Dynamic Contrast-Enhanced Magnetic Resonance Imaging As a Biomarker for Prediction of Radiation-Induced Neurocognitive Dysfunction

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Purpose: To determine whether early assessment of cerebral microvessel injury can predict late neurocognitive dysfunction after brain radiation therapy (RT).

Experimental Design: Ten patients who underwent partial brain RT participated in a prospective dynamic contrast-enhanced magnetic resonance imaging (MRI) study. Dynamic contrast-enhanced MRI was acquired prior to, at weeks 3 and 6 during, and 1 and 6 months after RT. Neuropsychological tests were done pre-RT and at the post-RT MRI follow-ups. The correlations between early delayed changes in neurocognitive functions and early changes in vascular variables during RT were analyzed.

Results: No patients had tumor progression up to 6 months after RT. Vascular volumes and blood-brain barrier (BBB) permeability increased significantly in the high-dose regions during RT by 11% and 52% (P < 0.05), respectively, followed by a decrease after RT. Changes in both vascular volume and BBB permeability correlated with the doses accumulated at the time of scans at weeks 3 and 6 during RT and 1 month after RT (P < 0.03). Changes in verbal learning scores 6 months after RT were significantly correlated with changes in vascular volumes of left temporal (P < 0.02) and frontal lobes (P < 0.03), and changes in BBB permeability of left frontal lobes during RT (P < 0.007). A similar correlation was found between recall scores and BBB permeability.

Conclusion: Our data suggest that the early changes in cerebral vasculature may predict delayed alterations in verbal learning and total recall, which are important components of neurocognitive function. Additional studies are required for validation of these findings.

Radiation therapy (RT) is a major treatment modality for malignant and benign brain tumors. The major limiting factor in its use is neurotoxicity. This neurotoxicity manifests as late neurologic sequelae and neurocognitive dysfunctions with or without gross tissue necrosis (1–4). Late neurocognitive dysfunction prominently affects working memory, learning ability, executive function, and attention span. Although a few studies find that tumor progression is associated with the deterioration of neurocognitive function after RT (5–7), a recent multicenter study of patients with low-grade gliomas who had no clinical signs of tumor recurrence at least 1 year after partial brain (90% of the patients) or whole brain RT showed that a high total dose correlated with a decline in working memory, and that a high dose per fraction interferes with long-term memory storage and retrieval (4). Also, in a randomized trial of low-dose (50.4 Gy) versus high-dose (64.8 Gy) partial brain RT in patients with supratentorial low-grade glioma, significant cognitive deteriorations from baseline were found in those without tumor progression, with rates of 8.2%, 4.6%, and 5.3% at years of 1, 2, and 5, respectively, as assessed by the Folstein Mini-Mental State Examination (MMSE; ref. 8), a relatively crude measure of neurocognitive function. Moreover, the rate of cognitive impairment in patients undergoing partial brain RT is even higher when assessed using a battery of neuropsychological tests that are much more sensitive to cognitive functions than the MMSE (4, 9–12). The potential effect of RT on neurocognitive outcomes is an important factor in the determination of the risks versus benefits of treatment (13), which should be an integral part of clinical decision-making. Given the delayed nature of neurocognitive dysfunction, it would be important to identify biomarkers for early assessment and prediction of late neurotoxicity.

Radiation-induced injury in cerebral tissue is a highly complex and interactive process involving multiple tissue elements (2, 14, 15). Vascular injury has long been considered to be of crucial importance for the development of cerebral tissue toxicity in response to irradiation. A large body of evidence suggests that vascular injury occurs acutely and precedes subacute demyelination and reactive astrocytic and microglial responses (16–19). Early histopathologic changes in
blood vessels after irradiation include dilation and thickening of blood vessels, endothelial cell nuclear enlargement, and hypertrophy of perivascular astrocytes. The dose-dependent endothelial cell death and apoptosis occur as early as 24 hours after irradiation (17, 18). The initial injury of vessels is followed by the formation of platelet matrix and thrombi, which eventually results in occlusion and thrombosis in microvessels within weeks to months (14, 20, 21). Furthermore, cerebral vascular injury is followed by degenerative structural changes in the white matter (22–25). The time lag between vascular injury and demyelination and necrosis in white matter diminishes with increased dose (22). Most of these histopathologic and biological studies have been carried out in rodent models using a single large dose of radiation. Whether the dose-dependent changes in histopathology in the human brain after 5 to 6 weeks of fractionated RT have the same time-dependent changes in histopathology in the human brain after 5 to 6 weeks of fractionated RT have the same biological sequences has yet to be determined. However, the more serious effects causing neurologic symptoms, including gross white matter necrosis and degeneration, are late effects that generally do not occur until 12 months or more after the completion of RT (1, 2).

