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Detailed Terms
Improved tumor oxygenation and survival in glioblastoma patients who show increased blood perfusion after cediranib and chemoradiation


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Contributed by Rakesh K. Jain, October 2, 2013 (sent for review August 8, 2013)

Antiangiogenic therapy has shown clear activity and improved survival benefit for certain tumor types. However, an incomplete understanding of the mechanisms of action of antiangiogenic agents has hindered optimization and broader application of this new therapeutic modality. In particular, the impact of antiangiogenic therapy on tumor blood flow and oxygenation status (i.e., the role of vessel pruning versus normalization) remains controversial. This controversy has become critical as multiple phase III trials of anti-VEGF agents combined with cytotoxics failed to show overall survival benefit in newly diagnosed glioblastoma (nGBM) patients and several other cancers. Here, we shed light on mechanisms of nGBM response to cediranib, a pan-VEGF receptor tyrosine kinase inhibitor, using MRI techniques and blood biomarkers in prospective phase II clinical trials of cediranib with chemoradiation vs. chemoradiation alone in nGBM patients. We demonstrate that improved perfusion occurs only in a subset of patients in cediranib-containing regimens, and is associated with improved overall survival in these nGBM patients. Moreover, an increase in perfusion is associated with improved tumor oxygenation status as well as with pharmacodynamic biomarkers, such as changes in plasma placenta growth factor and sVEGFR2. Finally, treatment resistance was associated with elevated plasma IL-8 and sVEGFR1 posttherapy. In conclusion, tumor perfusion changes after antiangiogenic therapy may distinguish responders vs. nonresponders early in the course of this expensive and potentially toxic form of therapy, and these results may provide new insight into the selection of glioblastoma patients most likely to benefit from anti-VEGF treatments.

Significance

This study demonstrates that antiangiogenic therapy increases tumor blood perfusion in a subset of newly diagnosed glioblastoma patients, and that it is these patients who survive longer when this expensive and potentially toxic therapy is combined with standard radiation and chemotherapy. This study provides fresh insights into the selection of glioblastoma patients most likely to benefit from antiangiogenic treatments.
underlying patient characteristics, different tumor types, or class and dose of antiangiogenic treatments. Given the recent failure of bevacizumab to extend overall survival when combined with chemoradiation in phase III trials in newly diagnosed GBM (nGBM), further investigation is essential to improve understanding of why antiangiogenic agents may be effective in certain patients but not in others (9).

Preclinical and clinical studies in a number of solid tumors, including recurrent GBM (rGBM), have demonstrated that after the administration of antiangiogenic therapies a subset of rGBM patients experience a transient period of vascular normalization characterized by increased perfusion, reduced vessel diameter and permeability, specific circulating biomarker changes, reduction in tumor interstitial pressure, and improved tumor oxygenation (10–16). These parameters can be used to generate a “vascular normalization index” to help identify rGBM patients most likely to benefit from antiangiogenic therapy (17, 18). However, whether tumor perfusion and oxygenation increase during combined antiangiogenic and cytotoxic treatments and whether this increased perfusion improves overall survival are not known. Increased tumor perfusion may enhance delivery of concurrently administered anticancer therapeutics, reduce hypoxia, and improve patient outcomes. Here, we demonstrate that cediranib, an oral pan-VEGF receptor tyrosine kinase (RTK) inhibitor, in combination with chemotherapy and radiation, increases perfusion and oxygenation in 50% of patients with nGBM, and that these patients survive 9-mo longer than those whose perfusion does not increase. In contrast, tumor perfusion increased in only 1 of 14 nGBM patients from a contemporary control group treated with chemotherapy and radiation without cediranib.

