CD44 Attenuates Activation of the Hippo Signaling Pathway and Is a Prime Therapeutic Target for Glioblastoma
Yin Xu1, Ivan Stamenkovic1,2, and Qin Yu1

Abstract
Glioblastoma multiforme (GBM) is the most aggressive brain tumor that, by virtue of its resistance to chemotherapy and radiotherapy, is currently incurable. Identification of molecules whose targeting may eliminate GBM cells and/or sensitize glioblastoma cells to cytotoxic drugs is therefore urgently needed. CD44 is a major cell surface hyaluronan receptor and cancer stem cell marker that has been implicated in the progression of a variety of cancer types. However, the major downstream signaling pathways that mediate its protumor effects and the role of CD44 in the progression and chemoresponse of GBM have not been established. Here we show that CD44 is upregulated in GBM and that its depletion blocks GBM growth and sensitizes GBM cells to cytotoxic drugs in vivo. Consistent with this observation, CD44 antagonists potently inhibit glioma growth in preclinical mouse models. We provide the first evidence that CD44 functions upstream of the mammalian Hippo signaling pathway and that CD44 promotes tumor cell resistance to reactive oxygen species–induced and cytotoxic agent–induced stress by attenuating activation of the Hippo signaling pathway. Together, our results identify CD44 as a prime therapeutic target for GBM, establish potent antiglioma efficacy of CD44 antagonists, uncover a novel CD44 signaling pathway, and provide a first mechanistic explanation as to how upregulation of CD44 may constitute a key event in leading to cancer cell resistance to stresses of different origins. Finally, our results provide a rational explanation for the observation that functional inhibition of CD44 augments the efficacy of chemotherapy and radiation therapy.

Introduction
It is now well established that the host tissue microenvironment provides an essential contribution to cancer progression and modulates the response of cancer cells to treatments, implying that elements within the tumor microenvironment constitute potentially important targets for anticancer therapy (1–4). The tumor microenvironment consists of resident and infiltrating host cells as well as the components of ECM. Physical interactions and functional cross-talk between tumor cells and their microenvironment are mediated primarily by cell surface receptors that are responsible for the cell-cell and cell-ECM adhesion, thereby providing potentially attractive therapeutic targets (5).

Malignant gliomas are the most common type of primary brain cancer, the most malignant being grade IV astrocytoma, also known as glioblastoma multiforme (GBM; ref. 6). Despite aggressive multimodal therapy, GBM remains incurable, with an estimated median survival of <1 year and with <3% of patients surviving longer than 5 years (6, 7). Identification of new therapeutic targets and means to improve the efficacy of existing forms of therapy are therefore urgently needed.

The central nervous system contains elevated levels of the glycosaminoglycan hyaluronan (HA; ref. 8) and glioma cells express the major cell surface HA receptor CD44 (9), which is implicated in diverse cellular functions (9–12). CD44 is upregulated in a broad range of malignant tumors, and its elevated expression correlates with poor prognosis of some cancer types (9–12). CD44 plays an important role in melanoma (13, 14) and breast cancer (15–17) growth and progression, but little is known about its contribution to the progression of GBM and the response of GBM cells to chemotherapy. CD44 has been associated with numerous signaling events and serves as a coreceptor of several receptor tyrosine kinases (RTK; ref. 9–12), but no single major downstream signaling pathway of CD44 has been defined to date.

The cytoplasmic domain of CD44 interacts with ezrin–radixin–moesin family proteins (18) and merlin (19, 20), which serve as linkers between cortical actin filaments and the plasma membrane (21, 22). In Drosophila, merlin functions upstream of the Hippo signaling pathway that plays an important role in restraining cell proliferation and promoting apoptosis (23–26). Although still incompletely characterized, the Hippo pathway is believed to be conserved in mammals (27, 28). Mammalian homologues of Hippo, Warts,
Yorke, and dIAP are, respectively, mammalian sterile twenty-like kinase 1/2 (MST1/2; refs. 26, 29), large tumor suppressor homologue 1/2 (Lats1/2; ref. 30), Yes-associated protein (YAP; ref. 31), and cellular inhibitor of apoptosis (cIAP1/2; ref. 28). However, the upstream components of the mammalian Hippo signaling pathway have not been identified.

