Cancer Therapy: Preclinical

Intratumoral Mediated Immunosuppression is Prognostic in Genetically Engineered Murine Models of Glioma and Correlates to Immunotherapeutic Responses

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Abstract

Purpose: Preclinical murine model systems used for the assessment of therapeutics have not been predictive of human clinical responses, primarily because their clonotypic nature does not recapitulate the heterogeneous biology and immunosuppressive mechanisms of humans. Relevant model systems with mice that are immunologically competent are needed to evaluate the efficacy of therapeutic agents, especially immunotherapeutics.

Experimental Design: Using the RCAS/Ntv-a system, mice were engineered to coexpress platelet-derived growth factor B (PDGF-B) receptor + B-cell lymphoma 2 (Bcl-2) under the control of the glioneuronal specific Nestin promoter. The degree and type of tumor-mediated immunosuppression were determined in these endogenously arising gliomas on the basis of the presence of macrophages and regulatory T cells. The immunotherapeutic agent WP1066 was tested in vivo to assess therapeutic efficacy and immunomodulation.

Results: Ntv-a mice were injected with RCAS vectors to express PDGF-B + Bcl-2, resulting in both low- and high-grade gliomas. Consistent with observations in human high-grade gliomas, mice with high-grade gliomas also developed a marked intratumoral influx of macrophages that was influenced by tumor signal transducer and activator of transduction 3 (STAT3) expression. The presence of intratumoral F4/80 macrophages was a negative prognosticator for long-term survival. In mice coexpressing PDGF-B + Bcl-2 that were treated with WP1066, there was 55.5% increase in median survival time (P < 0.01), with an associated inhibition of intratumoral STAT3 and macrophages.

Conclusions: Although randomization is necessary for including mice in a therapeutic trial, these murine model systems are more suitable for testing therapeutics, especially immunotherapeutics, in the context of translational studies. Clin Cancer Res; 16(23); 5722–33. ©2010 AACR.

The extrapolation of preclinical data, using murine models to determine clinical efficacy of novel therapeutics, is confounded by many issues including, but not limited to, immunologically incompetent model systems and clonotypic tumors that do not fully recapitulate the heterogeneous nature of human tumors (1, 2). In addition, many experimental cell lines, by being perpetuated in vitro (in some cases for decades), have significantly diminished immunosuppressive properties when compared with the phenotype and function of cancer cells isolated immediately from human tumors (3). Ideally, screening immunotherapeutic approaches for clinical trial implementation should be selected for robust responses in immunocompetent murine model systems in which the murine gliomas correlate with the biology of human malignant gliomas (4–6). The use of genetically engineered mouse models of malignancy has been shown to simulate human responses within the context of clinical trials (7, 8) and thus provides distinct advantages for evaluating immune prognostic factors and immunotherapeutics.

Ligand interaction of the platelet-derived growth factor B (PDGF-B) receptor, which is overexpressed in human malignant gliomas (9, 10), results in activation of prosurvival signaling pathways that promote tumor cell growth (11). Murine model systems have shown that overexpression of PDGF-B in the brain induces grade II/III oligodendroglioma (12). We and others have shown that expression of other genes can cooperate with PDGF-B to enhance tumor formation and promote progression to a higher grade tumor (T. Doucette, Y. Yang, W. Zhang, G.
Among the most frequently activated oncogenic proteins is G-protein receptors with associated Janus kinase-2 (JAK2). The ligand–receptor interaction, primarily under the control of physiologic conditions, STAT3 activation depends on Src kinase activity, rapidly phosphorylates the effector M1 phenotype to the immunosuppressive M2 phenotype (25, 26). Moreover, STAT3 expression can induce a polarization from immunocompetent to immunosuppressive cells (23). STAT3 expression in macrophages inhibits their activation (24) and induces a polarization from the effector M1 phenotype to the immunosuppressive M2 phenotype (25, 26). Moreover, STAT3 expression can reduce the cellular cytotoxicity of natural killer cells and neutrophils, as well as the expression of MHC II, CD80, CD86, and IL-12 in dendritic cells, rendering them unable to activate T cells and to generate antitumor immunity (27). Furthermore, STAT3 has been shown to be a transcriptional regulator of forkhead box protein (FoxP3; ref. 28) and regulatory T cell (Treg) functional activity (29). Finally, STAT3 has been shown to maintain the proliferation and multipotency in glioma cancer stem cells (30), including their immunosuppressive properties (31). Cumulatively, these data indicate that the STAT3 pathway is a key molecular hub in tumor-mediated immunosuppression.