Table 1. Patient demographics, primary diagnosis, and radiation dose

<table>
<thead>
<tr>
<th>Patient nos.</th>
<th>Age (y)/sex</th>
<th>Diagnosis</th>
<th>Location</th>
<th>Prescribed dose (Gy)</th>
<th>Fraction size (Gy)/no fraction</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>33/M</td>
<td>Grade 2 gemistocytic astrocytoma</td>
<td>Right temporal</td>
<td>59.4</td>
<td>1.8/33</td>
</tr>
<tr>
<td>2</td>
<td>64/M</td>
<td>Pituitary macroadenoma</td>
<td>Suprasellar</td>
<td>50.4</td>
<td>1.8/28</td>
</tr>
<tr>
<td>3</td>
<td>55/M</td>
<td>Sphenoid wing meningioma</td>
<td>Left medial sphenoid</td>
<td>54.0</td>
<td>1.8/30</td>
</tr>
<tr>
<td>4</td>
<td>29/M</td>
<td>Cranopharyngioma</td>
<td>Suprasellar</td>
<td>55.8</td>
<td>1.8/31</td>
</tr>
<tr>
<td>5</td>
<td>25/F</td>
<td>Low grade glioma</td>
<td>Left frontal</td>
<td>54.0</td>
<td>1.8/30</td>
</tr>
<tr>
<td>6</td>
<td>71/M</td>
<td>Null cell pituitary adenoma</td>
<td>Suprasellar</td>
<td>50.4</td>
<td>1.8/28</td>
</tr>
<tr>
<td>7</td>
<td>36/M</td>
<td>WHO III anaplastic supratentorial ependyma</td>
<td>Left frontal</td>
<td>59.4</td>
<td>1.8/33</td>
</tr>
<tr>
<td>8</td>
<td>55/M</td>
<td>Grade 2 astrocytoma</td>
<td>Bifrontal</td>
<td>54.0</td>
<td>1.8/30</td>
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<td>9</td>
<td>39/M</td>
<td>Grade 2 mixed oligoastrocytoma</td>
<td>Right frontotemporal</td>
<td>59.4</td>
<td>1.8/33</td>
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<tr>
<td>10</td>
<td>44/M</td>
<td>Pituitary macroadenoma</td>
<td>Suprasellar</td>
<td>50.4</td>
<td>1.8/28</td>
</tr>
</tbody>
</table>

Few prospective studies have investigated the effects of radiation on the human brain during a course of radiation and then after treatment. One of our previous studies assessed the temporal changes in normal-appearing large white matter fibers longitudinally, and revealed progressive changes beginning early in the course of RT to 9 months after the completion of RT (26). If there are early changes in cerebral vasculature, as has been observed in animal models, and if the early changes in vasculature are associated with late white matter degeneration and/or late neurologic symptoms and neurocognitive dysfunction, then early vascular changes could be a biomarker for late neurotoxicity.

We conducted a prospective study to investigate three questions: (a) how cerebral blood vessels in normal tissue of patients who undergo partial brain RT change over time, (b) how these changes are related to dose and dose-volume, and (c) if these changes are associated with neurocognitive dysfunction. We hypothesized that early monitoring of cerebral blood microvessels in response to fractionated RT would allow the prediction of late neurocognitive deficits. This predictive ability would permit the identification of a time window for neuroprotective therapeutic intervention.

**Materials and Methods**

**Patients.** Ten patients with newly diagnosed low-grade glioma, meningioma, cranopharyngioma, or benign tumor underwent three-dimensional conformal cranial RT with a median dose of 54 Gy (range, 50.4–59.4 Gy in 1.8-Gy fractions), and participated in a prospective, Institutional Review Board–approved, clinical magnetic resonance imaging (MRI) study (Table 1). The overall degree of physical function was assessed by using the Karnofsky performance status scale, which was ≥90 prior to RT in all but one patient (who had a Karnofsky score of 80), indicating that these patients were highly functioning.