**Results**

**Cediranib with Chemoradiation Normalizes nGBM Vasculature.** Forty-six patients with histologically confirmed nGBM were enrolled in a prospective phase IIb (n = 6)/II (n = 40) clinical trial of cediranib in combination with radiation and temozolomide (NCT00662506). All patients had at least 1 cm of measurable, residual contrast-enhancing tumor after surgery, as gross total tumor resection was an exclusion criterion. Patients received 6 wk of fractionated radiation along with daily temozolomide, the current standard of care, and cediranib was administered daily (Table 1 and Fig. S1). The median progression-free survival (PFS) was 15.6 mo (95% confidence interval (CI): 9.3, 26.0 mo) and median overall survival (OS) was 20.2 mo (95% CI: 16.7, 29.4 mo) for all 46 study subjects. With the exception of one patient who experienced biopsy-proven early disease progression, all patients responded to therapy with durable reductions in volume of contrast enhancement, volume of vasogenic edema [estimated by abnormal fluid-attenuated inversion recovery (FLAIR) hyperintensity and diffusion imaging], tumor vascular permeability (estimated by $K_{trans}$), and tumor vessel size (Fig. 1 and Fig. S2). These markers of vascular normalization persisted throughout the 6 wk of combined antiangiogenic and chemoradiation therapy. Moreover, 26 of 30 patients who were taking corticosteroids at the start of chemoradiation—to control vasogenic edema—were able to reduce or discontinue these antiedema drugs.

**Patients with Increased Perfusion Have Improved Oxygenation and Survival.** Twenty of 40 patients (50%) who underwent advanced imaging experienced a durable and consistent increase in microvessel tumor perfusion (Fig. 2A and Table S1), 10 patients (25%) experienced stable perfusion, and 10 patients (25%) experienced a decrease in perfusion. These perfusion changes were noted as early as day 1 of chemoradiation and the three groups remained stable and distinct during the 6 wk of combination treatment (Fig. 2B and Table S1). A similar durable increase in tumor perfusion was observed in only 1 of 14 contemporary patients with nGBM who underwent MRI at similar time points and were treated with radiation and temozolomide but not cediranib (NCT00756106). After stratifying patients based on O6-methyl guanine methyl transferase (MGMT) gene-promoter methylation status and performance status, established prognostic factors in nGBM, the median OS in patients with increased perfusion was 789 d (26.3 mo) compared with 510 d (17.0 mo) in those with stable or decreased perfusion ($P < 0.05$) (Fig. 2C and Table S1). Patients with MGMT methylation status or other favorable prognostic factors were not overrepresented in the increased perfusion group or underrepresented in the stable of decreased perfusion groups (Table 1). Patients in the standard treatment cohort had a median OS of 431.5 d (14.2 mo) with 95% CI from 340 d (11.2 mo) to 881 d (28.9 mo), which was comparable to the decreased/stable perfusion group (Table S2).

Vessel architectural imaging (VAI), which reflects the relative difference between arteriolar and venule oxygen saturation levels ($\Delta$SO$_2$) and thus tissue oxygen consumption, demonstrated that the average tumor $\Delta$SO$_2$ levels before treatment onset (day −1) were higher than normal-appearing reference tissue ($P < 0.05$). A higher value implies impaired delivery of oxygen to the tumor (19). During cediranib therapy and compared with baseline, abnormal $\Delta$SO$_2$ levels collectively decreased from day +1 through day +50 for patients with increased microvessel perfusion, reflecting a return of $\Delta$SO$_2$ levels to that of healthy brain tissue, consistent with improved delivery of oxygen to the tumor (Fig. 3, and Figs. S3 and S4). This finding was supported by normalization of abnormal arteriole $\Delta$SO$_2$ levels (Fig. S5A) and abnormal venule $\Delta$SO$_2$ levels (Fig. S5B). In contrast, patients with stable and decreased microvessel perfusion had stable or increased tumor $\Delta$SO$_2$ levels, reflecting a lack of improved

**Table 1. Patient characteristics**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cediranib + chemoradiation (n = 46)</th>
<th>Chemoradiation alone (n = 14)</th>
<th>Perfusion increased* (n = 20)</th>
<th>Perfusion stable/reduced* (n = 20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>57 (22–74)</td>
<td>60 (35–70)</td>
<td>59 (22–74)</td>
<td>57 (41–67)</td>
</tr>
<tr>
<td>KPS (0–100)</td>
<td>90 (60–100)</td>
<td>100 (60–100)</td>
<td>100 (90–100)</td>
<td>90 (60–100)</td>
</tr>
<tr>
<td>EOR (n)</td>
<td>36 subtotal resection</td>
<td>10 subtotal resection</td>
<td>16 subtotal resection</td>
<td>16 subtotal resection</td>
</tr>
<tr>
<td></td>
<td>10 biopsy</td>
<td>4 biopsy</td>
<td>4 biopsy</td>
<td>4 biopsy</td>
</tr>
<tr>
<td>Sex (n)</td>
<td>14 women</td>
<td>8 women</td>
<td>8 women</td>
<td>5 women</td>
</tr>
<tr>
<td></td>
<td>32 men</td>
<td>6 men</td>
<td>12 men</td>
<td>15 men</td>
</tr>
<tr>
<td>MGMT (n)</td>
<td>19 methylated</td>
<td>2 methylated</td>
<td>8 methylated</td>
<td>7 methylated</td>
</tr>
<tr>
<td></td>
<td>18 unmethylated</td>
<td>8 unmethylated</td>
<td>9 unmethylated</td>
<td>10 unmethylated</td>
</tr>
<tr>
<td></td>
<td>9 unable to determine†</td>
<td>4 unable to determine†</td>
<td>3 unable to determine†</td>
<td>3 unable to determine†</td>
</tr>
</tbody>
</table>