STAT3, and its downstream regulated genes such as Bcl-2, can be blocked with WP1066 (32), an orally bioavailable small molecule inhibitor with excellent central nervous system penetration and minimal dose-limiting toxicity (33). WP1066 can exert direct antitumor activity including the induction of caspase-dependent apoptotic cell death (32, 34, 35) and inhibition of angiogenesis (36). Moreover, WP1066 is a potent inducer of proinflammatory (37) responses and can reverse the functional immunosuppression of macrophages (26) and glioma cancer stem cells (31).

To study tumor-induced immunosuppression in endogenously arising gliomas, we used the RCAS/Ntv-a transgenic mouse system. In this system, a gene is cloned into a modified avian retrovirus (RCAS) that is replication defective in mammalian cells. The vector is introduced into Ntv-a mice that express TVA (avian leukemia virus subtype A receptor, the receptor for RCAS) under control of the Nestin promoter. Nestin-positive cells include glioneuronal precursors, the presumed cells of origin for glial tumors (5, 38). The gene is incorporated into the cell genome and is expressed by the constitutive retroviral promoter, long terminal repeat. This method of somatic cell gene transfer has been used to assess gene overexpression in vivo and to model various brain tumors (39–41). We used this model for PDGF-B and Bcl-2 coexpression. Bcl-2 lies downstream in the STAT3 signaling pathway, making tumors formed by the coexpression of PDGF-B + Bcl-2 relevant to the study of STAT3 biology. Because Ntv-a mice are immunocompetent, they are ideal for the study of immunosuppression induced by these gliomas. Most current murine model systems use either immunodeficient mice with human tumor xenografts or syngeneic clonotypic cell lines, which make it difficult, if not impossible, to appreciate the immunologic influence on tumor biology in the native animal.

We hypothesized that the gliomas formed in Ntv-a mice are immunosuppressive, that the high-grade gliomas would be more immunosuppressive relative to the low-grade gliomas, and that this model of endogenously arising malignant gliomas could be used to test immunotherapeutics. Here, we show that constitutive expression of PDGF-B + Bcl-2 in this model system induces intratumoral p-STAT3 and macrophages, similar to the induction of these cells observed in human malignant gliomas. We also show that this model system can be exploited for testing immunotherapeutics.
Materials and Methods

Vector construct

The RCAS-Bcl-2 vector was a gift of Dr. Daniel Fults (University of Utah) and the details of its creation are described elsewhere (42). Briefly, this vector was constructed by ligating a PCR-generated cDNA corresponding to the entire coding sequence of human Bcl-2 into the retroviral vector RCASBP. RCAS-PDGF-B was a gift of Dr. Wei Zhang (M. D. Anderson Cancer Center), and the details of its creation are described elsewhere (43).

Transfection of DF-1 cells

Live virus was produced using the plasmid versions of the RCAS vectors transfected into DF-1-immortalized chicken fibroblasts (grown in DME medium containing 10% FBS; Gibco) in a humidified atmosphere of 95% air/5% CO2 at 37°C, using FuGene6 (Roche).

Verification of transgene expression

Bcl-2 expression after infection with RCAS-Bcl-2 was verified by exposing untransfected DF-1 cells (cultured to 50% confluency) for 48 hours to filtered medium conditioned by DF-1/RCAS-Bcl-2-transfected cells. Cells were then fixed with 4% paraformaldehyde in PBS followed by treatment with cold methanol, and immunocytochemical labeling was done by standard methods, using a mouse monoclonal antibody against human Bcl-2 (1:200; Santa Cruz Biotechnology) and goat anti-mouse Alexa Fluor 594 fluorescent conjugate (1:500; Molecular Probes) for detection. After mounting and labeling of cell nuclei with Prolong Gold antifade reagent with DAPI (Molecular Probes), staining was examined using a Zeiss Axioskop 40 microscope. Western blotting was used for the verification of PDGF-B expression from DF-1 cells after infection. Whole-cell lysates were prepared from DF-1 cell cultures 48 hours after infection with virus-containing medium conditioned by DF-1 cells expressing RCAS-PDGF-B. Protein samples (10 μg) werefractionated by SDS-PAGE using gels containing 10% polyacrylamide, transferred to polyvinylidene difluoride membrane, and probed with the anti-HA antibody (1:1,000; F7, Santa Cruz Biotechnology) to detect PDGF-B expression. Secondary antibody used for detection was goat anti-mouse IgG (1:2,500; Pierce). The blots were developed with the ECL Plus Detection kit (GE Healthcare) following the manufacturer protocol.