**Dynamic contrast-enhanced MRI.** Patients underwent an MRI 1 to 2 wk prior to RT, at wk 2 to 3 and wk 5 to 6 during the course of RT, and at 1 and 6 mo following the completion of RT. All MRI scans were done on a 1.5-T scanner (General Electric Health Care). MRI included T1-weighted images, T2-weighted fluid-attenuated inversion recovery (FLAIR) images, diffusion tensor images, dynamic contrast-enhanced (DCE) T1-weighted images, post-contrast T1-weighted images, and two-dimensional proton spectroscopy images. DCE images were acquired with a three-dimensional gradient echo pulse sequence.
Fig. 1. The differences in the vascular volumes ($V_p$) and BBB permeability ($K^{\text{trans}}$) in three dose intervals at three observation times compared with the baseline values. In the high-dose region (>40 Gy), the vascular volumes increased significantly at wk 6 during the course of RT and then started decreasing after the completion of RT; whereas in the intermediate dose interval (20-40 Gy), the vessel volume increased slowly, reached a similar maximum value 1 mo after the completion of RT, and then started decreasing. The changes in the BBB permeability were significant in the high and intermediate dose regions at week 6 during the course of RT 10 wk, 1 mo after the completion of RT, and 32 wk, 6 mo after the completion of RT.

sequence with TE/TR = 1.08/3.4 ms, flip angle = 20 degrees, field-of-view = 220 × 220 × 132 mm$^3$, matrix size = 256 × 256 × 22, spatial resolution = 0.86 × 0.86 × 6 mm$^3$, and temporal resolution = 7.2 s. The three-dimensional slab was acquired in the sagittal plane to eliminate the time-of-flight effect from in-flow blood proton spins. A total of 38 dynamic volumes were acquired during 274 s. A single dose (0.1 mL/kg) of gadolinium-DTPA was injected at 2 mL/s, during which DCE image volumes were acquired. In this study, we focused on the analysis of DCE images and changes of variables estimated from the DCE data over time.

Image registration. All images including anatomic MRI, DCE-MRI, and treatment planning CT were coregistered by using the Mutual Information and Simplex optimization algorithm implemented in an in-house functional image analysis tool (27). DCE images were first registered within the series to correct possible misalignment prior to estimations of kinetic variables (described in detail below). After estimating kinetic variables, all sagittal parametric maps obtained at different follow-up times were coregistered to the axial post-contrast T1-weighted images acquired prior to RT. Finally, through coregistration of treatment planning CT with MRI, the planned dose distribution map was also coregistered with MRI.

Estimation of kinetic variables from DCE-MRI. The modified Toft model was used to estimate kinetic variables (28). In this model, the variables considered include the transfer constant ($K^{\text{trans}}$) for gadolinium influx from the intravascular space into the extravascular extracellular space, the fractional plasma volume ($V_p$) in tissue, and the back-flux constant rate for gadolinium efflux from the extravascular extracellular space back to the intravascular space. A small vessel hematocrit value of 0.45 was used. The artery input function was obtained from carotid arteries by thresholding to determine the earliest contrast uptake. Note that the $V_p$ obtained by this model was corrected for vascular leakage.

Temporal change and dose effect. We focused on the temporal change of the fractional volume of blood plasma ($V_p$) and the transfer constant ($K^{\text{trans}}$) of gadolinium-DTPA from the intravascular space into the extravascular extracellular space in normal-appearing cerebral tissue, which is defined as the cerebral tissue that appears normal on T1-weighted images and FLAIR images from pre-RT to 6 mo after the completion of RT. Changes in $K^{\text{trans}}$ reflect changes in blood-brain barrier (BBB) permeability to gadolinium-DTPA. To assess the changes in $V_p$ and $K^{\text{trans}}$ in relation to the radiation dose, cerebral tissue was divided into seven intervals based on receiving a biologically equivalent dose of 2 Gy per fraction (biodose, $\alpha/\beta = 2.5$), as 0 to 5, 5 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, and >50 Gy. The means of the biodose in the seven volumes of interest and the means of $V_p$ were calculated. To assess the effect of dose-volume, the brain volumes that received 0 to 20, 20 to 40, and >40 Gy were computed based on the treatment planning CT and dose distribution.

