maps were normalized to the contralateral normal white matter to generate rCBV. A semi-automated segmentation approach was used to generate a mask from the enhancing region by using the methods described earlier. The median DTI metrics and rCBV values from the enhancing region were measured. In addition, the lower 10th percentile MD values were measured from the enhancing region and reported as minimum MD. The top 90th percentile rCBV values were measured from the enhancing region and reported as rCBVmax. Data analysis tools, including DTI computing, image coregistration, and segmentation, were implemented by using IDL routines. The total time for postprocessing was approximately 2 hours.

Histologic Analysis

Pathologic samples were originally cut, mounted, and stained with hematoxylin–eosin by standard methods. Immunohistochemistry for Ki-67 (mouse monoclonal, MIB-1, IR62661; Dako, Carpinteria, California) and p53 (mouse monoclonal, 1:60; DO-7, M7001; Dako) was performed by using a Bond III automated system (Leica Biosystems, Buffalo Grove, Illinois). The entirety of submitted material for each case was examined by a board-certified neuropathologist (M.M.-L.) who was blinded to the results of the MR imaging studies. The slides were examined to determine the relative degree of recurrent glioma and treatment-related changes. The percentage of geo-
graphic tissue necrosis across the specimen was assessed in an initial approach, excluding normal or quasinormal brain parenchyma. Histologic features associated with treatment, including vascular necrosis, hyalinization, hemosiderin, lymphocyte and macrophage infiltrates, gliosis, fibrosis, and dystrophic calcification, were also documented. Tumor-specific characteristics within the specimen, including neoplastic high cellularity, the presence of pseudopalisading necrosis, endothelial cell proliferation, and increased mitotic activity were additionally used to either increase or decrease the weight-age for the presence of overall malignant features. The patients were grouped in 3 categories: 25% malignant features, PsP (8 patients; 3 women/5 men; 48.5 ± 12.72 years of age); 25%–75% malignant features, mixed tumor with treatment response (12 patients; 5 women/7 men; 58.25 ± 7.47 years of age); and >75% malignant features, TP (21 patients; 6 women/15 men; 57.0 ± 12.9 years of age). Strong and diffuse nuclear staining for p53 was used as supportive evidence of the presence of tumor, but the lack of staining did not reject the presence of recurrent glioma. We calculated the proliferative index with Ki-67 for each case as a percentage of positive tumor cells, avoiding areas of inflammatory infiltrates.

**Statistical Analysis**

A Mann-Whitney U test was used to compare the difference in the median MD, FA, CL, CP, CS, and rCBV values and minimum MD and rCBV$_{\text{max}}$ among PsP, mixed, and TP groups. Bonferroni correction was used to adjust for multiple comparisons, and a P value < .05 was considered significant. A multivariate logistic regression model (LRM) was used to determine the best classification model, and a leave-one-out cross-validation approach was applied to estimate the accuracy of the LRM. Areas under the receiver operating characteristic curves (AUCs) were computed by using the selected parameters and the LRM output. A cutoff value for each parameter was determined by maximizing the sum of sensitivity and specificity. All statistical analyses were conducted by using PASW Statistics, Version 18 (IBM, Armonk, New York).

**RESULTS**

Representative MR images and histologic photomicrographs from patients with PsP, mixed, and TP features are shown in Figs 1–3, respectively. MD maps demonstrate variable degrees of diffusivity from the enhancing parts of the tumor. Anisotropy and rCBV maps also show variability. However, quantitative analysis revealed significantly higher median FA, CL, and CP values and higher rCBV in patients with TP compared with PsP and mixed response (Fig 4). A pair-wise comparison of DTI and DSC parameters from enhancing tissue is shown in Fig 4. While median MD values did not show significant differences between groups (P > .05), significantly higher rCBV$_{\text{max}}$ (4.75 versus 2.90, P = .007), FA (0.14 versus 0.11, P = .008), CL (0.05 versus 0.04, P = .04), and CP (0.08 versus 0.06, P = .002), and decreased CS (0.87 versus 0.90, P = .004) were observed in TP compared with PsP. There were also significant differences between mixed and TP groups in rCBV$_{\text{max}}$ (4.75 versus 3.31, P = .02), FA (0.14 versus 0.11, P = .01), CP (0.08 versus 0.06, P = .001), and CS (0.87 versus 0.89, P = .02) measurements. None of the parameters demonstrated a significant difference between PsP and mixed response. Of all the parameters, CP and CS showed a significant difference between PsP

