


Review

Molecular Mechanisms and Clinical Challenges of Glioma Invasion

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Abstract: Glioma is the most common primary brain tumor, and its prognosis is poor. Glioma cells are highly invasive to the brain parenchyma. It is difficult to achieve complete resection due to the nature of the brain tissue, and tumors that invade the parenchyma often recur. The invasiveness of tumor cells has been studied from various aspects, and the related molecular mechanisms are gradually becoming clear. Cell adhesion factors and extracellular matrix factors have a strong influence on glioma invasion. The molecular mechanisms that enhance the invasiveness of glioma stem cells, which have been investigated in recent years, have also been clarified. In addition, it has been discussed from both basic and clinical perspectives that current therapies can alter the invasiveness of tumors, and there is a need to develop therapeutic approaches to glioma invasion in the future. In this review, we will summarize the factors that influence the invasiveness of glioma based on the environment of tumor cells and tissues, and describe the impact of the treatment of glioma on invasion in terms of molecular biology, and the novel therapies for invasion that are currently being developed.

Keywords: glioma; invasion; extracellular matrix; glioma therapy-related invasion



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1. Introduction

Gliomas are primary brain tumors that arise in the brain parenchyma and have histologically similar features to normal glial cells. Of these, glioblastoma is the most common tumor in adults and is a biologically aggressive tumor characterized by high cell density, pleomorphic tumors with mitosis, and either microvascular proliferation or necrosis [1]. The extent of resection is the most important independent predictor of overall survival (OS) and progression-free survival (PFS) [2], and an extent of resection of 78% or higher is required to improve prognosis [3]. Although the development of assistive technologies, such as awake surgery, intraoperative navigation, intraoperative magnetic resonance imaging, and 5-amino levulinic acid (5-ALA), has improved the removal rate [4,5], the prognosis for standard treatment remains unsatisfactory at approximately 15 months [2]. Tumor cells are highly infiltrative and often invade important brain regions, making it very difficult to obtain a negative tumor margin. Even if a total resection is achieved, patients often suffer from recurrence around the extraction cavity. Therefore, the control of invasive lesions is one of the issues to be solved in the treatment of glioma. This article will review the molecular mechanisms of glioma invasion, the impact of glioma treatment on invasion, and the developing treatments for glioma invasion.

2. The Characteristics of Glioma Invasion

2.1. Cell Dynamics

Unlike metastatic brain tumors, glial-derived tumors are prone to invade the normal brain. “Cell migration” is defined as the movement of cells from their original location to another, whereas “cell invasion” is defined as the ability of cells to navigate through the

extracellular matrix within a tissue or to infiltrate neighboring tissues [6]. Tumor cell invasion involves four steps: (1) detachment from the primary tumor mass, (2) adhesion to the extracellular matrix (ECM), (3) degradation of the ECM, and (4) movement and stretching of the invading cells [7,8]. The invasion of glioma follows the nature of neural progenitor cells [9], while glioma cells take the form of individual cells and cell clusters [7,8,10] and infiltrate along blood vessels and nerve fibers by saltatory migration [11–13]. The migration speed has been measured to be 51 to 100 $\mu\text{m}/\text{h}$ [13–15]. Cell division is often observed at the bifurcation of blood vessels [14].

2.2. Invasion to the Corpus Callosum and Subventricular Zone

The infiltration of glioma often presents with a butterfly appearance. Invasion through the corpus callosum is seen in 14% of cases, and gliomas presenting with invasion of the corpus callosum are more aggressive [16,17]. In highly invasive gliomas, invasion of the subventricular zone is also often seen. In particular, glioma stem cells (GSCs) are prone to invade the subventricular zone [18]. Invasion of the subventricular zone has a poor prognosis and high recurrence rate [19–21]. Involvement of the subventricular zone is associated with a high expression of pleiotrophin (PTN), also known as a heparin-binding growth-associated molecule, which is exerted by neural progenitor cells. PTN binds to secreted protein acidic and rich in cysteine (SPARC)/SPARC-like protein 1 (SPARCL1) and heat shock protein 90B (HSP90B) as the partners, activates Rho/Rho-associated protein kinase (ROCK) signaling, and promotes cell migration [22]. In addition, there are two types of PTNs: immobilized pleiotrophin (PTN18), which promotes migration via the cell surface receptor, the protein tyrosine phosphatase receptor zeta (PTPRZ1), and soluble pleiotrophin (PTN15), which is mainly involved in promoting glioblastoma proliferation [23]. PTN is a strong binder of glycosaminoglycans (GAGs) and has been shown to interact with a variety of receptors, including proteoglycans PTPRZ and syndecans and GAG non-containing integrin and nucleolin [24]. These interactions depend on the sulfation density of GAGs and activate many intracellular kinases, which are involved in cell activation and transformation [24,25].