We have shown recently that merlin activates the Lats2 signaling pathway in human glioblastoma cells, sensitizes the response of GBM cells to chemotherapeutic agents, and inhibits GBM growth in vivo (27) and that merlin exerts its tumor suppressor function by inhibiting the hyaluronan-CD44 interaction (32). We therefore addressed the possibility that CD44 may play a potentially important role in malignant glioma growth, progression, and response to chemotherapy by regulating the mammalian Hippo signaling pathway. Our results show that CD44 is upregulated in human GBM and that knockdown of CD44 expression inhibits GBM cell growth and sensitizes GBM cells to cytotoxic drugs in vitro. Moreover, we provide the first evidence that CD44 functions upstream of mammalian Hippo signaling pathway and protects GBM cells from reactive oxygen species (ROS)– and cytotoxic agent–induced stress and apoptosis by attenuating the activity of the entire Hippo signaling pathway and that of the downstream c-Jun NH2-terminal kinase (JNK)/p38 kinases and by decreasing induction of p53 expression. We further show that purified soluble CD44-Fc fusion proteins potently inhibit growth of preestablished intracranial GBM in mice and significantly extend survival of the animals. Our results thus identify CD44 as an important therapeutic target for GBM and help establish CD44 antagonists as potent anti-GBM agents. They also uncover the first candidate signaling pathway whose activation seems to be directly dependent on CD44 dysfunction and provide a mechanistic basis for CD44 involvement in GBM progression and chemoresistance.

Materials and Methods

Patient glioma samples and reagents. The glioma tissues were obtained from the Cooperative Human Tissue Network. Anti-MST1/2, -Lats1/2 (Bethyl Lab), -CD44, -Erk1/2, -AKT, -JNK, -p21, -p38, -p53, -cIAP1/2, and -merlin (Santa Cruz), -actin (Sigma), -v5 epitope, -phospho-merlin, -puma (Invitrogen), -cleaved caspase-3, -phospho-Erk1/2, -phospho-AKT, -phospho-JNK, -phospho-p38, -phospho-MST1/2, -phospho-Lats1, -phospho-YAP (Cell Signaling), -YAP, -phospho-Lats2 (Abnova), and -heparan sulfate (HS, CalBiochem) antibodies were used in the experiments. Apoptag kit was from Chemicon and anti-BrdUrd from Roche.

CD44-Fc fusion expression constructs, mutagenesis, and knockdown constructions. Three human soluble CD44-Fc (hsCD44) fusion proteins were generated by fusing the extracellular domain of human CD44v3-v10, CD44v8-v10, or CD44s to the constant region (Fc) of human IgG1. R41A mutants of these CD44-Fc fusion proteins were generated using the QuikChange mutagenesis kits (Stratagene) as described (16). Several shRNAmir and TRC constructs against human CD44 and a nontargeting shRNAmir and a nontargeting TBC control shRNA were obtained from Open Biosystems and Addgene.

Production and purification of soluble CD44-Fc and soluble CD44R41A-Fc fusion proteins. COS-7 cells infected with the retroviruses carrying hsCD44v3-v10-Fc, hsCD44v8-v10-Fc, hsCD44s-Fc, hsCD44v3-v10R41A-Fc, hsCD44v8-v10R41A-Fc, and hsCD44sR41A-Fc constructs were cultured in RPMI medium containing 10% fetal bovine serum (FBS) until confluence and were then switched to serum-free RPMI medium for an additional 3 d of culture. The conditioned cell culture medium was retrieved, and the fusion proteins were purified on protein A columns (GE Healthcare Biosciences). Before elution from protein A column, some preparations of the bound CD44-Fc fusion proteins were treated with heparinase I (10 units/mL) and heparinase III (2 units/mL) at 37°C for 4 h.

Western blot analysis, immunocytochemistry, and fluorescein-labeled HA binding assay. Western blots and immunocytochemistry were performed as described (27, 32). To assess fluorescein-labeled HA (FL-HA) binding, GBM cells were cultured in 35-mm dishes for 24 to 48 h; 20 μg/mL FL-HA were added to the cultured cells for an additional 12 h. The FL-HA binding assay was performed as described previously (33).

