Imaging and Therapy with Rituximab Anti-CD20 Immunotherapy in an Animal Model of Central Nervous System Lymphoma

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Abstract

Purpose: To evaluate the effect of rituximab monoclonal antibody (mAb) on MRI tumor volumetrics and efficacy in a rat model of central nervous system (CNS) lymphoma when delivery to the brain was optimized with osmotic blood–brain barrier disruption (BBBD).

Experimental Design: Female nude rats with intracerebral MC116 human B-cell lymphoma xenografts underwent baseline MRI and were randomized into 5 groups (n = 6 per group): (i) BBBD saline control; (ii) methotrexate with BBBD; (iii) rituximab with BBBD; (iv) rituximab and methotrexate with BBBD; and (v) intravenous rituximab. Tumor volumes were assessed by MRI at 1 week, and rats were followed for survival.

Results: BBBD increased delivery of yttrium-90-radiolabeled mAb in the model of CNS lymphoma. Control rats showed 201±102% increase in tumor volume on MRI 1 week after entering the study and median 14-day survival (range: 6–33). Tumor growth on MRI was slowed in the methotrexate treatment group, but survival time (median: 7 days; range: 5–12) was not different from controls. Among 17 evaluable rats treated with rituximab, 10 showed decreased tumor volume on MRI. All rituximab groups had increased survival compared with control, with a combined median of 43 days (range: 20–60, P < 0.001). There were no differences by route of delivery or combination with methotrexate.

Conclusions: Rituximab was effective at decreasing tumor volume and improving survival in a model of CNS lymphoma and was not affected by combination with methotrexate or by BBBD. We suggest that rituximab warrants further study in human primary CNS lymphoma.

Introduction

Primary central nervous system lymphoma (PCNSL) is an aggressive malignancy of the brain, spinal cord, and/or eye that accounts for up to 4% of primary brain tumors (1–3). The prognosis for patients with PCNSL remains poor, with median overall survival of only 16 to 40 months (4–9). Treatment of PCNSL usually consists of high-dose methotrexate-based chemotherapy, with or without the addition of whole-brain radiotherapy (WBRT) or bone marrow transplantation (4, 7, 10, 11). However, at least 50% of patients relapse, usually within 2 years of initial diagnosis, and combined methotrexate and WBRT is associated with high rates of delayed neurotoxicity, particularly in long-term survivors older than 60 years (4, 6, 8, 11). A treatment regimen providing long-term effectiveness and minimal toxicity is necessary in PCNSL.

Approximately 95% of PCNSLs are diffuse, large B-cell lymphomas that express the membrane-associated phosphoprotein CD20 (12). The chimeric anti-CD20 monoclonal antibody (mAb) rituximab is approved for the treatment of B-cell lymphomas and has improved the prognosis of diffuse, large B-cell lymphomas lacking central nervous system (CNS) involvement (13, 14). Case studies and small trials suggest that intraventricular and/or intravenous rituximab has potential antitumor activity in PCNSL (15–20). In addition, targeting CD20 with the radioimmunoconjugate yttrium-90 (90Y)-labeled ibritumomab tiuxetan has also shown efficacy in PCNSL (15, 21). We have hypothesized that the high molecular weight of rituximab likely limits penetration and therefore efficacy in PCNSL, particularly in the tumor-infiltrated brain around the main tumor mass.

Limited leakage of chemotherapy and mAbs across the blood–brain barrier (BBB) can be overcome by the osmotic BBB disruption (BBBD) technique to increase the transvascular delivery to brain tumors. BBBD improves delivery and efficacy of chemotherapy and immunoconjugate therapy in
Translational Relevance

The standard of care for primary central nervous system lymphoma (PCNSL) is currently undefined, with clinicians moving away from radiotherapy options that cause cognitive loss. Two options are the addition of rituximab anti-CD20 monoclonal antibody to target lymphoma B cells, or the use of osmotic blood–brain barrier disruption (BBBD) to enhance the delivery of methotrexate (MTX) chemotherapy to infiltrating tumor cells throughout the brain. We assessed the effects of rituximab in a rat model of human CNS lymphoma and tested the hypothesis that enhanced delivery with BBBD and/or combination with high-dose methotrexate would improve the antitumor efficacy. We also measured early changes in tumor volume on MRI to determine whether this outcome correlated with survival. We found that rituximab was effective as a single agent in extending survival in the rat model of CNS lymphoma. We suggest that rituximab warrants additional clinical trials in PCNSL.