Glioma infiltration of the subventricular zone is also related to C-X-C motif chemokine receptor type 4 (CXCR4)/C-X-C motif chemokine ligand 12 (CXCL12 or stromal derived factor-1, SDF-1) [26]. The CXCR4/CXCL12 axis upregulates the downstream phosphoinositide-3 kinase/serine-threonine protein kinase B/nuclear factor-kappa B (PI3K/Akt/NF- κ B) pathway and is involved in cell survival, migration, and stemness [27]. Compared to non-invasive tumor cells, gliomas have higher expression of CXCR4 [28]. CXCL12 induces the invadopodia formation and the expression of membrane type-2 matrix metalloproteinase (MT2-MMP), which degrades the surrounding ECM and is involved in glioma invasion [29,30]. Invadopodia consist of actin-rich protrusions that facilitate the invasion of tumor cells from the tumor cell mass to the surrounding healthy parenchyma [31]. MMPs are enriched and secreted at the tips of invadopodia, mediating the degradation of the ECM [32].

3. Hypoxia

One of the mechanisms of cancer cell invasion is hypoxia-driven motility, which is enhanced in hypoxic conditions [33]. Although oxygen is essential for the maintenance of cell life, cancer cells proliferate so rapidly that insufficient angiogenesis results in the formation of hypoxic areas. Hypoxia-inducible factor (HIF)-1 α is an important factor in hypoxic conditions. Semenza et al. found that HIF-1 α is upregulated in cancer cells under hypoxic conditions [34]. HIF-1 α is normally subjected to prolyl hydroxylation under normal oxygen conditions, and is further degraded by proteasomes after ubiquitination by von Hippel–Lindau. In contrast, in hypoxic conditions, HIF-1 α is not hydroxylated and is transferred to the nucleus. As a result, it binds to HIF-1 β and causes various gene expressions related to angiogenesis, migration, cell survival, and glucose metabolism [35].

Activation of the HIF-1 pathway is a common feature in glioma, and HIF-1 regulates target genes in activators of angiogenesis and invasion in glioma [36]. In hypoxic areas, HIF accumulates and enhances glioblastoma invasiveness through increased delta like non-canonical Notch ligand 1 (DLK1) expression [37]. HIF-1 α stabilizes and upregulates the Notch intracellular domain (NICD) to activate the Notch pathway, which is involved in maintaining GSCs [38] and enhancing cell invasion [39]. Activation of the PI3K/Akt/mTOR pathway by HIF-1 α has also been reported to cause enhanced invasiveness [40]. Thus, the HIF-1 pathway contributes significantly to the invasiveness of glioma.

4. Factors Associated with ECM

Tumor cell adhesion and degradation to the ECM, which is important for tumor cell invasion, involves various factors at the cell surface and in the intercellular space. The tumor microenvironment provides gliomas with invasion, proliferation, and resistance to treatment. The extracellular matrix plays roles in scaffolding and the maintenance of tissue homeostasis, and its degradation and changes have a major impact on cancer invasion. Factors involved in ECM adhesion include integrin, brain-specific angiogenesis inhibitor (BAI1), cysteine-rich 61/connective tissue growth factor/nephroblastoma overexpressed (CCN1), proteoglycans, fibronectin, laminin, cadherin, collagen, CD44, and factors involved in degradation include protease, such as matrix metalloproteinases (MMPs), a tissue inhibitor of MMP (TIMP) [8]. In this section, we describe MMPs, integrin, CCN1, and proteoglycans. The ECM and cell surface factors involved in glioma invasion are summarized in Figure 1.