EOR, extent of resection.

*Total n = 40 patients in the phase II component of study.

†Technical failure or insufficient tissue.
A number of potential pharmacodynamic and combination therapy decreased plasma basic FGF, sVEGFR1, sVEGFR2, and Ang-2, and increased plasma VEGF, placental growth factor (PIGF), stromal cell-derived factor 1α (SDF1α), IL-6, IL-8, TNF-α, and carbonic anhydrase IX (CAIX) (Table S3). The changes in plasma PIGF and sVEGFR2 were significantly different in patients treated with cediranib and chemoradiation compared with patients treated with chemoradiation alone (Tables S4 and S5).

No baseline or early change in biomarkers showed consistent association with outcomes. However, high levels of plasma sVEGFR1 at day 29 correlated with poor PFS [hazard ratio (HR) = 1.84 (1.02, 3.32), n = 40] and OS [HR = 1.90 (1.01, 3.58), n = 40] (both P < 0.05). Similarly, high levels of IL-8 at day 43 (end of combination therapy) correlated with poor PFS [HR = 2.74 (1.57, 4.80), n = 38; P < 0.001] and showed a nonsignificant trend for association with poor OS [HR = 1.48 (0.93, 2.35), n = 38; P = 0.09]. No other proangiogenic or inflammatory protein showed correlations with outcome. Of note, an increase in blood perfusion was significantly associated with greater increases in plasma PIGF and with greater decreases in sVEGFR2 during treatment, but not with their baseline values (Fig. 4 and Table S6).

**Impact of RTK Amplification Profile on Survival.** To investigate whether amplification of EGFR, PDGFRα, and MET genes predicts response or resistance to cediranib, we evaluated initial diagnostic samples of these patients for EGFR, PDGFRα, and MET amplification. EGFR was tested in 45 cases, and PDGFRα and MET could be tested in 31 samples (Table S7). The presence of EGFR, MET or PDGFRα amplification showed no association with response to combination therapy or survival. Interestingly, we observed that amplification of EGFR was associated with stable or decreased perfusion (P < 0.05) (Table S8).

**Discussion**

Cediranib, a small-molecule tyrosine kinase inhibitor of all three VEGF receptors as well as platelet derived growth factor receptor (PDGFR) and c-kit, showed promising activity in nGBM. These results in our overall study population of nGBM patients undergoing only biopsy or subtotal resection compared favorably to historic controls treated with radiation and temozolomide alone, as well as preliminary data from a phase III trial of patients with nGBM treated with bevacizumab and chemoradiation (3, 9). However, as observed in other trials of antiangiogenic therapies in GBM, the beneficial clinical impact is primarily on PFS and disease progression is typically rapid after conventional radiographic progression, accounting for the more modest improvement in OS (9, 22, 23).

Our physiological MRI evaluations showed that the addition of cediranib to chemoradiation improved vascular integrity and perfusion in 20 out of 40 (50%) patients, compared with only 1 out of 14 (7%) patients treated with conventional chemoradiation alone. Temozolomide may have mild antiangiogenic properties when given at a low daily dose (i.e., a “metronomic” schedule), which might explain the elevated perfusion in this one patient (24). However, the higher prevalence of increased perfusion in patients treated with cediranib suggests that antiangiogenic therapy with cediranib contributed to the elevated blood perfusion. The impact of increased perfusion was evident with stratification based on MGMT methylation status, so even patients with unmethylated MGMT seemed to benefit from increased tumor perfusion. Although a randomized control group would be ideal for comparative purposes, this is not feasible in a single institution study using advanced imaging and comprehensive blood biomarker analyses. Moreover, the successful replication of advanced MRI techniques and protocols, similar to those used in this study, across multiple institutions and imaging platforms has yet to be achieved in the randomized trial setting in the glioblastoma patient population. Therefore, although imperfect, the inclusion of a contemporary control group with similar study eligibility criteria from within our own institution offered the best opportunity for comparisons.