**FIG1.** Axial MR images of a 44-year-old man with PsP. Contrast-enhanced T1-weighted image (A) shows a new enhancing lesion in the left parietal lobe. CBV map (B) shows moderately increased CBV from the lesion. MD (C) looks similar to the normal white matter. Decreased FA (D), CL (E), and CP (F) and increased CS (G) are observed from the enhancing part compared with normal white matter. Photomicrograph of a histologic section (H, hematoxylin-eosin stain, 50 × magnification) reveals most of the tissue with treatment-related changes, including extensive geographic necrosis and vascular fibrinoid necrosis (90%).
FIG 2. Axial images from the brain of a 59-year-old woman with mixed features of response, including areas of treatment-related changes and TP. Contrast-enhanced T1-weighted image (A) shows a new enhancing lesion in the left parietal lobe. The lesion shows slightly elevated perfusion on the CBV map (B) and lower MD (C). Lower FA (D), CL (E), CP (F), and higher CS (G) values from the enhancing part are noticed relative to the normal white matter. The imaging appearance looks similar to that of PsP (Fig 1). Photomicrograph of a histologic section (H, hematoxylin-eosin stain, 50× magnification) has similar amounts of treatment-related changes (50%) and viable tumor (50%).

FIG 3. Axial brain images from a 54-year-old man showing TP. Contrast-enhanced T1-weighted image (A) shows a ring-enhancing lesion in the left parietal lobe. High rCBV (B) and increased MD (C) are observed from the lesion. The enhancing part of the lesion demonstrates decreased FA (D), CL (E), and CP (F) and increased CS (G). Findings in a photomicrograph of a histologic section (H, hematoxylin-eosin stain, 50× magnification) are similar to the patient’s de novo glioblastoma, with areas of high tumor cellularity, pseudopalisading necrosis (asterisks), and endothelial proliferation (arrow) and increased mitotic activity.
and TP, and CP showed a significant difference between mixed and TP after Bonferroni correction ($P < .006$).

**Discrimination of TP versus PsP and Mixed Response**
The discrimination analysis was first performed to distinguish TP from PsP and mixed response. CP was the single best predictor for classification (AUC = 0.78, Table). The imaging parameters were then used for a multivariate logistic regression analysis with backward stepwise selection, which indicated that the best classification of TP from non-TPs, including PsP and mixed response, was achieved with 2 parameters, FA and rCBV$_{max}$, as follows:

$$f(FA, rCBV_{max}) = \frac{1}{1 + \exp\left(-\left(\beta_0 + \beta_1 FA + \beta_2 CL + \beta_3 rCBV_{max}\right)\right)}$$

where $\beta_0 = -3.59$, $\beta_1 = 23.52$, and $\beta_2 = 0.62$. Figure 5B shows the receiver operating characteristic curves for the best LRM and selected parameters. The cutoff value for the LRM was 0.77 with sensitivity = 79%, specificity = 75%, and AUC = 0.807 (Table). Leave-one-out cross-validation analysis revealed that 63.4% of cases were correctly classified by using the LRM.

**Discrimination of PsP versus TP and Mixed Response**
The single best predictor for classification was CP (AUC = 0.74), followed by rCBV$_{max}$ (AUC = 0.73) and FA (AUC = 0.70, Table). The best LRM for classification of PsP from non-PsPs, including TP and mixed response, was achieved with 2 parameters, FA and rCBV$_{max}$, as follows:

$$f(FA, rCBV_{max}) = \frac{1}{1 + \exp\left(-\left(\beta_0 + \beta_1 FA + \beta_2 rCBV_{max}\right)\right)}$$

where $\beta_0 = -16.17$, $\beta_1 = 194.01$, $\beta_2 = -285.65$, and $\beta_3 = 1.21$. Figure 5A shows the receiver operating characteristic curves for the best LRM and selected parameters. The cutoff value for the LRM was 0.55 with a sensitivity = 76%, specificity = 95%, and AUC = 0.905 (Table). Leave-one-out cross-validation analysis revealed that 78% of cases were correctly classified by using the LRM. Although CP was the single best predictor, it was not selected by the statistical model for highest sensitivity. Using forward stepwise selection, the best model included CP and rCBV$_{max}$ resulting in an AUC of 0.89, similar to the model FA, CL, and rCBV$_{max}$. In addition, there was a high correlation ($r = 0.84$) between FA and CP (On-line Figure), suggesting that the results from either model were similar.