Animal use and tumor inoculation

The care and use of animals were approved by the Institutional Animal Care and Use Committee and were supervised by the Department of Comparative Medicine, Oregon Health & Science University (OHSU), Portland, OR. Female athymic nude rats (nu/nu, 180–240 g, from the OHSU Blood-Brain Barrier Program in-house colony) were used for all studies. Intracerebral tumor inoculation was done as previously described (26, 27). Rats were anesthetized with intraperitoneal ketamine (60 mg/kg) and intraperitoneal diazepam (7.5 mg/kg). Animals received 1.2 × 10^6 to 1.5 × 10^6 of more than 80% viable MC116 cells in a volume of 15 μL, stereotactically injected in the right caudate putamen (vertical, bregma 6 mm; lateral, bregma 3.1 mm). The needle was initially advanced to a depth of 6.5 mm and then withdrawn to a depth of 6 mm to limit reflux up the needle track. Our previous studies have shown that intracerebral growth of the MC116 model is very inconsistent (26, 27); therefore, all rats were treated with intraperitoneal cyclophosphamide (100 mg/kg) 24 hours prior to tumor implantation and 2 weeks after tumor implantation to decrease the innate immunity as a mechanism to improve the consistency of tumor growth (27, 29).

Pharmacology study design

Ibritumomab tiuxetan (Zevalin; Biogen Idec, Inc.) was conjugated with the high-energy β-emitting radioisotope 90Y by using a kit supplied by the manufacturer. Rats with MRI-confirmed tumor received 0.2 mCi/kg 90Y-Zevalin given intravenously with or without BBBD. At 10 minutes, 24 hours, or 3 days after mAb administration, rats (n = 3 per group per time point) were perfused with saline to clear the vasculature. The brains were harvested and radioactivity was measured in tumor, 1 to 2 mm brain around tumor (BAT), 1 to 2 mm ipsilateral brain distant to tumor (BDT), and contralateral [left hemisphere (LH)] normal brain.

Treatment study design

Rats with MRI-confirmed tumor were randomized into 5 groups: (i) control with BBBD and intra-arterial saline (n = 6); (ii) methotrexate 1 g/m² intra-arterially with BBBD (n = 6); (iii) rituximab 375 mg/m² intravenously with BBBD (n = 6); (iv) rituximab 375 mg/m² intravenously + methotrexate 1 g/m² intra-arterially with BBBD (n = 5); and (v) intravenous rituximab 375 mg/m² (n = 7). Saline or methotrexate was injected into the internal carotid artery immediately after BBBD, and rituximab was given into the femoral vein just prior to BBBD. In the methotrexate groups (groups 2 and 4), a rescue regimen of folic acid (leucovorin 40 mg/kg intraperitoneal), sodium bicarbonate (334 mg/kg intraperitoneal), and subcutaneous saline was administered twice daily for 3 consecutive days starting 24 hours after methotrexate treatment. The rats were scanned again 7 days after treatment, or earlier (days 5 and 6 after treatment) if clinical symptoms necessitated early sacrifice. Some animals received a third MRI if they survived more than 2 weeks after treatment. The animals were examined...
and weighed at least weekly and were sacrificed by intracardiac thiopental injection (0.5 mL) if they showed severe clinical symptoms or more than 20% weight loss. The predetermined end time for the study was 60 days (approximately 4 x control survival); rats that survived to 60 days were killed.