Neurocognitive function tests. All patients underwent a battery of standardized neurocognitive tests prior to RT and at each of the post-RT MRI follow-ups. The neurocognitive tests included Trail Making Tests A and B (29), the Hopkins Verbal Learning Test (HVLT; refs. 30, 31), and the Controlled-Oral Word Association test (32, 33). Trail Making Test A assesses information processing efficiency. Trail Making Test B and Controlled-Oral Word Association assess executive function. HVLT assesses verbal memory (recall, delayed recall, and recognition components) and learning (learning component). In addition, the MMSE was administered. These neuropsychologic tests were used in Radiation Therapy Oncology Group trials of prophylactic cranial irradiation for patients with limited small cell lung cancer disease (RTOG 0212) and motexafin gadolinium, and whole-brain radiation for patients with brain metastases (5). All tests were administered by trained and certified research associates for Radiation Therapy Oncology Group trials and standards.

A score of 1.5 SD below the mean of age-matched normative data has been considered to have impairment in neurocognitive function (30, 31). Therefore, if a score of a neurocognitive test in a patient prior to RT was 1.5 SD below the mean of the age-matched normative data, the patient was considered to have pre-existing neurocognitive function impairment.

Statistical methods. The linear mixed model was used to assess the dose effect and the dose-volume effect on the brain vasculature properties of $V_p$ and $K^{\text{trans}}$. First, we tested the dose effect at different time points, during the course of RT and after the completion of RT, to evaluate the evolution of the dose effect over time. The linear mixed model was considered as:

$$\Delta P_{i,j} = \alpha_i + \beta_i \times D_{ij} + \gamma_i,$$

where subscripts $i$, $j$, and $t$ denote, respectively, subject, region, and time; $\Delta P$ is the change of $V_p$ or $K^{\text{trans}}$ observed at time $t$ compared with that patient’s baseline; and $D_{ij}$ is the biologically corrected dose received in region $j$ of subject $i$ by time $t$. $\beta_i$ is the slope at time $t$, and its change over time would suggest the dose effect evolving. $\alpha_i$ and $\gamma_i$ are the global intercept and the individual subject intercept at time $t$, respectively. Second, we tested the dose-volume effect as a possible additional factor contributing to injury of the cerebral vasculature. The model was tested given by:
The correlation between the early changes in $V_p$ and $K_{trans}$ during the course of RT and the early delayed changes (6 mo after RT) in neurocognitive functions were tested by Pearson correlation coefficient. Because we predicted the direction of expected changes, one-tailed $P < 0.05$ was considered to be significant.

### Results

**Clinical and radiological findings.** None of the patients evidenced tumor progression at 6 months (of 10 eligible patients) or 18 months (of 5 eligible patients) after the completion of RT. Also, none of the 10 patients showed gross radiation-induced lesions on T2-weighted FLAIR and post-gadolinium T1–weighted images up to 6 months after RT. All patients with glioma and the patient with ependymoma had associated signal increases on T2-weighted FLAIR images in the tumor and in its vicinity prior to RT. These tumor-related hyperintensities on T2-weighted FLAIR images did not substantially change during the 6-month follow-up. In one patient with glioma, mild scattered focal areas of increased T2/FLAIR signal abnormalities were present in the central semiovale and periventricular white matter prior to RT, consistent with old ischemic changes. These areas showed no further change over time. No additional areas of radiation-induced abnormalities were present during follow-up. In patients with pituitary adenomas and in the patient with craniopharyngioma, no signal abnormality outside the tumor was present pretreatment and no interval change was seen during the 6-month follow-up. In the patient with sphenoid wing meningioma, postsurgical changes were shown, and no changes on T2 and FLAIR signals beyond the surgical cavity were seen over the 6-month follow-up.