In vivo somatic cell transfer in transgenic mice

Creation of the transgenic Ntv-a mouse has been previously described (44). The mice are mixtures of the following strains: C57BL/6, BALB/C, FVB/N, and CD1. To transfer genes via RCAS vectors, transfected DF-1 producer cells (1 × 10^5 cells in 1–2 μL of PBS) were injected into the right frontal brain lobe of Ntv-a mice from an entry point just anterior to the coronal suture of the skull using a 10-μL gas-tight Hamilton syringe. Mice were injected within 24 to 72 hours after birth because the population of Nestin-positive cells producing TVA receptors diminishes progressively with time. For coinjection of RCAS-PDGF-B and RCAS-Bcl-2, equal numbers of DF-1 cells were injected. The mice were sacrificed 90 days after injection or sooner if they showed neurologic morbidity related to tumor burden, including hydrocephalus or disability. The brains were fixed in formalin, embedded in paraffin, sectioned for immunohistochemical analysis, and analyzed for tumor formation. Histologic verification of tumor formation and determination of low- or high-grade type were carried out by the study neuropathologist (G.N.F.). High-grade tumors were differentiated by the presence of microvascular proliferation, mitotic activity, and necrosis. The animal experiments described in this research were approved by the Institutional Animal Care and Use Committee at the University of Texas M. D. Anderson Cancer Center (protocol 08-06-11632).

Immunohistochemistry

Formalin-fixed, paraffin-embedded 4-μm sections of the glioma were first deparaffinized in xylene and rehydrated in ethanol. Endogenous peroxidase was blocked with 0.3% hydrogen peroxide/methanol for 10 minutes at room temperature. Then, the ThermoScientific PTModule (Thermo Fisher Scientific) with citrate buffer (pH 6.0) was used for antigen retrieval. Immunohistochemical staining was done using the Lab Vision Immunohistochemical Autostainer 360 (Thermo Fisher Scientific). The staining was visualized using an avidin-biotin complex technique with diaminobenzidine (Invitrogen) as the chromogenic substrate and hematoxylin as the counterstain. A mouse monoclonal anti-HA antibody (1:50; Santa Cruz Biotechnology) was used to detect the HA epitope tag on the PDGF-B gene. To detect expression of human Bcl-2 expressed by RCAS, we used a primary monoclonal antibody specific for human Bcl-2 (1:100; Santa Cruz Biotechnology). To detect GFAP expression, a rabbit polyclonal anti-GFAP antibody was used (1:500; DAKO/Cytomation). To detect p-STAT3 expression, we used a rabbit polyclonal anti-p-STAT3 (Tyr705) antibody (1:50; Cell Signaling Technology). To detect expression of the macrophage-restricted cell surface glycoprotein F4/80, a purified anti-mouse F4/80 (1:50; Biolegend) antibody was used. To detect FoxP3 expression, a purified mouse anti-FoxP3 antibody (1:50; Biolegend) was used.

Two independent observers (L.-Y.K., A.W.) quantitatively evaluated p-STAT3, FoxP3, and F4/80 expression by analyzing the tumors with high-power fields (max: 400× objective and 100× eyepiece) of each specimen in the regions, with the highest relative positive staining for that individual specimen. The analysis was reviewed again by the neuropathologist (G.N.F.). The observers examined each tumor in a blinded fashion and in duplicate. Each observer recorded the absolute number of cells with positive staining. The duplicate numbers were then averaged for the final number of cells with positive expression per specimen.
Mitotic index
To detect and quantify mitotic activity, formalin-fixed, paraffin-embedded, tumor-bearing tissue sections were immunostained with an antibody against pH3. The number of positively stained cells in the area of highest tumor cell density were counted in 10 nonoverlapping high-power microscopic fields (magnification × 400) from 5 different tumor-bearing brains from the RCAS-PDGF-B and RCAS-PDGFB + RCAS-Bcl-2 mice. The mitotic index was calculated as the number of positive cells divided by the number of total cells in each field. The median number of cells counted was 1,795 (range, 616–3,003).

STAT3 inhibitor
WP1066, which blocks p-STAT3, was synthesized and supplied by Dr. Waldemar Priebe (M. D. Anderson Cancer Center). It was dissolved in dimethylsulfoxide (DMSO; Sigma-Aldrich).