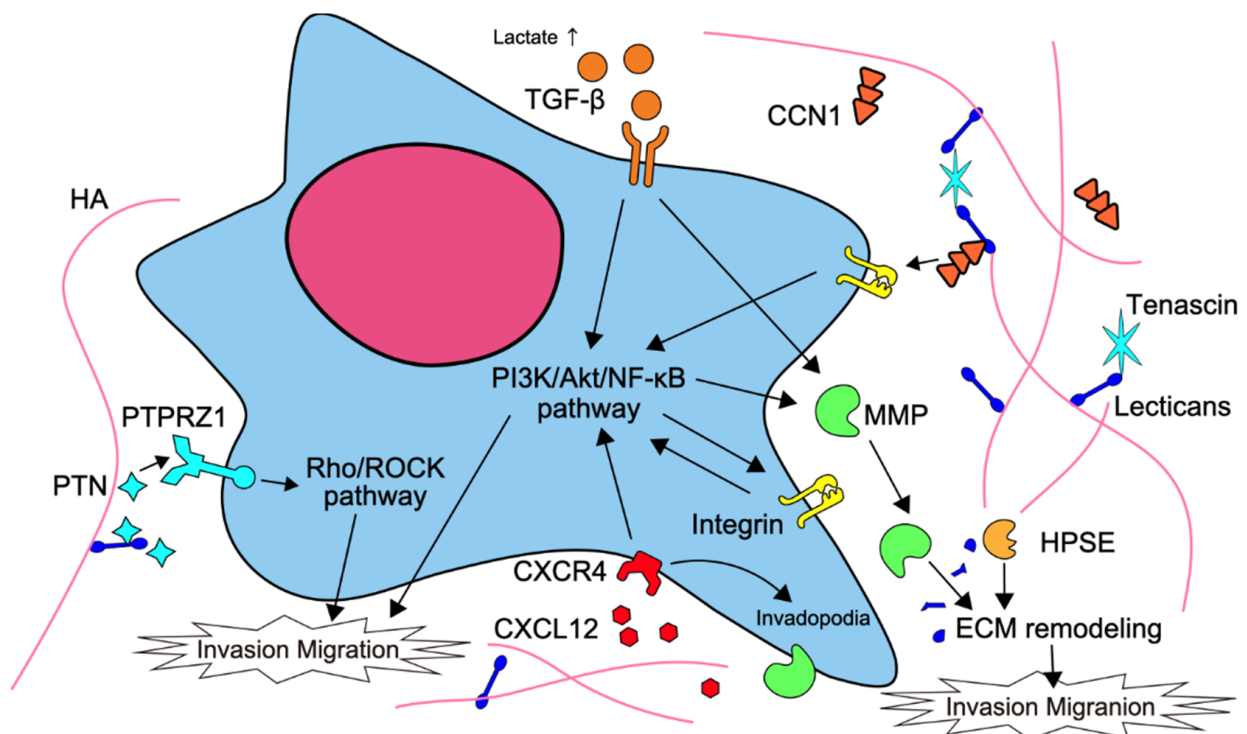


Figure 1. Summary of the ECM and cell surface factors involved in glioma invasion.

4.1. Matrix Metalloproteinases (MMPs)

MMPs are members of the zinc-dependent endoproteases family that play a role in ECM remodeling by degrading the proteins responsible for various ECM structures. In malignant tumors, MMPs promote invasion and metastasis behavior in the epithelial-mesenchymal transition (EMT) [41]. MMP-2 and MMP-9 are the most well-studied and major promoters of tumor cell invasion. The expression of MMP-2 in glioma has been reported to be an important key molecule involved in malignancy and invasion [42,43].