Subcutaneous and intracranial tumor growth experiments and bioluminescence imaging analysis of the intracranial gliomas. Mice were used in accordance with the approved Institutional Animal Care and Use Committee Protocol. Pooled populations of transduced U87MG and U251 glioma cells were used in subcutaneous and intracranial tumor growth experiments as described (27). Briefly, 2 or 5 × 106 glioma cells were injected subcutaneous into each immunocompromised B6.129S7-Rag1tmMom (Rag1, Jackson Lab) mouse. For the intracranial tumor growth experiments, U87MG (4 × 105 cells in 10 μL HBSS/Rag1 mouse) or U251 cells (2 × 105 cells in 10 μL HBSS/Rag1 mouse) were injected as described (27). Following the injections, mice were monitored closely and the duration of their survival was recorded. Mice that showed signs of distress and morbidity were euthanized and considered as if they had died on that day. Survival rates were calculated as follows: survival rate (%) = (number of mice still alive / total number of experimental mice) × 100%. Bioluminescence imaging approach is used to monitor the growth of intracranial gliomas in live animal as described (27) using IVIS-200 imaging system (Xenogen). Images were obtained 12 min after injection of α-luciferin using the same intensity scaling.

Statistics. One-way ANOVA statistical analyses were performed to analyze differences of the tumor volumes and growth rates between the control and experimental groups. Log-rank analyses were performed for the survival experiments. Differences were considered statistically significant at P < 0.05.

Results

CD44 is upregulated in human GBM. To determine CD44 expression levels in GBM, we mined available gene
In all four independent data sets, CD44 transcripts were consistently upregulated in human GBM compared with either normal brain (Fig. 1A, studies 1, 2, and 4; refs. 35–37) or normal white matter (study 3; ref. 38). In addition, immunohistochemistry analysis of paraffin sections of primary tumors showed that CD44 was upregulated in all 14 GBM cases analyzed compared with eight cases of normal human brain (Fig. 1B; data not shown).

To address the role of CD44 in GBM growth and progression, we analyzed CD44 protein levels in a variety of human glioma cell lines. We found that the majority of the glioma cells tested express higher levels of CD44 than normal human astrocytes (NHA) and that the standard 85 to 90 kDa form (CD44s; Fig. 1C) is the predominant isoform expressed. Based on their high CD44 expression level and their tumorigenicity in immunocompromised mice, U87MG and U251 glioma cells were selected to investigate how CD44 contributes to GBM growth and progression.

Lentiviral-based shRNAs effectively knock down CD44 expression in human GBM cells. To knock down endogenous CD44 expression in GBM cells, we screened a set of human CD44-specific shRNA constructs (shRNA-TRC-CD44#1–#5 and shRNAmir-CD44#1–#3, Open Biosystems) Nontargeting (NT) control shRNAs (shRNA-TRC-NT and shRNAmir-NT) were included as the negative controls. We found that two of three shRNAmir (shRNAmir-CD44#1 and #3) and one to two TRC-shRNAs (shRNA-TRC-CD44#3 and/or #4) knocked down CD44 expression efficiently in U87MG and U251 GBM cells, as assessed by real-time qPCRs (data not shown), Western blot analysis (Supplementary Fig. S1A), and immunocytochemistry (Supplementary Fig. S1B), whereas nontargeting controls displayed no effect. Furthermore, effective knockdown of CD44 expression dramatically reduced binding and endocytosis of FL-HA, whereas nontargeting shRNAs had no effect (Supplementary Fig. S1C).

Knockdown of CD44 expression inhibits subcutaneous growth of GBM cells by inhibiting their proliferation and promoting their apoptosis in vivo. Pooled populations of the transduced U87MG and U251 cells with different degrees of CD44 depletion were used in subcutaneous tumor growth experiments. Decreased CD44 expression in these cells correlated with reduced tumor volume (Fig. 2A) and significantly reduced growth rates in vivo (Fig. 2B). We observed that the shRNAs that knocked down CD44 expression, but not the
nontargeting shRNAs, inhibited glioma cell proliferation (Fig. 2C, middle) and promoted apoptosis in vivo (Fig. 2C, bottom), consistent with the notion that CD44 plays an important role in regulating GBM cell growth and survival.

**Knockdown of CD44 expression inhibits intracranial GBM growth.** To determine how CD44 knockdown affects intracranial glioma growth, the double-drug-resistant pooled populations of U87MG-Luc/U251-Luc cells that express luciferase and display efficient CD44 knockdown were injected intracranially into Rag-1 mice. We found that suppression of CD44 expression significantly inhibited intracranial tumor growth and extended the survival of the experimental mice compared with the animals injected with U87MG/U251-Luc cells transduced with nontargeting shRNAs (Fig. 3A and B).