Treatment schema and animal randomization
After receiving the injection of the PDGF-B + Bcl-2 constructs as described, littermates were randomized to the treatment or control groups. Twenty-one days after introduction of the glioma-inducing transgenes, treatment was started with WP1066, administered by oral gavage (o.g.) in a vehicle of DMSO/PEG300 (20 parts/80 parts) once per day, every other day schedule (5 days on, 2 days off) for a total of 3 weeks. Fifteen mice per experimental group were used including treatment with the DMSO/PEG300 vehicle alone in the control group. This methodology of using RCAS/Ntv-a mice to determine treatment efficacy has been described previously (45).

Statistics
Kaplan–Meier product-limit survival probability estimates of overall survival were calculated (46) and log-rank tests (47) were carried out to compare overall survival times between treatment groups and the control arm. Ex vivo or in vitro data are presented as the mean ± standard error of means (SEM). The Student t test was used. Comparisons of proportions were made using the Fisher exact test. A P value below 0.05 was considered statistically significant.

Results
Tumor heterogeneity in Ntv-a murine models of glioma
Both low-grade and high-grade malignant oligodendrogliomas with features of diffuse infiltration, pseudopallissading necrosis, endothelial cell proliferation, and tracking along white matter fibers were observed in animals that were transfected with PDGF-B or PDGF-B + Bcl-2 (Fig. 1A). The gliomas expressed GFAP (Fig. 1B). In mice injected

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**Fig.1.** A, representative hematoxylin and eosin-stained light microscopy images showing the phenotypic features of de novo (i) low- (50×) and (ii) high-grade gliomas (50×) in the PDGF-B + Bcl-2 mouse, including (i, ii) diffuse infiltration, (ii) pseudopallissading necrosis (arrow showing), (iii) white matter tracking (100×), and (iv) vascular proliferation (400×). B, induced tumors in the PDGF-B + Bcl-2 mice showing positive expression of (i) GFAP, (ii) hemagglutinin epitope tag (detecting PDGF-B expression), and (iii) Bcl-2 (400×; scale bar, 100 μm). C, Kaplan–Meier survival curves showing overall survival of PDGF-B-alone mice and PDGF-B + Bcl-2 mice. Median survival was longer than 90 days in the PDGF-B-alone mice and 52.5 days in the PDGF-B + Bcl-2 mice (P = 0.005). Animals surviving for longer than 90 days were terminated for histopathologic tissue examination and analysis. 
with RCAS-PDGF-B alone, 42% (11/26) developed gliomas and 19% overall (5/26) developed high-grade malignant gliomas. In contrast, when mice were injected with both RCAS-PDGF-B + RCAS-Bcl-2, 82% (27/33) developed gliomas, with 61% overall (20/33) being high-grade malignant gliomas (Table 1). In mice that were transfected only with PDGF-B, 81% survived for 90 days at which time the experiment was terminated. In comparison, in mice that were cotransfected with PDGF-B + Bcl-2, only 44% survived to day 90 (P = 0.002; Fig. 1C). Mice injected with RCAS-Bcl-2 did not develop tumors.

The level of p-STAT3 expression correlates with in vivo malignancy and survival

Because a subset of mice that were injected with RCAS-PDGF-B, an inducer of p-STAT3, and the majority of mice injected with RCAS-PDGF-B + RCAS-Bcl-2 developed high-grade malignant gliomas, we determined whether these tumors showed induction of STAT3. The p-STAT3 expression within tumors in each group was measured using immunohistochemistry and expressed as the percentage of p-STAT3–positive cells (Fig. 2A). We observed p-STAT3 expression in all tumors regardless of model system or grade. Next, we quantified the extent of p-STAT3 expression by counting the number of p-STAT3–positive cells. In the tumors induced by PDGF-B alone (Fig. 2B), the percentage of cells that expressed p-STAT3 was 27.9 ± 11.1% in high-grade tumors (range, 11.5%–48.8%, n = 3) and 1.0 ± 0.1% in low-grade tumors (range, 0.8%–1.3%, n = 3). In the PDGF-B + Bcl-2 mice, the percentage of cells that expressed p-STAT3 was 24.1 ± 5.4% in high-grade tumors (range, 0.1%–49.7%, n = 3) and 1.0 ± 0.1% in low-grade tumors (range, 0.8%–1.3%, n = 3). The intensity of staining within tumor groups appeared similar.