The MC116 model of CNS lymphoma shows inconsistent tumor take and growth, as shown in our previous studies (26, 27). Therefore, rats were entered into the treatment study only if intracerebral tumor volume between 4 and 40 mm³ was confirmed on T2-weighted MRI. Rats underwent MRI beginning approximately 16 days after cell implantation; rats lacking tumors on MRI were scanned again at weekly intervals and were excluded from the study if they did not meet the inclusion criterion by 4 to 6 weeks after tumor implantation. In rats lacking tumor, little or no signal change was detected along the needle track on T2-weighted MRI (data not shown). A total of 92 rats were used in this study; 87 rats survived the tumor inoculation, and 56 showed tumors on MRI (64% tumor take). Among these, 5 showed tiny tumors that did not grow to meet the inclusion criterion, 4 had tumors that were too large for inclusion, and 6 died because of anesthesia or technical issues during MRI. Thus, 41 rats entered the survival study. Eleven rats died during or within 24 hours of therapy because of technical error or treatment-related toxicity. Treatment deaths were in the following groups: group 1, n = 1; group 2, n = 2; group 3, n = 2; group 4, n = 5; and group 5, n = 1. The high number of deaths in group 1. The high number of deaths in group 5,430 milliseconds, TE = 78 milliseconds, and T2 = 750 milliseconds and echo time (TE) = 12 milliseconds, and T2 turbo SE (TSE; TR = 5,430 milliseconds, TE = 78 milliseconds, and turbo factor = 13). The voxel size was 0.26 × 0.26 × 2 mm³ for coronal scans. Horizional and coronal T1 scans were done before and after intravenous gadolinium (Omniscan; Amersham Health AS) at a dose of 0.1 to 0.3 mmol/kg. Pre- and post-gadolinium T1–weighted MRI scans and T2-weighted images were evaluated for tumor response and changes in tumor characteristics by a neuroradiologist (E.D.) who was blinded to treatments. Images were uploaded in MIPAV (Medical Image Processing, Analysis, and Visualization, BIRSS; NIH, Bethesda, MD). The lesions were outlined on each MR image, and the software calculated the tumor volume. Volumetric analysis was expressed in units of cubic millimeter. T1-weighted volume measurements were generally smaller and more variable than the T2 data, consistent with our previous findings (26); therefore, we present only the T2 results.

**Osmotic BBBD**

Rats were anesthetized with isoflurane (5% induction, 2% maintenance Aerrane; Anaquest, Inc.) and then switched to 1.5 L/min of 50% N₂O and intravenous propofol anesthesia (800 µg/kg/min; Zeneca Pharmaceuticals). A catheter filled with heparinized saline was tied into the right external carotid artery for retrograde infusion (22, 24, 30). Mannitol (25%) warmed to 37°C was infused into the right internal carotid artery via the right external carotid artery catheter at a rate of 0.09 mL/s for 25 seconds, using a Harvard Instruments model 11-Plus constant flow pump (Harvard Apparatus, Inc.). Rituximab was administered intravenously in a volume of 1 to 1.5 mL prior to BBBD. Methotrexate in 1 to 1.5 mL saline, or saline alone, was delivered via the carotid cannula over 5 minutes immediately after infusion of mannitol for BBBD. The external carotid artery was ligated after drug infusion, and the skin was sutured closed.

**Histology**

Brains were excised and fixed in 10% buffered formalin for vibratome sectioning at 100 µm in the coronal plane. For tumor volumetrics, every sixth brain section was stained with hematoxylin and then imaged at high resolution (35-µm pixel diameter) on an Epson 1640XL flatbed scanner using Adobe Photoshop software. Tumor volume was assessed using NIH ImageJ software by a biologist blinded to treatments (L.L.M.) as previously described (26, 27). Histologic volume included the caudate inoculation site and infiltrating tumor in the cortex, subdural space, and ventricles. Ventricle volume was measured in the brain section just anterior of the fornix, using NIH ImageJ software.

**Statistical considerations**

No power calculations were made a priori or post hoc. ⁹⁰Y-Zevalin delivery to tumor and brain regions was compared using a mixed-model, repeated-measures ANOVA with a first-order autoregressive covariance structure. MRI tumor volume data obtained from T2-weighted scans were compared using the generalized Wilcoxon test. Differences from baseline (7-day volume minus baseline volume) were compared using an ANOVA to compare each active arm with the control after adjusting for the baseline volume. A mixed-model, repeated measures ANOVA model was also fit to T2 volumes by using an unstructured covariance structure. T1 scans had smaller values but greater variations and were not fit. Covariance structures were selected from among multiple candidate structures by using the Akaike Information Criterion. Changes from baseline volume,
with each animal serving as its own pretreatment control, were also compared using Student’s t test. Overall survival, calculated from the day of treatment until death, was estimated using the Kaplan–Meier product limit method. A Cox proportional hazards model was fit to compare groups (each active group is compared with control) and control for the percentage change in T2-weighted tumor volume from day 0 to day 7. The significance level was 0.05 (2-sided) for all statistical tests. All analyses were done with Microsoft Excel or version 9.2 of SAS (SAS Institute; 2002–2008).