**Reduced CD44 expression sensitizes GBM cells to cytotoxic drugs in vivo.** The first-line cytotoxic drugs for GBM are temozolomide (TMZ) and carmustine (BCNU). We therefore investigated whether reduced CD44 expression sensitizes glioma cells to BCNU and TMZ treatment in vivo. We observed that BCNU and TMZ displayed a weak and a moderate inhibitory effect on the glioma growth, respectively, when used as single agents (Fig. 3C). However, CD44 depletion sensitized the response of U87MG and U251 GBM cells to BCNU and TMZ and the combination of CD44 knockdown and treatment with BCNU or TMZ resulted in a synergistic inhibition of intracranial glioma progression as determined by markedly prolonged median survival of the experimental mice (Fig. 3D).

**CD44 attenuates activation of the mammalian equivalent of Hippo signaling pathway and plays a key role in regulating stress and apoptotic responses of human GBM cells.** Radiation therapy and some cytotoxic agents generate ROS that constitute a major inducer of cell death and underlie their antglioma effects. To address the molecular...
mechanisms that underlie the observed chemosensitizing effect of CD44 depletion on glioma cells, we investigated how reduced CD44 expression affects GBM cell response to oxidative stress induced by H2O2 and cytotoxic stress induced by TMZ. Our results showed that the GBM cells depleted of CD44 responded to oxidative stress with robust and sustained phosphorylation/activation of MST1/2 and Lats1/2, phosphorylation/inactivation of YAP, and reduced expression of cIAP1/2 (Fig. 4A and B). These effects correlated with reduced phosphorylation/activation of merlin, increased levels of cleaved caspase-3, and reduced cell viability (Figs. 4B and 2C; data not shown). By contrast, high expression of endogenous CD44 promoted phosphorylation/inactivation of merlin, attenuated stress-induced activation of the entire mammalian equivalent of Hippo signaling pathway, and upregulated cIAP1/2 leading to inhibition of caspase-3 cleavage and apoptosis (Figs. 4A and 2C; data not shown). Together and for the first time, these results place CD44 upstream of the mammalian Hippo signaling pathway (merlin-MST1/2-Lats1/2-YAP-cIAP1/2) and suggest a functional role of CD44 in attenuating tumor cell responses to stress and stress-induced apoptosis.

Because MST1/2 kinases have multiple downstream effectors, we investigated whether known effectors of MST1/2 also function downstream of the newly discovered CD44-MST1/2 signaling axis. Knockdown of CD44 was observed to result in elevated and sustained activation of JNK and p38 stress kinases in U87MG cells exposed to oxidative stress, as well as sustained upregulation of p53, a known downstream effector of JNK/p38, and its target genes, p21 and puma (Fig. 4D). By contrast, GBM cells with high levels of endogenous CD44 displayed transient and attenuated activation of JNK/p38 and reduced induction of p53, p21, and puma (Fig. 4C).

To address the mechanism whereby CD44 depletion sensitizes glioma cells to cytotoxic drugs in vivo (Fig. 3C and D), we performed experiments similar to those outlined in Fig. 4 but using TMZ instead of H2O2 to induce cytotoxic stress in U87MG cells expressing a high or low level of CD44. Similar to their response to oxidative stress, GBM cells depleted of CD44 mounted more robust and sustained activation of MST1/2 upon exposure to TMZ, along with phosphorylation/inactivation of YAP that correlates with reduced levels of cIAPs, activation of p38 but not JNK, and upregulation p53 and its target gene p21 (Supplementary Fig. S2). Together, these results establish a novel CD44 signaling pathway and a novel role of CD44 in inhibiting stress/apoptotic responses of tumor cells by attenuating activation of the mammalian Hippo signaling pathway and provide a first mechanistic explanation as to how upregulation of CD44 in advanced/malignant cancers may constitute a key event in leading to their resistance to stress of various origins, including host defense and therapeutic intervention.