Given the robust development of high-grade gliomas with marked lethality in the mice injected with RCAS-PDGF-B + RCAS-Bcl-2, this particular model system was selected for the analysis of prognostic markers both for survival and for treatment studies. The percentage of cells that expressed p-STAT3 was 35.0 ± 4.2% (range, 12.9%–49.7%, n = 8) in mice that died from tumor progression compared with 2.4 ± 1.2% (range, 0.1%–5.4%, n = 4) in long-term survivors that survived past 90 days and were euthanized without succumbing to their tumor (Fig. 2C). Indeed, all mice with less than 10% of cells expressing p-STAT3 survived for the entire 90-day duration, and all mice with cells expressing a p-STAT3 level of more than 10% died (Fig. 2D).

Intratumoral immunosuppression is prognostic for survival

Because STAT3 is known to regulate Tregs and immunosuppressive macrophages, we next evaluated the presence and prognostic influence of intratumoral immunosuppression. Mice that developed high-grade gliomas developed a marked intratumoral influx of macrophages as determined by F4/80 immunohistochemical staining. There was a propensity in the PDGF-B + Bcl-2 model system for the F4/80-positive cells to colocalize with tumor along the infiltrating subependymal/periventricular edge

### Table 1. Characteristics of induced gliomas

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<tr>
<th></th>
<th>High-grade glioma</th>
<th>Low-grade glioma</th>
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<tr>
<td>Key histologic features</td>
<td>Anaplasia</td>
<td>No anaplasia</td>
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<td></td>
<td>Mitotic activity</td>
<td>Minimal mitotic activity</td>
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<tr>
<td></td>
<td>Microvascular proliferation</td>
<td>No microvascular proliferation</td>
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<tr>
<td></td>
<td>Pseudopallisading necrosis</td>
<td>No necrosis</td>
</tr>
<tr>
<td>Equivalent human grade</td>
<td>WHO grade III</td>
<td>WHO grade II</td>
</tr>
<tr>
<td>Equivalent human pathology</td>
<td>Anaplastic oligodendroglioma</td>
<td>Oligodendroglioma</td>
</tr>
<tr>
<td>PDGF-B murine system</td>
<td>Incidence of gliomas</td>
<td>19% (5/26)</td>
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<tr>
<td></td>
<td>GFAP staining</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td>Mitotic index</td>
<td>1.8%</td>
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<tr>
<td></td>
<td>Bcl-2 staining</td>
<td>Minimal</td>
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<tr>
<td></td>
<td>% cells expressing p-STAT3</td>
<td>27.9 ± 11.1</td>
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<tr>
<td></td>
<td>% of macrophages</td>
<td>16.2 ± 1.7</td>
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<tr>
<td></td>
<td>% of FoxP3-positive cells</td>
<td>5.7 ± 0.1</td>
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<tr>
<td>PDGF-B+Bcl-2 murine system</td>
<td>Incidence of gliomas</td>
<td>61% (20/33)</td>
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<td></td>
<td>GFAP staining</td>
<td>Positive</td>
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<td></td>
<td>Mitotic index</td>
<td>11.0%</td>
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<tr>
<td></td>
<td>Bcl-2 staining</td>
<td>High</td>
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<tr>
<td></td>
<td>% cells expressing p-STAT3</td>
<td>24.1 ± 5.4</td>
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<td></td>
<td>% of macrophages</td>
<td>25.6 ± 3.8</td>
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<tr>
<td></td>
<td>% of FoxP3-positive cells</td>
<td>3.6 ± 0.4</td>
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of the tumors and at markedly higher levels in high-grade tumors than in low-grade tumors, which had few, if any, macrophages (Fig. 3A). In the PDGF-B–only mice, macrophage infiltration was 16.2 ± 1.7% (range, 13.2%–19.0%, n = 3) in high-grade tumors and 0.5 ± 0.2% (range, 0.3%–1.0%, n = 3) in low-grade tumors (Fig. 3B). In the PDGF-B + Bcl-2 group, high-grade tumors showed macrophage infiltration of 25.6 ± 3.8% (range, 3.3%–43.7%, n = 12), whereas low-grade tumors had macrophage infiltration of 1.7 ± 0.9% (range, 0.3%–4.0%, n = 5). In the PDGF-B + Bcl-2 mice with high-grade gliomas, increased macrophage infiltration was associated with reduced survival time (Fig. 3C). Among long-term survivors (defined henceforth as mice surviving to 90 days that were euthanized without succumbing to their tumor), infiltration of F4/80-positive macrophages was 11.3 ± 3.8% (range, 3.3%–19.5%, n = 4), whereas in the mice that succumbed to intracranial tumors prior to 90 days, there was a macrophage infiltration of 32.8 ± 3.2% (range, 21.7%–43.7%, n = 8). Indeed, all mice with macrophage infiltration of less than 20% survived for the entire 90-day duration, and all mice with macrophage infiltration of more than 20% died (Fig. 3D).