MMPs are promoted by transforming growth factor (TGF)- β , a key molecule in the EMT, while TIMPs are suppressed by TGF- β [41,44,45]. In addition, tumor cells use aerobic glycolysis in energy metabolism despite adequate oxygenation; excess extracellular lactate enhances the expression of MMP-2 and integrin $\alpha v \beta 3$ via high expression of TGF- $\beta 2$, which enhances glioma cell migration [46,47]. Heparanase (HPSE) degrades heparan sulfate and shortens the heparan sulfate chains on Syndecan-1, which makes the core protein susceptible to degradation by protease. Furthermore, HPSE is involved in tumor metastasis and angiogenesis by regulating the expression of downstream effector genes such as HGF, MMP-9, and VEGF [48].

4.2. Integrin

Integrins are cell surface proteins that are key molecules involved in cell-extracellular matrix adhesion and cell-cell adhesion, and play a role in initiating various signaling cascades through the binding of α and β subunits. Twenty-four heterodimers are formed from 18 α -subunits and 8 β -subunits, and the ligand preference is determined by collagen-, laminin-, RGD motif-binding-, and leucocyte-specific receptors. Binding of integrins to the ECM promotes proliferation, invasion, and metastasis. Integrins enhance pathways such as the PI3K/AKT pathway, RAS, or small GTPases and mitogen-activated protein kinase (MAPK). In glioblastomas, $\alpha v \beta 3$ and $\alpha v \beta 5$ are upregulated, and $\alpha v \beta 3$ co-localizes with MMP-2 in tumor cells [49]. TGF- β promotes glioma cell migration via $\alpha v \beta 3$ integrin expression [50]. Collagen accumulation and crosslinking increase ECM stiffness and integrin clustering promotes focal adhesions and drives tumor invasion [51,52].

4.3. Cysteine-Rich 61/Connective Tissue Growth Factor/Nephroblastoma Overexpressed (CCN1)

The Cysteine-rich 61/connective tissue growth factor/nephroblastoma overexpressed (CCN) protein family is found on the ECM and cell surface and is involved in cell-matrix interactions, such as cell proliferation, attachment, migration, differentiation, wound healing, and angiogenesis. CCN1 interacts with $\alpha 6 \beta 1$, $\alpha v \beta 3$, $\alpha v \beta 5$, and $\alpha II \beta 3$ integrins to trigger downstream signals such as PI3K/Akt, TGF- β , and vascular endothelial growth factor (VEGF) signaling [53–55]. CCN1 has been reported to be overexpressed in 48 to 69% of primary gliomas and is associated with PFS and OS [55,56]. CCN1 is secreted by differentiated glioblastoma cells rather than glioma stem cells, which promotes the migration of macrophages into the tumor and contributes to GSC-dependent tumor progression [57].

4.4. Proteoglycans

The major extracellular matrix components of the adult brain are glycosaminoglycan hyaluronic acid, proteoglycans of the lectican family, and link proteins [44]. Proteoglycans (PGs) are molecules consisting of a core protein and GAG side chains such as chondroitin sulfate (CS) and heparan sulfate (HS). Chondroitin sulfate proteoglycans (CSPGs) are critical regulators of brain tumor histopathology, and the low content of CSPGs is related to the active invasion of glioma cells [58]. Extracellular proteoglycans can bind to matrix proteins, trapping ligands such as growth factors [59].

The lectical subfamily of CSPG includes aggrecan, syndecan, neurocan, versican, and brevican. Syndecan-1, a transmembrane HS proteoglycan, is particularly upregulated in glioblastoma and is activated in an NF κ B-dependent manner. Syndecan-1 interacts with HPSE and enhances growth factor signaling to promote the growth of glioma cells [60–62]. Moreover, brevican, a member of the lectican family of CSPG is upregulated in gliomas and its expression induces glioma invasion, which is especially enriched in the glioma stem cell (GSC) niche [63]. The HPSE is an endo- β -D-glucuronidase that degrades the heparan sulfate side chain of HSPG. It is an important regulator of ECM remodeling and is involved in the growth and invasion of glioma [64]. HPSE upregulates extracellular signal-regulated kinase (ERK) and AKT pathways to increase glioma cell proliferation and worsen prognosis [64,65].