**Temporal changes in vascular volumes and BBB permeability.** The averaged fractional volume of blood plasma ($V_p$, representing the vascular volume when corrected with hematocrit) in normal-appearing cerebral tissue in the patients was 1.4 mL/100 g prior to RT, which is in the reference range. The temporal changes in $V_p$ exhibited a complex pattern in relation to radiation dose variables. First, the temporal changes in $V_p$ were evaluated in three dose intervals as 0 to 20, 20 to 40, and $>40$ Gy, which have been used in previous studies to assess the dose-volume effect (34). The time courses of the changes in $V_p$ depended on the dose received by the tissue regions (Fig. 1). For the cerebral tissue regions that received the low dose ($0-20$ Gy), $V_p$ exhibited nonsignificant changes ($P > 0.05$). In the tissue regions that received 20 to 40 Gy, $V_p$ increased by 4% (0.05 ± 0.08 mL/100 g; mean ± SE) at week 3 during RT. The increase reached 7% (0.10 ± 0.05 mL/100 g) at week 6 during RT and by 12% (0.16 ± 0.10 mL/100 g) 1 month after the completion of RT. The increase was significant at week 6 during RT ($P = 0.05$). Then, at 6 months after the completion of RT, $V_p$ decreased from the value observed 1 month after RT and returned to the values of week 3 during RT (Fig. 1), suggesting that in this intermediate dose range, vessels are dilated initially and then either return to normal or undergo regression. In the brain region that received $>40$ Gy, $V_p$ rapidly increased by 10% (0.14 ± 0.09 mL/100 g) at week 3 during the course of RT, and by 11% (0.15 ± 0.07 mL/100 g) at week 6 during RT, approximately the maximum value observed in the 20 to 40 Gy brain region 1 month after RT. The increase in $V_p$ at week 6 during RT was significant ($P < 0.05$). After the completion of RT, $V_p$ values decreased from the elevated values during RT to the value at 6 months (0.10 ± 0.10 mL/100 g), which was still 7% greater than the baseline value, suggesting that this higher dose range evokes rapid vessel dilation, followed by vessel regression or renormalization after the completion of RT. The transition occurred sooner in the high dose range than the intermediate dose range.

Temporal profiles of the changes in $K_{trans}$ (reflecting BBB permeability to gadolinium-DTPA) of normal-appearing brain were similar to those in $V_p$ (Fig. 1). In the regions which received low doses ($0-20$ Gy), $K_{trans}$ exhibited nonsignificant changes. In the region that received 20 to 40 Gy, $K_{trans}$ values increased significantly by 39% (0.042 ± 0.016 $10^{-2}$ min$^{-1}$) at week 6 during the course of RT ($P < 0.02$). After the completion of RT, the $K_{trans}$ values started to decrease from the elevated values at the end of RT, but still remained elevated by 23% (0.025 ± 0.014 $10^{-2}$ min$^{-1}$) 1 month post-RT, and eventually returned to the pre-RT values 6 months post-RT. In the tissue region that received $>40$ Gy, the $K_{trans}$ values increased significantly by 52% (0.057 ± 0.019 $10^{-2}$ min$^{-1}$) at week 6 during the course of RT ($P < 0.01$). After the completion of RT, the $K_{trans}$ values decreased from the elevated values at the end of RT, which is similar to the temporal pattern that we observed previously in the tumor of a different group of patients (35).