Treg infiltration was determined using immunohistochemical staining for FoxP3. Similar levels of infiltration by FoxP3-positive cells were seen in both high- and low-grade tumors and at markedly higher levels in high-grade tumors than in low-grade tumors, which had few, if any, macrophages (Fig. 3A). In the PDGF-B–only mice and PDGF-B + Bcl-2 mice that developed gliomas, p-STAT3 levels were significantly higher in high-grade tumors than in low-grade tumors (*P < 0.05). B, in the PDGF-B–alone mice and PDGF-B + Bcl-2 mice that developed gliomas, p-STAT3 levels were significantly higher in high-grade tumors than in low-grade tumors (*P < 0.05). C, in PDGF-B + Bcl-2 mice with high-grade gliomas, animals that survived past 90 days had significantly lower tumor p-STAT3 expression than animals that succumbed to intracranial tumors before 90 days (**P < 0.0001). D, mean p-STAT3 expression in individual mice in the PDGF-B + Bcl-2 group bearing high-grade tumors plotted against overall survival time showing long-term survival of all animals with p-STAT3 expression of <10%. *, animals sacrificed after surviving past 90 days. Error bars represent standard error of the mean.
grade tumors (Fig. 4A). In the PDGF-B–only mice, Treg infiltration was 5.7/\% (range, 5.4%–5.9, n = 3) in high-grade tumors and 3.5/\% (range, 2.2%–5.0%, n = 3) in low-grade tumors (Fig. 4B). In the PDGF-B/Bcl-2 mice, high-grade tumors had Treg infiltration of 3.6/\% (range, 2.0%–6.4%, n = 12), whereas low-grade tumors had Treg infiltration of 2.8/\% (range, 2.1%–3.0%, n = 3). In the PDGF-B/Bcl-2 mice with high-grade gliomas, increased infiltration of the tumors by the Tregs was not associated with decreased survival time (Fig. 4C). Among long-term survivors, infiltration of FoxP3-positive cells was 3.6/\% (range, 2.9%–5.1%, n = 4), whereas in the mice that succumbed to intracranial tumors prior to 90 days, the FoxP3-positive cells was 3.6/\% (range, 2.0%–6.4%, n = 8). There was no correlation between the number of FoxP3-positive cells and survival duration (Fig. 4D).

WP1066 inhibits intratumoral immunosuppression that correlates with treatment response

Because coexpression of RCAS-PDGF-B and RCAS-Bcl-2 in Ntv-a mice induces tumors that express p-STAT3 and have a high incidence of glioma formation, this model was utilized to test the feasibility of ascertaining the in vivo efficacy of WP1066. Treatment with WP1066 (o.g.) commenced on day 21 after the RCAS vector injection.
median survival time for the control group was 57 days, whereas for mice treated with WP1066, the median survival times were more than 90 days ($P = 0.07$) in comparison with the vehicle control–treated mice (Fig. 5A and summarized in Table 2). For the mice treated by o.g. with WP1066 at a dose of 40 mg/kg ($n = 15$), 73% survived long term (>90 days) (chi-square test, $P = 0.07$ relative to the control group in which 40% survived long term), and there was at least a 58% increase in median survival time when the experiment was terminated at 90 days (Fig. 5A). In addition, after 90 days, all 11 of 15 (73.3%) of the surviving mice treated with WP1066 had no evidence of any intracranial tumor on histopathologic examination compared with 5 of 15 (33.3%, $P = 0.03$) of the control mice. High-grade tumors developed in 1 of 15 (6.7%) of the WP1066-treated mice relative to 4 of 15 (26.7%) in the control mice ($P = 0.16$). The tumors in the mice treated with WP1066 showed a marked decrease in p-STAT3 expression (3.6 ± 1.6%; range, 0.6%–5.9%, $n = 3$) compared with the untreated mice (36.3 ± 10.6%; range, 6.1%–51.5, $n = 4$, $P = 0.05$; Fig. 5B). Similarly, WP1066 also decreased macrophage infiltration of tumors, with treated mice having 5.0 ± 3.3% F4/80-positive cells (range, 1.6%–11.5%, $n = 3$) compared with 17.4 ± 4.9% (range, 6.0%–26.9%, $n = 4$, $P = 0.05$) in control mice (Fig. 5C). WP1066 did not affect Treg infiltration of tumors, with treated mice having 6.1 ± 3.7% FoxP3-positive cells (range, 0.7%–13.3%, $n = 3$) compared with 6.1 ± 2.0% (range, 1.6%–12.8%, $n = 5$, $P = 0.99$) in control mice (Fig. 5D).