Results

Pharmacology study
To evaluate the effect of BBBD on the delivery of mAb to the CNS lymphoma tumor mass and tumor-infiltrated rat brain, we used 90Y-Zevalin, which targets CD20 expressed on B cells, similar to rituximab (15, 21, 31). BBBD improved Zevalin delivery throughout the disrupted hemisphere compared with intravenous mAb administration (Fig. 1A). At 10 minutes, there was a significant interaction \((P = 0.0291)\) between site in the brain and delivery method (BBBD vs. intravenous) in the repeated-measures ANOVA model. Site \((P = 0.0152)\) and delivery methods \((P = 0.0361)\) were also significant. Comparisons between the delivery methods were statistically significant only for BDT \((P = 0.0271)\) and not for the other 3 sites \((P > 0.25)\). Levels of mAb in tumor-infiltrated BAT and BDT were elevated at 10 minutes and 24 hours but not at 3 days (Fig. 1B).

Treatment study
Early changes in tumor volumes were evaluated by MRI in 29 rats in the imaging and therapy study. Three response patterns were found: tumor growth on MRI with short survival (Fig. 2A), tumor growth with long survival (Fig. 2B), and decreased tumor volume (tumor response) with long survival (Fig. 2C). No rats showed a decrease in tumor volume on MRI accompanied by short survival. In the control rat, as shown in Figure 2A, tumor volume increased from 10.3 \( \text{mm}^3 \) at baseline to 48.9 \( \text{mm}^3 \) at 6 days and the animal died from tumor burden. Hematoxylin histochemistry showed tumor in the caudate inoculation site, also spreading to the subdural space and the contralateral ventricle, which was not detected by MRI. Figure 2B shows a tumor that initially increased in volume on MRI after treatment with rituximab administered with BBBD, from a baseline of 7.4 to 11.1 \( \text{mm}^3 \) at 1 week, and then subsequently regressed. Histochemistry after death at day 44 shows trauma and macrophage infiltration in the inoculation area, without tumor, whereas tumor growth is evident in the cortex, base of the brain, and contralateral ventricle. The tumor (Fig. 2C) showed a rapid response to the combination of rituximab and methotrexate administered with BBBD, from a baseline of 19.6 to 4 \( \text{mm}^3 \) at 1 week, which was maintained for more than 7 weeks. After sacrifice at the predetermined endpoint (60 days), histology showed trauma and macrophage infiltration in the inoculation area, without tumor, with tumor growth detected in the cortex.

Baseline T2-weighted tumor volumes were not significantly different among all groups (Table 1; \( P = 0.77 \)). All control rats (saline with BBBD) showed more than a doubling of tumor volume at 1 week (Fig. 3 and Table 1). Mean volume increased from 10.6 \( \pm 3.9 \) to 30.2 \( \pm 11.3 \) \( \text{mm}^3 \) (mean \( 201 \pm 102\% \) increase from baseline). All tumors in group 2 (methotrexate with BBBD) showed increased tumor volumes on T2-weighted MRI 1 week after treatment; however, the mean increase of 70 \( \pm 42\% \) was reduced compared with controls \((P = 0.016)\). Among rats

Figure 1. BBBD increases antibody delivery in the rat model of CNS lymphoma. Rats with intracerebral MC116 xenografts received \(^{90}\text{Y}-\text{Zevalin} (0.2 \text{ mCi/kg})\) intravenously with or without BBBD \((n = 3 \text{ per group per time point})\). A, radiolabel in tumor, BAT, ipsilateral BDT, and contralateral LH was determined 10 minutes after antibody administration. There was a significant effect of BBBD in the repeated-measures ANOVA model \((P = 0.0361)\). B, radiolabel localized in BDT is shown at 10 minutes, 24 hours, and 3 days after antibody administration. Data are indicated as mean \( \pm \) SD of % delivered dose.
in all treatment groups receiving rituximab, more than half (10/17) showed a decrease in tumor volume on MRI 1 week after therapy (Fig. 3), but several animals showed markedly increased tumor volume. In the analysis of covariance (ANCOVA) model, there is a significant difference between group 4 and control ($P = 0.0044$) and between group 5 and control ($P = 0.0010$). Group 5 (intravenous rituximab) showed a significant decrease in tumor growth compared with control, with an actual reduction of tumor volume from 18.8 ± 15.1 mm$^3$ at baseline to 10.4 ± 10.1 mm$^3$ after 1 week (mean 39 ± 36% decrease in tumor volume).