CD44 modulates ErbB and c-Met RTK-mediated activation of growth signaling pathways in glioma cells. Our in vivo results have shown that CD44 knockdown inhibits proliferation of GBM cells in vivo (Fig. 2C). Previous studies have shown that CD44 is a costimulator of ErbB and c-Met RTK signaling pathways (12, 39, 40). To determine whether CD44 knockdown diminishes the activation of downstream signaling
pathways induced by epidermal growth factor (EGF) family ligand and HGF in GBM cells, we treated serum-starved CD44-high or -low U87MG cells with EGF family ligands, HGF, nerve growth factor (NGF), and 10% FBS. Our results showed that reduced CD44 expression diminished EGF family ligand- and HGF- but not NGF- and FBS-induced phosphorylation of Erk1/2 kinase but not that of AKT kinase (Fig. 5), suggesting that CD44 preferentially modulates proliferation but not survival signaling pathways activated by these growth factors.

Antagonists of CD44, hsCD44v3-v10-Fc, hsCD44v8-v10-Fc, and hsCD44s-Fc serve as effective therapeutic agents against human GBM in mouse models. To determine whether CD44 antagonists can be used to inhibit GBM progression in preclinical mouse models, we developed several fusion proteins composed of the constant region of human IgG1 (Fc) fused to the extracellular domain of human CD44v3-v10, CD44v8-v10, or CD44s. Successful attempts to generate antagonists of RTKs and CD44 using this approach have been reported (41, 42). Receptor-Fc fusion proteins are believed to function by trapping ligands and/or interfering with endogenous receptor functions.

U87MG and U251 cells were transduced with retroviruses carrying the expression constructs encoding these CD44-Fc fusion proteins or empty expression vector. Pooled puromycin resistance cells expressed high levels of hsCD44v3-v10-Fc, hsCD44v8-v10-Fc, and hsCD44s-Fc fusion proteins (Fig. 6A; Supplementary Fig. S3A). We first assessed whether the soluble CD44-Fc fusion proteins are capable of altering FL-HA binding to endogenous GBM cell surface CD44 and found that expression of the fusion proteins reduced binding of FL-HA to the GBM cells (Supplementary Fig. S3B). These cells were then compared with empty vector-transfected cells for subcutaneous and intracranial growth in Rag-1 mice. hsCD44v3-v10-Fc, hsCD44v8-v10-Fc, and hsCD44s-Fc expression markedly inhibited subcutaneous and intracranial growth of U87MG and U251 cells and significantly extended survival of mice bearing the intracranial tumors. The hsCD44v3-v10-Fc fusion protein displayed the most profound inhibitory effect (Fig. 6B and C).

CD44 plays an important role in regulating immune and inflammatory responses, which affect tumor progression (43). Our experiments thus far were performed in Rag-1 mice that have innate immunity but no mature T or B cells. To determine whether CD44-Fc fusion proteins display similar antiGBM activity in the mice with functional adaptive immunity, we assessed their effect on intracranial growth of a mouse glioma cell, GL261, in immunocompetent mice. GL261 cells form aggressive invasive intracranial tumors in syngeneic C57BL/6 mice that have intact adaptive immunity. Overexpression of hsCD44-Fc proteins in GL261 cells inhibited their intracranial growth in C57BL/6 mice similar to their effect on U87MG/U251 human GBM cells in Rag-1 mice (data not shown), suggesting that the results obtained were not significantly affected by lack of the adaptive immunity in Rag-1 mice and are broadly applicable.

The v3 exon of CD44 contains a Ser-Gly-Ser-Gly motif for covalent attachment of HS side chains (44). To assess whether hsCD44v3-v10-Fc proteins are modified by HS, purified hsCD44v3-v10-Fc proteins were treated with or without heparinase I/III before elution from protein A columns. These proteins were then coated on Elisa plates in triplicate. After blocking with bovine serum albumin, the coated proteins were tested for reactivity with anti-HS antibody. The intensity of the reaction, as assessed by a colorimetric assay, was normalized.

Figure 4. CD44 functions upstream of the Hippo signaling pathway and plays an essential role in attenuating the apoptotic response of glioma cells induced by oxidative stress. Western blots were performed using the cell lysates derived from U87MG-NT cells infected with a mixture of lentiviruses carrying nontargeting shRNAs (A and C) and U87MGshRNA-CD44 cells infected with a mixture of lentiviruses carrying CD44-specific shRNAs (B and D). These cells were treated with or without 60 μM H2O2 for 30 min, 2 h, 24 h, 48 h, and 72 h as indicated in the panels. Total protein (100 μg) was loaded in each lane. Actin was included as an internal control for protein loading. The antibodies used against the different signaling mediators are indicated in the panels.
by the reactivity with anti-CD44 antibody, which provides relative quantity of the coated fusion proteins on the plates. Our results showed that only hsCD44v3-v10-Fc was modified by HS and stained positively with anti-HS antibody. The observed reactivity was sensitive to heparinase I/III treatment (Supplementary Fig. S3C).