Fig. 4. A, representative light microscopy images showing immunohistochemical staining of FoxP3 to identify infiltrating Tregs in a high-grade tumor at (i) low (100×) and (ii) high (400×) magnification, and a low-grade tumor at (iii) low (100×) and (iv) high (400×) magnification, and (v) mouse IgG isotype control (100×). B, in the PDGF-B–alone mice and PDGF-B + Bcl-2 mice, the level of Treg infiltration was observed to be similar in high- and low-grade tumors. C, in the PDGF-B + Bcl-2 group, no significant differences were observed in mean levels of Treg infiltration between mice with high-grade gliomas who survived longer than 90 days and those that succumbed to intracranial tumors before 90 days. D, in the PDGF-B + Bcl-2 group, the mean degree of Treg infiltration in individual high-grade tumor-bearing mice did not correlate with the length of survival. * animals sacrificed after surviving past 90 days. Error bars represent standard error of the mean.
There are several distinctive and novel findings in this study. The first is that WP1066 shows efficacy in a heterogeneous, orthotopic glioma model system. Utilizing the RCAS/Ntv-a system, we showed that the histopathologic characterization of the tumors recapitulated many of the fundamental characteristics seen in human high-grade gliomas, including pseudopallisading necrosis, infiltration along white matter tracts, and diffuse infiltration. Previous preclinical studies of the effects of WP1066 on gliomas were confined to a clonotypic glioma in a nonorthotopic position in an immunosuppressed murine model (35).

Second, WP1066 is exerting a therapeutic effect on A, Kaplan-Meier survival curve showing improved survival in PDGF-B and Bcl-2 mice treated with the p-STAT3 inhibitor WP1066 compared with untreated controls. B, WP1066 treatment significantly reduced levels of p-STAT3 expression. Representative light microscopy images show immunohistochemistry of p-STAT3 (brown nuclear staining) in a high-grade glioma from a vehicle control-treated mouse and a WP1066-treated mouse (400×), *P < 0.05. C, WP1066 also suppressed F4/80-positive macrophage infiltration. Representative light microscopy images showing immunohistochemistry of F4/80 (brown cytoplasmic staining) showing infiltrating macrophages/microglia in a high-grade glioma from a vehicle control-treated mouse and a WP1066-treated mouse (400×), *P < 0.05. D, WP1066 did not suppress the number of intratumoral FoxP3-positive cells. Representative light microscopy images showing immunohistochemistry of FoxP3 (brown staining) from a vehicle control-treated mouse and a WP1066-treated mouse (400×).

Table 2. Treatment response of WP1066-treated RCAS-PDGF-B + RACSBcl-2–induced gliomas

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<thead>
<tr>
<th></th>
<th>Control</th>
<th>WP1066</th>
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<tr>
<td>Median survival, d</td>
<td>57</td>
<td>90</td>
</tr>
<tr>
<td>Development of high-grade gliomas on day 90</td>
<td>26.7%</td>
<td>6.7%</td>
</tr>
<tr>
<td>% of p-STAT3–expressing cells</td>
<td>36.3 ± 10.6</td>
<td>3.6 ± 1.6</td>
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<tr>
<td>% of macrophages</td>
<td>17.4 ± 4.9</td>
<td>5.0 ± 3.3</td>
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<tr>
<td>% of Tregs</td>
<td>6.1 ± 2.0</td>
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</table>