Individual and mean survival times for each treatment group and Kaplan–Meier survival estimates are shown in Figure 4A and B, respectively. Median survival in the saline control was 14 days (range: 6–33). Survival time after methotrexate (median: 7 days; range: 5–19) was not significantly different from controls ($P = 0.18$). All rituximab groups had increased survival compared with control.

### Table 1. Early antitumor efficacy determined by T2-weighted MRI tumor volumetrics

<table>
<thead>
<tr>
<th>Treatment group</th>
<th>1 (control)</th>
<th>2 (MTX) $\pm$ 3.9</th>
<th>3 (RTN)</th>
<th>4 (RTN + MTX) $\pm$ 9.8</th>
<th>5 (RTN IV) $\pm$ 10.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume day 0, mm$^3$</td>
<td>10.6 ± 1.8</td>
<td>12.5 ± 9.9</td>
<td>10.1 ± 4.7</td>
<td>14.4 ± 9.8</td>
<td>18.8 ± 15.1</td>
</tr>
<tr>
<td>Volume day 7, mm$^3$</td>
<td>19.5 ± 11.3</td>
<td>19.5 ± 14.3</td>
<td>22.4 ± 22.5</td>
<td>10.6 ± 4.9</td>
<td>10.4 ± 10.1</td>
</tr>
<tr>
<td>Volume change, mm$^3$</td>
<td>19.5 ± 9.8</td>
<td>7.0 ± 5.3</td>
<td>12.3 ± 18.1</td>
<td>−3.8 ± 10.6</td>
<td>−8.5 ± 10.5</td>
</tr>
<tr>
<td>% change</td>
<td>201 ± 102</td>
<td>72 ± 42</td>
<td>88 ± 105</td>
<td>85 ± 176</td>
<td>−39 ± 36</td>
</tr>
</tbody>
</table>

NOTE: Means ± SD are indicated for tumor volume (in mm$^3$) on day 0 before treatment and days 5 to 7 after treatment, the absolute change in volume (in mm$^3$), and the paired % change comparing treatment with baseline.

Abbreviations: MTX, methotrexate; RTN, rituximab; RTN IV, intravenous rituximab; all RTN, combined groups 3, 4, and 5.

$^aP < 0.05$ compared with day 0.

$^bP < 0.01$.

$^cP < 0.05$.

$^dP < 0.001$ compared with control.
control: group 3 (rituximab BBBD) median 37.5 days, range 20 to 60 days, \( P = 0.013 \); group 4 (rituximab and methotrexate BBBD) median 42 days, range 27 to 60, \( P = 0.0042 \); and group 5 (intravenous rituximab) median undefined, range 26 to 60, \( P = 0.0049 \). There were no obvious differences among the rituximab groups, but the study lacks adequate power to determine whether there were minor differences.

We evaluated differences among the groups and whether or not the percentage change in T2-weighted tumor volume on MRI was associated with survival. There were significant differences between the control group and group 2 (HR = 9.11; \( P = 0.0081 \)) and between the control group and group 5 (HR = 0.14; \( P = 0.0450 \)). There were no significant differences between the control group and groups 3 (HR = 0.30; \( P = 0.092 \)) and 4 (HR = 0.29; \( P = 0.091 \)). The association between the change in T2 volume and survival was significant (\( P = 0.017 \)), with an HR of 1.85 (for each 100% increase in T2 volume).

Six rats, all from the rituximab treatment groups, survived until the predetermined endpoint of 60 days. Three of these rats showed complete tumor response on histology. In rats that died from tumor burden, histologic tumor volume was similar between groups, although variability was increased in the treatment groups: control mean tumor volume at death was 182 ± 21 mm\(^3\) (range: 158–212 mm\(^3\), \( n = 6 \)), methotrexate mean 213 ± 156 mm\(^3\) (range: 16–413 mm\(^3\), \( n = 6 \)), and combined rituximab treatment groups excluding the six long term survivors, mean 232 ± 134 mm\(^3\) (range: 11–397 mm\(^3\), \( n = 9 \)). In the controls, tumor was largely localized to the caudate nucleus inoculation site, although infiltration into the cortex, subdural space, and contralateral ventricle was common (Fig. 2A).