### Table 2. Linear mixed models

<table>
<thead>
<tr>
<th>Time</th>
<th>3 wk</th>
<th>6 wk</th>
<th>10 wk</th>
<th>32 wk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta_t$</td>
<td>$P$</td>
<td>$\beta_t$</td>
<td>$P$</td>
</tr>
<tr>
<td>$V_p$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td>1.1 $\times 10^{-2}$</td>
<td>0.0001</td>
<td>4.8 $\times 10^{-3}$</td>
<td>0.0002</td>
</tr>
<tr>
<td>Model 2</td>
<td>3.5 $\times 10^{-5}$</td>
<td>0.0001</td>
<td>1.3 $\times 10^{-5}$</td>
<td>0.0001</td>
</tr>
<tr>
<td>$K_{trans}$</td>
<td>2.0 $\times 10^{-5}$</td>
<td>0.001</td>
<td>7.8 $\times 10^{-6}$</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**NOTE:** Model 1 includes dose effects, whereas model 2 includes dose-volume effects. Units of $\beta_t$; (mL/100 g) per Gy for model 1 of $V_p$, per Gy per mL for model 2 of $V_p$, and per min per Gy for model 1 of $K_{trans}$. Weeks were counted from the start of RT; 10 wk, 1 mo after the completion of RT; 32 wk, 6 mo after the completion of RT.
Dose effects. The dose effects on the cerebral vasculature were analyzed using the linear mixed model. In model 1 (Eq. A), only the dose effect on the cerebral vasculature and the evolution of the dose-dependency changes over time were examined. The dose-dependence of $V_p$ was the largest at week 3 during the course of RT ($P < 0.0001$; Table 2). At week 6 of RT, the dose-dependence of $V_p$ was high ($P < 0.0001$), but even though the dose received by these tissues was approximately double that at week 3, the dose-dependence of $V_p$ was approximately half of the one observed at week 3 (Table 2). After the completion of RT, the dose-dependent change in $V_p$ continued decreasing, and by 6 months after RT, the dose-dependence of $V_p$ was diminished. This evolution of the dose-dependent changes in $V_p$ can also be seen in the scatter plots of Fig. 2.

Using the linear mixed model, the changes in $K_{trans}$ (BBB permeability to gadolinium-DTPA) both during the course of RT and after the completion of RT were found to depend significantly on the accumulated doses at the time of the MRI observation ($P = 0.001$ to $P = 0.03$; Table 2; Fig. 2). The linear slopes ($\beta_t$) that reflect $K_{trans}$ value changes per unit dose were $2.0 \times 10^{-5}$, $7.8 \times 10^{-6}$, $6.1 \times 10^{-6}$, and $4.5 \times 10^{-6}$ min$^{-1}$/Gy at week 3 and week 6 during the course of RT and 1 month and 6 months after the completion of RT, respectively, indicating the strongest dose-response at week 3 during RT.

Dose-volume effects. To evaluate whether the volume of brain irradiated affects blood volume in addition to the dose, we developed model 2, which includes the dose-volume effect (Eq. B). The changes in $V_p$ were found to depend on the product of the biodose received at the time of observation and the volume of brain receiving a total dose of >40 Gy ($V_{>40}$), indicating that the effect of higher doses of radiation was greater with increasing brain volume irradiated with the high doses (Table 2). The dose and dose-volume ($D \times V_{>40}$) dependent changes in $V_p$ were significant both during and after the completion of RT (Table 2). Again, the strongest interactive effect of the dose and the dose-volume on $V_p$ was observed at week 3 during the course of RT, and the effect remained significant 6 months after the completion of treatment ($P < 0.007$; Table 2). There was no significant dose-volume effect on $K_{trans}$ values found using the linear mixed model.

Neurocognitive function changes. All patients had MMSE scores of 27 or above prior to RT, and this measure showed little change over the 6 months after the completion of RT (Table 3). HVLT assesses multiple verbal memory and learning components, e.g., recall, learning, and delayed recall. Scores of total recall (sum of three trials), learning, and delayed recall (20-minute delay) pre-RT, and 1 month and 6 months after the completion of RT are given in Table 3. Prior to RT, the total recall scores of five patients were more than 1.5 SDs below the means of the age-matched normative data; the delayed recall scores of three patients were more than 1.5 SDs below the means of their age-matched normative data, indicating pre-RT existing conditions in several of the patients. Three patients had borderline impaired learning scores, approximately 1.5 SD below the means of the age-matched normative data, indicating that pre-RT memory abilities were more compromised than learning abilities in these patients in terms of both severity and frequency.