Discussion

There are several distinctive and novel findings in this study. The first is that WP1066 shows efficacy in a heterogeneous, orthotopic glioma model system. Utilizing the RCAS/Ntv-a system, we showed that the histopathologic characterization of the tumors recapitulated many of the fundamental characteristics seen in human high-grade gliomas, including pseudopallisading necrosis, infiltration along white matter tracts, and diffuse infiltration. Previous preclinical studies of the effects of WP1066 on gliomas were confined to a clonotypic glioma in a nonorthotopic position in an immunosuppressed murine model (35). Second, WP1066 is exerting a therapeutic effect on
oligodendrogliomas, which has not been previously described. Finally, we are not aware of any previous attempts at correlating a novel, murine model system, including tumor-mediated immunosuppression mechanisms, with human immune prognostic biology in the context of an immunotherapeutic strategy. Specifically, we showed that the expression in vivo of STAT3 in the RCAS-PDGF-B and RCAS-PDGF-B + RCAS-Bcl-2 models of glioma correlated with glioma grade and prognosis, similar to the findings in human glioma patients (18). In addition, the murine gliomas also showed an influx of macrophages that correlated with grade and prognosis seen in human glioma patients (48–51). These tumor-associated macrophages have previously been shown to enhance tumorigenesis, invasion, and angiogenesis in the tumor microenvironment (26, 52–55). There was a propensity of the macrophages to distribute in the subependymal region in the murine models, likely related to the mechanism of induction of tumor, in contrast to the localization of macrophages in regions of pseudopallisading necrosis commonly seen in human gliomas. Finally, we found FoxP3-positive cells were present, albeit low at 6% in the murine glioma microenvironment they did not correlate with grade and were not prognostic. These findings are comparable with observations in human patients with oligodendrogliomas (56). It is possible that the FoxP3 expression was occurring within the cancer cells (57); however, we confined our counts to those cells that had a lymphocyte morphology. These data, in conjunction with another study showing that the immune infiltration in spontaneous mouse astrocytomas evolved along with the stages of tumor development (58), indicate that these murine model systems may be suitable for the study of immunotherapeutic approaches because many features of tumor-mediated immunosuppression observed in these systems seem similar to those seen in human glioma patients.

The STAT3 inhibitor WP1066 exerted a therapeutic benefit, inhibited intratumoral p-STAT3 expression, and suppressed intratumoral macrophage infiltration that correlated with treatment response. Although FoxP3 expression is under transcriptional control of STAT3 (28, 59) and WP1066 has been previously shown to inhibit Tregs in the systemic circulation (29, 60), we did not find a decrease in the level of FoxP3 expression during treatment with WP1066. The failure of WP1066 to further decrease the numbers of FoxP3-expressing cells in the oligodendroglioma-like tumors in this animal model system may simply reflect the low baseline levels. Although p-STAT3 is not ubiquitously expressed in all tumor cells in the murine model system, there is nonetheless marked in vivo efficacy. This discrepancy can be resolved by the activity of WP1066 exerting direct effects both on tumor cells expressing p-STAT3 and on the immune cells expressing p-STAT3, which restraints their antitumor activity including recognition of tumor-associated and tumor-specific antigens. The inhibition of p-STAT3 restores antitumor immune clearance (27, 61) and therefore we suspect that WP1066 exerts a bystander effect on p-STAT3 negative–expressing cells by eradicating those tumor cells that can be immunologically recognized. This contention is supported by the fact that therapeutic efficacy of WP1066 is lost in nude models systems and with in vivo depletions of the CD4 and CD8 subpopulations (unpublished data).

A confounding problem in the use of these model systems is that tumor incidence is not 100% and thus a randomization schema is necessary. Furthermore, it is unpredictable which mice develop tumors, the exact onset of tumor development, and the pathologic grade at the time of treatment initiation. Finally, because the transgenes are introduced in the neonatal period, onset of treatment also needs to be stratified and/or randomized on the basis of age because most facilities would be unlikely to be able to accommodate sufficient breeding pairs to have adequate numbers of animals for entry into treatment groups. This did not pose a significant hardship in the current studies in which only 2 experimental cohorts were utilized; however, for much more complex immunotherapeutic efficacy trials, especially those involving combinational approaches, this will introduce complexity in the design. A recent study by Singh et al. proposed that the use of genetically engineered murine models might more reliably predict human clinical outcomes (62). In the context of their study, a correlation was made with chemotherapeutics. We now propose that these genetically engineered murine models may also be suitable for the testing of immunotherapeutics based, in part, on the biology recapitulating many of the hallmark features of high-grade gliomas, on the correlative nature of the immunosuppressive biology and, specifically, the intratumoral biology.

Disclosure of Potential Conflicts of Interest

W. Priebe and A.B. Heimberger hold patents and have a financial interest in the development of WP1066.

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