**Discrimination between TP and Mixed Response**
A subanalysis was performed to differentiate TP from mixed response so that the patients with mixed response could be closely monitored with short-interval imaging scans or enrolled in novel therapeutic trials. CP was again the single best predictor for classification (AUC = 0.83), followed by FA (AUC = 0.76) and rCBV$_{max}$ (AUC = 0.74, Table). The LRM for classification of TP from mixed response was achieved with 3 parameters, including FA, CL, and rCBV$_{max}$, as follows:

$$f(FA, CL, rCBV_{max}) = \frac{1}{1 + \exp\left(-\left(\beta_0 + \beta_1 FA + \beta_2 CL + \beta_3 rCBV_{max}\right)\right)}$$

FIG 4. Boxplots of diffusion (minimum MD, FA, CL, CP, and CS) and perfusion (maximum rCBV) characteristics for patients with posttreatment glioblastomas in TP (gray), PsP (white), and mixed tumor (dotted). The solid line inside each box represents the median value, while the edges represent the 25th and 75th percentiles. The straight line (bars) on each box indicates the range of data distribution. Circles represent outliers (values >1.5 box length from the 75th/25th percentiles). The asterisk indicates a significant difference ($P < .05$) for group comparison.
of cases were correctly classified by using the LRM. (Table). Leave-one-out cross-validation analysis revealed that 72.7%

overproduced extracellular matrix.11,28 Glioblastoma tumor cells

High FA in glioblastomas is probably related to the orientation of

mixed responses was based on FA, CL, and rCBVmax. Higher an-

surgery or enrollment in alternative clinical trials. The LRM anal-

Identification of TP could prevent further delays in repeat

our proposed analytic approach may aid in individualized treat-

DISCUSSION

The heterogeneity and variability in response did not allow differ-

DSC imaging can be helpful in differentiating tumor recur-

Identification of PsP from Mixed Response

A final analysis to differentiate patients with PsP from those with

Identification of TP

Early identification of TP could prevent further delays in repeat

Identification of Mixed Response

On a practical level, posttreatment new enhancing lesions usually

Sensitivity, specificity, and cutoff values of best models for classification

<table>
<thead>
<tr>
<th>Model</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Cutoff Value</th>
<th>AUC</th>
<th>95% CI</th>
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</thead>
<tbody>
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<td>TP vs PsP + mixed</td>
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<td>0.90</td>
<td>0.07</td>
<td>0.84</td>
<td>0.72–0.96</td>
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<tr>
<td>TP vs mixed</td>
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<td>0.07</td>
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<td>0.59–0.89</td>
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<tr>
<td>PsP vs TP + mixed</td>
<td>0.71</td>
<td>0.75</td>
<td>0.13</td>
<td>0.78</td>
<td>0.64–0.93</td>
</tr>
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Note:—

| MDmin indicates minimum MD.

where $\beta_0 = -15.43$, $\beta_1 = 202.14$, $\beta_2 = -313.99$, and $\beta_3 = 1.20$. Figure 5C shows the receiver operating characteristic curves for the best LRM and selected parameters. The cutoff value for the LRM was 0.65 with sensitivity = 76%, specificity = 100%, and AUC = 0.901 (Table). Leave-one-out cross-validation analysis revealed that 72.7% of cases were correctly classified by using the LRM.

Identification of PsP

Accurate identification of PsP is critical for patient manage-

Pseudoprogression is predominantly a subacute treatment-re-

Identification of Mixed Response

On a practical level, posttreatment new enhancing lesions usually

cellular space,28 which may explain the elevated anisotropy ob-

seen in patients with TP. However, a previous study reported no

tional reasons for this discrepancy may be because we divided

Pseudoprogression has been defined as the presence of new or

Heterogeneity and variability in response did not allow differ-

Early identification of TP could prevent further delays in repeat

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most previous studies have attempted to only differentiate between PsP and TP. DTI and DSC imaging findings between viable neoplasm and treatment-induced changes are variable and difficult to synthesize on routine visual inspection. We believe the quantitative analysis of imaging parameters should yield a better estimate of each component. Our findings indicate that DTI and perfusion may have a complementary predictive value for the evaluation of treatment response and demonstrate that a combination of FA, CL and rCBV\textsubscript{max} can differentiate mixed response from TP with high sensitivity. Although similar trends were observed between PsP and mixed response, DTI parameters had relatively modest utility in distin-
guishing mixed response from PsP. Because dynamic contrast-enhanced MR imaging is increasingly being used to assess brain tumors, we believe future studies including quantitative dynamic contrast-enhanced–based parameters may further enhance the sensitivity of our method in differentiating PsP from mixed response.

While these results are promising, the study has some limitations, including a retrospective analysis design and a relatively smaller sample size. In addition, image-guided biopsy may be necessary to evaluate the pathophysiologic basis of higher CP and FA in TP. A clinical follow-up study by using progression-free or overall analysis as end points for determination of PsP and TP at the time of initial MR imaging is desirable because not all patients will undergo repeat surgery for confirmation of imaging findings.

CONCLUSIONS
Our study shows that a combination of DTI and DSC perfusion parameters can help in the evaluation of treatment response in glioblastomas and may aid in the optimal management of these patients.

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