Many of the rituximab-treated tumors showed decreased tumor localization in the injection site and increased localization elsewhere (Fig. 2B and C), although this was highly variable. Animals in the rituximab treatment groups that died from tumor burden showed increased cerebral ventricular volume (6.2 ± 4.0 mm\(^3\), \( P = 0.039 \); Fig. 2C) compared with the control (2.3 ± 0.9 mm\(^3\)) and methotrexate (2.1 ± 1.5 mm\(^3\)) treatment groups, which may represent hydrocephalus ex vacuo.
Discussion

The investigation of CNS lymphoma biology, pathology, imaging characteristics, and novel treatment approaches has been difficult in humans, mainly due to the rarity of the disease. Animal models of human CNS lymphoma are relatively rare (26, 27, 32). Intracerebral implantation of MC116 human B-cell lymphoma cells in nude rats provides an animal model of CNS lymphoma that closely mimics human PCNSL (26, 27). We have previously reported our experience with intravenous methotrexate- and rituximab-based treatment regimens in the rat model by using changes in tumor volume on MRI imaging modalities as endpoints (26). The current study confirms our previous results and extends the findings to the effects of these agents on survival when delivery to the brain tumor is enhanced with BBBD.

The major finding is that rituximab was highly effective at extending survival in the rat model. Although BBBD enhanced the delivery of radiolabeled mAb in the model of CNS lymphoma, a single treatment with rituximab BBBD did not improve survival compared with intravenous rituximab. In addition, the efficacy of a single dose of rituximab did not improve by combination with methotrexate.

The imaging results in this study indicate that the snapshot provided by a single MRI scan is not sufficient to discern efficacy. Several of the tumors in the rituximab treatment groups initially increased in volume on the 1-week scan but then showed subsequent decreased tumor volume and long survival (Fig. 2B), indicating that serial imaging may be more appropriate to monitor efficacy. Decreased tumor volume on MRI correlated with increased survival, but a partial response, as indicated by reduced rate of growth, did not. This mimics the human situation, in which PCNSL patients with partial responses to methotrexate chemotherapy have the same overall survival as those with progressive disease (33). The imaging did not show the subdural or intraventricular growth of tumor that was evident on histology (Fig. 2). A contrast agent that can delineate inflammatory cell infiltration may be better than T2-weighted images or standard T1-weighted MRI with gadolinium-based contrast for detecting infiltrative tumor. In this context, iron oxide nanoparticle–based MRI contrast agents have shown utility for imaging tumor-associated inflammation (34).

Previously, we reported that MC116 cells are highly sensitive to methotrexate in vitro, but efficacy in vivo was modest, as determined by changes in tumor volume on MRI (26, 27). High-dose methotrexate-based chemotherapy, with or without WBRT, is commonly used to treat PCNSL, but responses are often transitory (4, 5, 7, 35). We have hypothesized that enhancing the delivery of chemotherapy to the brain tumor with osmotic BBBD would improve the antitumor efficacy of methotrexate. Osmotic BBBD and intra-arterial methotrexate-based chemotherapy, without WBRT, is safe and effective in patients with newly diagnosed PCNSL (5). In our recent report of 149 subjects, the overall response rate was 81.9% and median overall survival was 3.1 years. Low-risk patients (younger than 60 years with Karnofsky performance score ≥70) survived a median of 14 years, with a plateau after about 8 years (5). These results are superior to other clinical studies and were obtained without the cognitive loss due to WBRT.

We tested the hypothesis that enhanced BBBD delivery would improve the efficacy of a single dose of methotrexate in the rat model of CNS lymphoma. MRI 1 week after treatment confirmed that BBBD delivery of methotrexate slowed tumor growth but the magnitude of responses was not elevated compared with our previous report (26). Survival in the MC116 model of CNS lymphoma was not enhanced by a single dose of methotrexate even when delivery was optimized with BBBD. A number of issues may explain the discordance between the in vitro sensitivity and positive MRI effects versus the lack of improvement in survival. This experiment used a single treatment with a relatively low dose of methotrexate (1 g/m²) compared with the clinical BBBD regimen of 2 consecutive days every 4 weeks for a year (5, 25). A higher dose (3 g/m²) was evaluated in several animals; however, this dose induced dehydration and diarrhea even with 3 days of hydration and folinic acid rescue. Rats showed no obvious toxicities at the 1 g/m² dose. Methotrexate has a 3- to 10-hour half-life, so the effective dose is low in the rat. BBBD can be done only once in the rat because of surgical cannulation of the external carotid artery (23, 24). Without extensive tumor kill with the single treatment, there may be accelerated repopulation after the initial slowed tumor growth, as shown by increased tumor volumes at death in many animals in the methotrexate group. Overall, the transient response to a single, low dose of methotrexate without increased survival shows that the rat model of CNS lymphoma is not appropriate to assess multiple courses with high-dose chemotherapy, as is done in humans.