To further explore the link between perfusion and oxygenation, we recently developed a technique (VAI) to measure ΔSO₂ (the fractional saturation of hemoglobin with oxygen) in tumors (19). The ΔSO₂ parameter, as measured by MRI, is sensitive to changes in deoxygenated blood and reflects the relative difference between arteriole and venule oxygen saturation levels, and thus tissue oxygen consumption. Using VAI, we demonstrated that the same nGBM patients who respond to cediranib with increased perfusion also have improved delivery of oxygen to the tumor. The current study in nGBM patients mirrors this finding. Specifically, we observed that nGBM patients with improved tumor blood perfusion after cediranib treatment had improved OS, controlling for the established prognostic markers in this study.

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Type of brain cancer. Because this marker of vascular normalization was observed in a subset of nGBM patients in the trial, despite almost all patients experiencing a decrease in contrast enhancement and brain edema, the improvement in survival could not solely be attributed to the antipermeability and antiedema effect of cediranib. We hypothesize that the critical factor is improved vascular function, which (i) enhanced tumor oxygenation and potentially sensitized tumor cells to the cytotoxic actions of chemoradiation, and (ii) potentially improved tumor delivery of temozolomide (25, 26). A study in a murine U87 GBM model demonstrated that intratumoral concentrations of temozolomide were higher when administered with cediranib (27). Furthermore, cediranib has also been reported to have its own tumoricidal effects (18, 28). Thus, improved tumor delivery of this agent through normalization also might have benefited patients through a direct cytotoxic effect in both rGBM and nGBM patients. Finally, vascular normalization after antiangiogenic therapy can reprogram the immunosuppressive microenvironment that is characteristic of tumors and inhibits the body’s native defenses against cancer development. As a result, there may be enhanced native antitumor immune responses (29, 30).

To date, no validated blood biomarkers of tumor vascular normalization have been identified in cancer patients treated with antiangiogenic therapies. Circulating VEGF level has been a natural candidate biomarker for response. However, we observed no association of circulating VEGF with outcomes after cediranib with chemoradiation in this trial, consistent with a lack of correlation with outcomes seen in many studies of anti-VEGF agents (21). Furthermore, consistent with the results from a study of cediranib in rGBM (10), we detected an association between sVEGFR1 levels after 4 wk of treatment and PFS after cediranib/chemoradiation in nGBM. We previously proposed that sVEGFR1—a negative regulator of the VEGF pathway—is a potential resistance biomarker to anti-VEGF therapy (31). However, because cediranib significantly decreases sVEGFR1 levels in circulation, future studies should determine if the associations observed are because of the biological effects of sVEGFR1 or because of “pharmacodynamic” changes in its level as a result of treatment.
Moreover, cediranib with chemoradiation—but not chemoradiation alone—consistently increased PlGF and decreased plasma sVEGFR2. We and others have demonstrated that anti-VEGF therapy is invariably associated with increases in PlGF and decreases in plasma sVEGFR2 across different anti-VEGF tyrosine kinase inhibitors (e.g., cediranib, sorafenib, vandetanib, sunitinib) and different cancers (10, 31–36). Thus, data from our study support the notion that PlGF and sVEGFR2 should be further explored as pharmacodynamic biomarkers (i.e., surrogate biomarkers of biological activity). The biological activity of anti-VEGF agents has been assumed to be an antivascular effect reflected by a decrease in tumor vascular density and decreased blood perfusion. However, our data show that a greater increase in PlGF or decrease in sVEGFR2 is actually associated with an improvement in blood perfusion in nGBM. Future studies should validate this concept and establish whether PlGF—the increase of which is largely a result of systemic effects of anti-VEGF therapy—has any direct role in mediating vascular function in nGBM (37).