Next, we tested the association between early changes in $V_p$ and $K_{trans}$ during the course of RT and early delayed changes (6 months after the completion of RT) in HVLT recall, learning,
and delayed recall scores. We found that the changes in the verbal learning scores 6 months after RT compared with pre-RT were correlated significantly with the percentage of changes in $V_p$ of left frontal lobes ($P = 0.032$) and left temporal lobes ($P = 0.017$) at week 3 during the course of RT (Fig. 3). There was no significant correlation between the early delayed changes in learning scores and the early changes in $V_p$ of right frontal or temporal lobes, consistent with presumed left hemisphere predominance for language and therefore for verbal learning. The declines in verbal learning scores 6 months after RT versus pre-RT were significantly correlated with the percentage of changes in $K_{trans}$ of left frontal lobes at week 3 during the course of RT ($P = 0.007$), but not with the changes in $K_{trans}$ of right frontal lobes or left and right temporal lobes at week 3 during RT. There was no significant correlation between the early delayed changes in total recall or delayed recall scores and the early changes in $V_p$ during the course of RT of left or right frontal or temporal lobes. The changes in total recall scores 6 months after RT were significantly correlated with the percentage of changes in $K_{trans}$ of left temporal lobes ($P = 0.028$) at week 3 during the course of RT. There was no significant correlation between the early delayed changes in Trail Making Test B or Controlled-Oral Word Association test and the early changes in $V_p$ or $K_{trans}$ during the course of RT of left or right frontal or temporal lobes.

**Discussion**

In this study, we assessed the early vascular changes during the course of RT and the changes that occurred up to 6 months after the completion of RT. The vascular volume and BBB permeability showed an initial increase during the course of RT, and then a gradual decrease after the completion of RT. The regions receiving the highest doses showed the most rapid and significant changes. The initial increase in vascular volume is most likely due to vessel dilation in response to accumulated modest amounts of radiation (14, 15, 17, 22). The early delayed decrease represents either vascular regression such as capillary collapse and occlusion after progressive loss of endothelial cells and formation of platelet clusters and thrombi (14, 17, 18) or vessel renormalization. The temporal profile of the changes in BBB permeability of normal tissue is similar to what we have observed previously in the tumor of a different patient population (35). The increase in BBB permeability could be due to endothelial cell death and apoptosis in response to irradiation, which is directly correlated to the dose. However, the dose effect on the cerebral vasculature volume is observed during the course of RT, and then diminishes over time after the completion of RT, whereas the dose-volume effect persists up to 6 months after RT. This evolution from the dose effect to the dose-volume effect has not previously been shown. Finally, these early changes (week 3 during the course of RT) in the cerebral vascular volume and BBB permeability are associated with the early delayed changes in learning and recall scores of HVLT. These findings suggest that early changes in the cerebral vasculature may predict delayed changes in verbal learning and total recall, which are key components in neurocognitive function. Additional studies are required for the validation of these findings.

Our understanding of the histopathologic and biological changes in cerebral vasculature and tissue after RT is derived mainly from the studies of rodent models. Most of these studies have been carried out by using a single dose of modest to high size, although some recent studies have used fractionated radiation (21, 36). One such study that used 2 Gy per fraction, for a total of 40 Gy over 4 weeks in mice, found no early BBB disruption until 90 days after the completion of fractionated irradiation (36). In the present study, we found early vascular changes including the vessel volume and BBB disruption, in which the most apparent changes were seen in the brain regions that received >40 Gy. Nevertheless, several studies of rodent models report early vascular changes after a single dose (17, 18); the time course of progressive injury of cerebral tissue in these models differs somewhat from what we observed in humans who received fractionated RT (2, 14, 15, 22). In clinical studies, T2 lesions are located predominantly in periventricular regions, indicating demyelination, and start appearing 2 to 6 months after RT. The T2 lesions increase over the next year. Necrosis does not occur until a year after RT. In the rodent models, a commonly observed pattern of cerebral tissue injury begins with early vascular injury as vessel dilation and endothelial apoptosis and cell death, progresses to subacute