5. Glioma Stem Cells (GSC)

Glioma stem cells (GSCs), also called glioma-initiating cells, are cellular subpopulations that, like normal stem cells, are capable of self-renewal and differentiation to produce secondary tumors. A heterogeneity is created by cells that have a tendency to differentiate from the GSC at the top of the hierarchy [66]. Among them, GSCs are responsible for the distinctive feature of glioma invasion [67]. GSCs are characterized by the presence of CD133, CD44, leucine-rich repeat-containing G protein-coupled receptor 5 (LGR5) as surface markers [68]. The factors involved in the invasion of glioma stem cells are summarized in Figure 2.

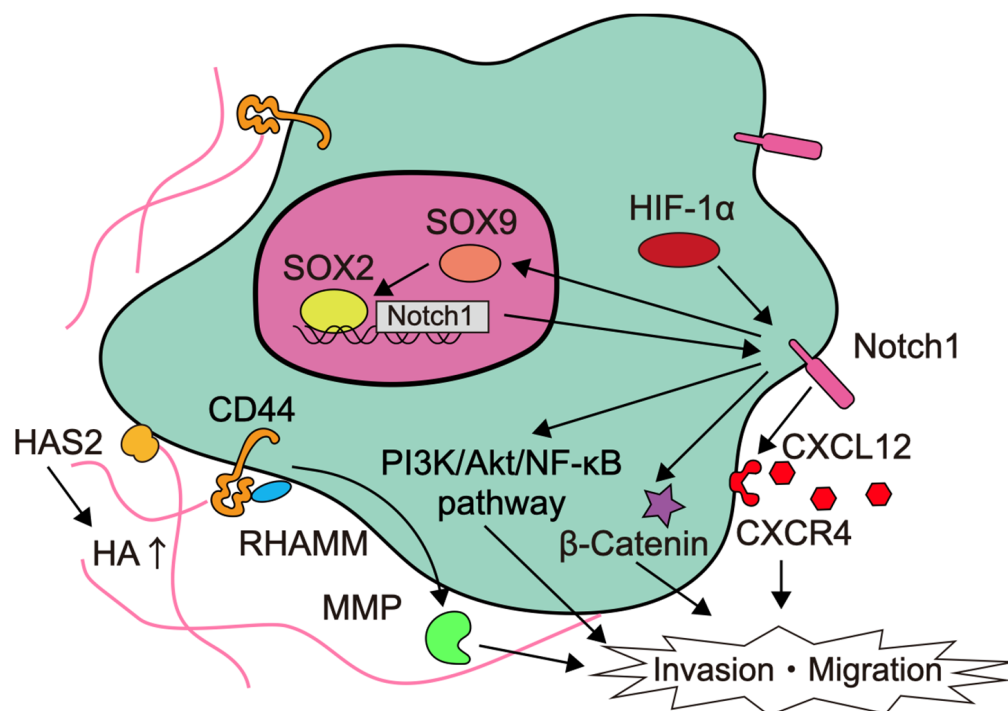


Figure 2. Summary of the factors involved in glioma stem cell invasion.

The expression of delta-like canonical Notch ligand (DLL)-1, Notch1, nestin, and Sox2 is upregulated in GSCs compared to conventional cell lines [69]. In particular, Notch is a signal that functions in cell fate determination during tissue construction, and is involved in the maintenance and regulation of neural stem cells and progenitor cells differentiation during central nervous system development [70]. In white-matter GSCs, Notch-induced transcription factor Sox9 upregulates Sox2 and attenuates Notch1 promoter methylation to enhance Notch1 expression. This positive feedback loop increases invasiveness and worsens the prognosis [71]. Notch1 also activates the PI3K/Akt pathway and stimulates β -catenin and NF- κ B signaling to promote the migratory and invasive properties of glioma [69,72,73]. In addition, Notch1 signaling upregulates CXCR4 expression and activates the CXCL12/CXCR4 autocrine/paracrine loop to enhance GSC survival and invasiveness [69,74]. Thus, signaling through increased Notch expression in glioblastoma, especially in GSCs, is thought to be highly relevant to tumor invasion, and Notch inhibitors are being developed [70,75].