Inflammatory factors have been linked with resistance to anti-VEGF therapy in multiple studies in glioblastoma (10, 38). Here, we detected increases in multiple cytokines in circulation during and after cediranib with chemoradiation, which were concomitant with plasma elevations in the hypoxia marker CAIX. However, only plasma levels of IL-8 after treatment showed an association with poor survival outcomes and warrants further exploration as an escape biomarker in larger studies.

Finally, we examined if genetic heterogeneity in nGBMs may account for differences in response to cediranib and chemoradiation. EGFR, PDGFRA, and MET are the most frequently amplified genes in GBM, and PDGFRA is often amplified with KIT and VEGFR2 because all three are located on chromosome 4q12 (39–41). PDGFRA, KIT, and VEGFR2 RTK activity is directly inhibited by cediranib, whereas that of EGFR and MET is not. We observed no correlation between the presence of EGFR, MET, or PDGFRA amplification and survival after treatment. This result may be because of the low number of PDGFRA or MET amplified GBM cases or to concomitant EGFR or MET amplification in two tumors, which also harbored PDGFRA amplification. The importance of these concurrent subclones is currently unknown but highlights the complexity of treating these tumors with single targeted drugs. Of note, we observed a correlation between EGFR amplification and a lack of increase in perfusion after treatment. Future studies should determine whether EGFR amplification is causally related to changes in vascular function after anti-VEGF therapy or is merely a poor prognostic variable (42).

In conclusion, we provide direct evidence that improved tumor perfusion—a consequence of vascular normalization—is associated with improved oxygenation and longer OS in nGBM patients treated with combination antiangiogenic and cytotoxic therapy. These results are consistent with our finding that rGBM patients treated with cediranib monotherapy had improved OS in a subset of subjects with increased perfusion (18). Taken together, these observations suggest that anti-VEGF agents improve OS only in the subset of GBM patients who experience increased tumor perfusion and oxygenation and not in all patients. This finding may account for the failure of cediranib and bevacizumab to extend OS in randomized phase III trials conducted in unselected nGBM and rGBM patient populations (9, 43, 44). We also identified tissue markers, as well as circulating blood proteins that may serve as biomarkers of changes in tumor perfusion and oxygenation during anti-VEGF therapy. This finding indicates that vascular normalization—and not vessel pruning—is a potential mechanism of benefit for GBM patients.

Materials and Methods

Study Design. Data were obtained from two prospective, concurrent clinical studies (NCT00662506 and NCT00756106) performed at the Massachusetts General Hospital Cancer Center and the Dana Farber Cancer Institute (SI Materials and Methods).

Fig. 3. Relative arteriole-to-venule oxygen saturation ($\Delta SO_2$) levels. In patients with increased tumor perfusion, $\Delta SO_2$ decreases suggesting improved oxygenation, whereas $\Delta SO_2$ increased in patients with decreased perfusion suggesting impaired delivery of oxygen to the tumor.

Fig. 4. Kinetics of VEGF family proteins in nGBM patients treated with cediranib and chemoradiation. (A) Circulating PlGF. (B) Circulating sVEGFR2. Data are shown as median levels (pg/mL) in patients with increased, stable, or decreased perfusion after treatment.
Analyses of RTK Gene Amplification in nGBM Tissue Specimens. Evaluation of the three most commonly amplified RTK genes in glioblastoma was performed in all cases with sufficient tissue using FISH, as previously described (39) (SI Materials and Methods).

Circulating Biomarkers. Peripheral blood was obtained from all patients with advanced imaging studies (n = 40 from NCT00662506 and n = 14 from NCT00756106) and evaluated as previously described (11) (SI Materials and Methods).

MRI. MRI studies were performed before and at multiple time points after treatment. MRI scans were obtained weekly during the 6 wk of concurrent chemoradiation and cediranib, then monthly. MRI scans included scout, pre- and postcontrast T1-weighted images, FLAIR, dynamic susceptibility contrast imaging, dynamic contrast-enhanced imaging, diffusion tensor imaging, and VAI analysis (SI Materials and Methods).

Statistical Analysis. Groups were compared using exact Mann-Whitney and Fisher tests (for comparisons of circulating biomarkers and genotypes), as well as stratified log-rank test and Wald test in Cox regression analysis with log-transformed covariates (for survival data). Biomarker changes were expressed as ratios, reported as median with interquartile intervals, and tested using exact paired Wilcoxon test. P values of less than 0.05 were considered statistically significant.

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