### Table 3. MMSE and HVLT scores

<table>
<thead>
<tr>
<th>Patient nos.</th>
<th>MMSE (pre-RT, 1m, 6m)</th>
<th>HVLT total recall (pre-RT, 1m, 6m)</th>
<th>HVLT learning (pre-RT, 1m, 6m)</th>
<th>Delayed recall (pre-RT, 1m, 6m)</th>
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<td>1</td>
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<td>26, 25, 34</td>
<td>3, 4, 2</td>
<td>9, 10, 11</td>
</tr>
<tr>
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<td>27, 27, 28</td>
<td>17, 1, 14, 13</td>
<td>4, 5, 6</td>
<td>10, 10, 9</td>
</tr>
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<td>29, 26, 29</td>
<td>28, 29, 28</td>
<td>5, 6, 3</td>
<td>12, 12, 12</td>
</tr>
<tr>
<td>4</td>
<td>30, 30, 30</td>
<td>33, 26, 25</td>
<td>12, 12, 12</td>
<td>1, 1, 1</td>
</tr>
<tr>
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NOTE: Maximum score of MMSE = 30; maximum score for total recall = 36; maximum score delayed recall = 12.
Abbreviations: 1m, 1 mo post-RT; 6m, 6 mo post-RT.
*Score is <1.5 SD below the mean of the age-matched normative data.
†Score is equal to 1.5 SD below the mean of the age-matched normative data (borderline value).
demyelination, and is followed by vessel thrombi and diminution, diffuse demyelination, and necrosis. The major discrepancy between clinical observations and rodent models seems to be a lack of the equivalence of the doses to produce similar symptoms. Given that it is extremely difficult to obtain human brain samples to study cerebral normal tissue injury after RT, we must continue to rely on animal models including rodents to understand the histopathology and biology of radiation-induced neurotoxicity. However, extrapolating findings from animal models to humans needs to be done with caution.

The radiation dosimetry variables such as total dose, fraction size, and dose-volume distribution, affect late brain tissue degeneration and neurologic and neurocognitive sequelae in a complex fashion. Our knowledge of the dose-volume effect on the human brain is derived primarily from the reports of late neurologic sequelae and neurocognitive dysfunctions of long-term survivors who have undergone whole brain radiation (3, 9). However, the effect of dose-volume distribution on cerebral tissue injury and neurocognitive outcomes is less clear for partial brain irradiation. Recent efforts have been made to develop statistical models to determine the dose-volume distribution in relation to children’s IQ scores months and years after cranial irradiation treatment (34). In the present study, we found that high dose had a greater effect in the patient in whom a large volume of the brain received the high dose. Our preliminary findings indicate that reducing the volume of the brain that receives high doses, e.g., by intensity-modulated RT, may benefit the patients who have a reasonable prospect for long-term survival.

It has been recognized in recent years that the radiation doses below the threshold of causing tissue neurosis poses risks for a patients’ cognitive functions years after cranial irradiation (4, 8). For instance, the vascular changes after partial rodent brain irradiation by doses both above and below the threshold of necrosis are associated with impairments of cognitive functions, whereas the low dose affects cognitive functions to a lesser extent (37). In the present study, we show the association between early vascular changes and early delayed neurocognitive function changes in patients who received 50.4 to 59.4 Gy at 1.8 Gy per fraction, in whom no radiation-induced necrosis or white matter abnormality were observed on conventional MRI up to 6 months after RT. Patient variations in tumor locations most likely contribute to neurocognitive abnormalities prior to RT and possibly after RT. In our patients, the verbal learning scores of HVLT prior to RT ranged from borderline deficient to normal and were less compromised by the pre-RT conditions than total recall and

Figure 3. Correlations between the changes in learning scores 6 mo after RT and the changes in $V_p$ of left frontal (top left) and temporal (top right) lobes at week 3 during RT, between the changes in learning scores 6 mo after RT and the changes in $K_{trans}$ of left frontal lobes at week 3 during RT (bottom left), and between the changes in total recall scores 6 mo after RT and the changes in $K_{trans}$ of left temporal lobes at week 3 during RT (bottom right).
delayed recall. There were consistent correlations between the early delayed changes in learning scores and the early changes in the two vascular variables. It is important to point out that the changes in learning, total recall, and delayed recall scores 6 months after RT were not correlated with the dose, the dose-volume, or the interaction of the dose and dose-volume in either left or right frontal or temporal lobes (P > 0.5; data not shown), suggesting that dosimetric variables may not be good surrogates for late delayed neurocognitive function outcomes. This is primarily due to individual sensitivity to radiation, which is not accounted for in the dosimetric variables. A better prediction for the delayed clinical symptoms and neurocognitive outcomes may be gained from assessing individual patient responses to radiation. In one of our recent works, we showed that substantial differences exist between individual patients in the sensitivity of the liver to radiation (38). Assessing individual risks for brain injury after irradiation using functional imaging could allow us to develop individualized patient treatment strategies, which would likely improve outcomes and patient quality of life.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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