Current clinical PCNSL treatment regimens with high-dose methotrexate and WBRT are not optimal and are often neurotoxic, so it is critical to evaluate new approaches (4, 6, 8, 11). Rituximab seems an obvious choice for treatment of human PCNSL. Alone or in combination with chemotherapy, the anti-CD20 mAb is effective against non–Hodgkin’s B-cell lymphoma lacking CNS or ocular involvement (13, 14). The use of rituximab in PCNSL is supported by a number of preclinical studies (26, 36) and small clinical studies (3, 16, 17, 19, 20, 35, 37). In mouse models of CNS and intraocular lymphoma, intracerebral and intravitreal injections of rituximab, respectively, induced tumor regression (36). However, mice were treated only 1 day after cell injection, before the development of tumor, and the authors did not evaluate intravenous rituximab. In patients with a new diagnosis of PCNSL, addition of rituximab nearly doubled the rate of complete response to an aggressive chemotherapy (methotrexate, procarbazine, and vincristine) and WBRT regimen (35). In recurrent PCNSL, rituximab has shown potential for disease control in combination with methotrexate (15), temozolomide (16), and multiple chemotherapy regimens (17).

Prior to this study, we hypothesized that intravenous rituximab would show minimal or transient efficacy in
PCNSL because the high molecular weight of rituximab and the low permeability of the BBB would limit the delivery of the mAb to the brain tumor. Others have argued that the BBB does not play a role in PCNSL, at least in the main tumor mass with its relatively permeable vasculature (2, 3, 19, 37). Data from anti-CD20 radioimmunotherapy support the idea that the BBB limits efficacy. Both Doolittle and colleagues and Maza and colleagues have shown responses, targeting CD20 with intravenous $^{90}$Y-Zevalin radioimmunoconjugate (15, 21). Sufficient mAb crossed the leaky BBB within the PCNSL mass to provide an effective dose of radiotherapy to the tumor cells, as shown by regression of the original enhancing mass. However, response to Zevalin was transient, with recurrence in multiple additional locations distant to the original lesion (15). Nevertheless, the survival results indicate that the rat model may be effective for evaluating the potential efficacy of intravenous therapies.

In the model of CNS lymphoma in immunocompromised athymic rats, single-dose, single-agent rituximab was effective at increasing survival in the immunologically privileged site of the brain. This result suggests that rituximab may be appropriate for immunocompromised patients who retain some immune function, as can occur with AIDS (38). In contrast to our original hypothesis, the efficacy of a single dose of rituximab was not enhanced by BBBD or by combination with methotrexate. The lack of additional effect from methotrexate is likely due to the single, low dose and short half-life, as discussed previously. In contrast, the single dose of intravenous rituximab was effective alone. BBBD significantly enhanced delivery of $^{90}$Y-Zevalin in the MC116 model of CNS lymphoma, as previously reported (Fig. 2B and C), similar to the findings with $^{90}$Y-Zevalin therapy in human PCNSL (15). Thereby, we hypothesize that to obtain a complete and durable response, multiple courses of enhanced delivery will be necessary to treat micrometastases in tumor-infiltrated brain far from the main enhancing tumor mass.

In conclusion, our results show good evidence of rituximab efficacy in a model of CNS lymphoma and suggest that this mAb should be investigated as a single agent in the clinic. Rituximab may improve outcomes for patients with a new diagnosis of PCNSL, either alone or in conjunction with high-dose methotrexate, and allow patients to avoid or delay WBRT. We hypothesize that in PCNSL with areas of low BBB permeability in disseminated tumor, BBBD will enhance the efficacy of rituximab. Unpublished pilot data from this group in patients with a new diagnosis of PCNSL treated with BBBD-enhanced delivery of rituximab in combination with high-dose methotrexate, without WBRT, suggest that rituximab increases progression-free survival to 3.5 years compared with previously reported progression-free survival of 1.8 years without rituximab (5). A multicenter clinical trial of rituximab with high-dose methotrexate-based BBBD in patients with newly diagnosed PCNSL is currently underway.

**Disclosure of Potential Conflicts of Interest**

No author has a financial conflict of interest.

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