CD44 has multiple ligands including HA, osteopontin, heparin binding growth factors, fibronectin, serglycin, laminin, MMP-9, and fibrin (9–12, 44) and cooperates with several RTKs and other cell surface receptors (9, 11, 40). Many of CD44 functions are mediated through its interaction with HA (12) that is abolished by the single R41A mutation (45). To determine whether the CD44-HA interaction alone is responsible for the GBM promoting activity of CD44, we generated pooled populations of U87MG and U251 cells expressing hsCD44sR41A-Fc or hsCD44v3-v10R41A-Fc and compared their anti-GBM effects with that of the wild-type counterparts. We showed that unlike wild-type CD44-Fc fusion proteins, CD44R41A-Fc proteins are incapable of inhibiting FL-HA binding to the GBM cells (Supplementary Fig. S3B; data not shown). However, whereas hsCD44sR41A-Fc displayed a weak anti-GBM effect, hsCD44v3-v10R41A-Fc retained a substantial level of anti-GBM activity (Fig. 6C, right; data not shown), consistent with our earlier observations that hsCD44v3-v10-Fc fusion protein exerts the most potent anti-GBM effect of the three CD44-Fc fusion proteins tested, suggesting a mechanism of action in addition to trapping HA. Together, these results suggest that CD44 and especially CD44 variants promote tumor progression both in a HA-dependent and HA-independent fashion.

Finally, we assessed the anti-GBM efficacy of purified hsCD44s-Fc fusion proteins in preestablished intracranial gliomas resulting from injection of 5 × 10⁵ U87MG or U251 cells into Rag-1 mice. Intracranial tumors were grown for 5 days before the mice were treated i.v. injection of 0.9% NaCl containing 5 mg/kg human IgG or purified hsCD44s-Fc fusion proteins every third day until completion of the experiments. Systemic delivery of hsCD44s-Fc fusion proteins but not human IgG markedly inhibited intracranial growth of U87MG and U251 cells and significantly (P < 0.001) extended median survival of the experimental mice (Fig. 6D, left and middle). GBM and brain issue were collected at the time of mouse euthanasia, sectioned, and stained with antihuman IgG antibody to assess the biodistribution of hsCD44-Fc fusion proteins. Our results showed that hsCD44-Fc fusion proteins readily penetrated tumor blood vessels and displayed a remarkable intraglioma distribution pattern (Fig. 6D, right), whereas negligible fusion proteins were observed in normal adjacent brain tissue, most likely due to the presence of an intact blood-brain barrier (Fig. 6D). These results suggest CD44-Fc proteins preferentially accumulate within the tumor tissue, which contains leaky blood vessels. Together, our results show that hsCD44-Fc fusion proteins are potentially attractive therapeutic agents for GBM.

**Discussion**

**CD44 promotes malignant glioma progression and is a prime target for antiglioma therapy.** We have shown that...
CD44 is upregulated in human GBM and that knockdown of CD44 reduces GBM growth in vivo by inhibiting glioma cell proliferation and promoting apoptosis. Furthermore, we established for the first time that depletion of CD44 sensitizes GBM cells to chemotherapeutic agents in vivo and that CD44 antagonists in the form of CD44-specific shRNAs and CD44-Fc fusion proteins serve as effective GBM growth inhibitory agents in mouse models.

Current anticancer therapeutic strategies and target selection are heavily concentrated on frequently mutated kinases whose activity cancer cells become addicted to (46). Although these approaches are supported by notable successes, they are hampered by emergence of resistant tumor cells capable of bypassing the targeted signaling pathways through mechanisms that may be related to the frequently mutated nature of the targets themselves. It is now well accepted that therapeutic interventions targeting only a single signaling pathway, no matter how seemingly important, are relatively easily evaded by cancer cells as they acquire new genetic and epigenetic alterations. An alternative strategy may therefore be to identify versatile molecules that, unlike the key drivers of oncogenesis, are not central to any single tumor cell property but participate in multiple functions, including modulation of diverse signaling pathways and regulation of interactions between tumor cells and the host tissue microenvironment and tumor cell responses to various forms of stress. Based on their obvious contributions to tumor growth and progression, such molecules are likely to be upregulated in malignant tumors but unlikely to be frequently mutated. Selective inhibition of these types of broad-spectrum functional regulators, especially in combination with chemotherapy and radiation therapy as well as other targeted therapies, may therefore achieve more efficacious and/or long lasting clinical benefits. Our present observations indicate that CD44 may be one such target in GBM and our preclinical results provide strong support for therapeutic potential of targeting CD44 and potential usage of CD44 antagonists against malignant glioma.
CD44 Inhibits the Hippo Signaling Pathway

CD44 functions upstream of the mammalian Hippo signaling pathway and attenuates its activation induced by oxidative and cytotoxic stress. CD44 has been implicated in the modulation of several signaling pathways (9–12), but no single intact core pathway that mediates CD44-derived signals has been established thus far. In Drosophila, merlin functions upstream of the Hippo signaling pathway, but a definitive link between merlin and the mammalian Hippo pathway homologues has not been established. The present study shows for the first time that CD44 functions upstream of merlin-MST1/2-Lats1/2-YAP-cIAP1/2 and two other downstream stress kinases, JNK and/or p38, along with their effectors, p53, and caspases (Fig. 4; Supplementary Fig. S2). It also provides evidence that CD44 plays an essential novel role in attenuating activation of these stress and apoptotic signaling pathways induced by chemotherapeutic agents and ROS whereas loss of CD44 function leads to their sustained activation that promotes apoptosis of GBM cells, which constitutes a plausible mechanism underlying the chemosensitizing effect of CD44 antagonists.

Resistance to cytotoxic agents and radiation constitutes the major obstacle to successful treatment of GBM. Increasing evidence suggests the existence of glioma cancer stem cells (GBM CSC) that are highly resistant to chemotherapy and radiation therapy and may be responsible for GBM recurrence after therapeutic intervention (47, 48). Although the implication of CD44 in GBM CSC remains to be elucidated, CD44 is a major cell surface CSC marker in numerous tumors (9). We show in the present studies that CD44 attenuates the activation of the Hippo stress/apoptotic signaling pathway in GBM cells and provides a chemoprotective function in vivo. It will be of interest to determine whether CD44 exerts the same effects on GBM CSCs.

CD44-Fc fusion proteins and CD44-specific shRNAs are effective therapeutic agents against malignant glioma. CD44 antagonists, shRNAs against CD44, and hsCD44-Fc fusion proteins, when expressed by GBM cells or delivered systemically, displayed potent anti-GBM activity in mouse models. Human sCD44-Fc fusion proteins may not only interfere with the function of CD44 expressed by GBM cells but also with that expressed by host cells infiltrating the tumors, including immune, inflammatory, and stromal cells, which are known to regulate tumor progression (43, 49). The host inflammatory response can exert both antitumor and protumor effects, and CD44 plays an important role in limiting and resolving inflammation (43, 50). We found that overexpression of hsCD44-Fc proteins in GL261 mouse GBM cells inhibited their intracranial growth in C57BL/6 mice that have intact immunity (data not shown), suggesting the anti-GBM effect of CD44-Fc fusion proteins was not significantly affected by lack of the adaptive immunity in Rag-1 mice and are broadly applicable. Furthermore, we have shown that CD44v3-v10-Fc fusion proteins can be produced as HS proteoglycans (S3). It is not surprising that this fusion protein, which is likely capable of sequestering heparin-binding growth factors in addition to trapping other CD44 ligands, is the most efficacious one among the fusion proteins tested and that CD44v3-v10R41A-Fc, which is incapable of binding to HA, still retained a certain degree of anti-GBM activity (Fig. 6C).

Currently available first line treatment options for human GBM are chemotherapy and radiation therapy, although both are largely palliative. One hope for a better clinical outcome is to identify targets that play essential roles in mediating the microenvironment-derived survival signal and -mediated drug resistance and that their antagonists sensitize the response of GBM cells to radiation and chemotherapeutic drugs. Our observation that CD44 plays an important role in protecting cancer cells from oxidative and cytotoxic stress-induced apoptotic signaling whereas enhancing RTK signaling (Supplementary Fig. S4) suggests that it may serve as an ideal therapeutic target to sensitize malignant glioma to radiation and chemotherapy and to the inhibitors of these RTKs.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Yin Xu, Ivan Stamenkovic and Qin Yu

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