CD44 is a transmembrane glycoprotein that mediates cell-cell or cell-matrix interactions with hyaluronic acid (HA) as the main ligand, and is strongly involved in tumor progression, apoptosis evasion, multidrug resistance, and cell invasion. CD44-mediated signaling has been implicated in MMP-mediated matrix degradation, tumor growth, and tumor invasion [76]. HA is a major component of white matter, a frequent route of glioma invasion, and increases the invasiveness of glioblastoma in a dose-dependent manner [77,78]. CD44 binding with HA stimulates a number of signaling pathways, such

as PI3K/Akt/mTOR, Ras, focal adhesion kinase (FAK), and ERK signaling, and induces MMP-9 expression [79,80]. Receptors for HA-mediated cell motility (RHAMM), CD44, and osteopontin, which is a ligand for CD44, are involved in HA-mediated migration, invasion, proliferation, radiation therapy, and chemotherapy resistance [80,81]. Tumor-associated mesenchymal stem cells interact with glioblastoma and increase invasiveness by remodeling the ECM. Tumor-associated mesenchymal stem cells increase HA levels in the ECM by upregulating HA synthase-2 (HAS2) expression [82].

6. Epithelial-Mesenchymal Transition (EMT)

Cell invasion requires a reduction in the adhesive connections that maintain cell-to-cell adhesion. The EMT is a reversible change found in cells of epithelial origin, and mesenchymal phenotype changes are associated with increased cell motility and resistance to apoptosis [83]. In general, the EMT produces cell detachment from the basement membrane and the formation of a mass of mesenchymal cells at sites away from the origin. EMTs are classified into three subtypes according to the biological setting. Type 1 EMT is associated with embryogenesis and gives rise to the mesoderm and endoderm and to mobile neural crest cells. Type 2 EMT is a program that begins as part of a tissue repairment that normally generates fibroblasts and other related cells in order to reconstruct tissues following trauma and inflammatory injury. Unlike these subtypes, type 3 EMT occurs in neoplastic cells. Carcinoma cells undergoing a type 3 EMT may invade and metastasize [83]. The term proneural-mesenchymal transition is also used for glioma, as well as EMTs for other aggressive cancers [84]. The EMT is an important driver of invasiveness and recurrence of glioblastoma, with cellular reprogramming causing cytoskeletal remodeling and loss of adhesion molecules [85]. The main executors of the EMT are EMT-activated transcription factors (EMT-TF), such as SNAIL, TWIST, and ZEB family [86]. SNAIL induces MMP-9 expression triggered by TGF- β [87]. Notch signaling is required for the conversion of hypoxic stimuli into the EMT [39].

TGF- β is a major key molecule that induces the EMT via various transcription factors [88]. TGF- β is an important cytokine that maintains homeostasis, and the TGF- β pathway acts as an oncogenic factor to induce angiogenesis, immunosuppression, cell invasion, and proliferation in tumor progression, including glioblastoma [89,90]. TGF- β 1 activates a variety of downstream signaling pathways, including PI3K, Smads, and MAPK, which are key players of the TGF- β -induced EMT [83,86]. Proteolytic degradation by MMPs plays a central role in the EMT process, and the EMT-related pathway is one of the regulatory mechanisms for MMP expression. In oral squamous cell carcinoma, TGF- β 1 facilitates MT1-MMP-mediated MMP-9 activation and stimulates invasion of the tumor in collaboration with MT1-MMP and MMP-2 [91]. Elevated TGF- β activity is associated with poor prognosis in glioma patients [89,92]. In addition, TGF- β is also involved in tumor initiation and recurrence via CD44 and inhibitors of DNA-binding protein (Id)-1 [93].

7. Effect of Glioma Therapy on Tumor Invasion

As mentioned above, various molecular signaling pathways are intricately involved in the invasion of glioma cells. In the current treatment of glioma, the preclinical impact on glioma invasion is being studied.

7.1. Radiation Therapy

The standard of care for glioma is postoperative chemotherapy and radiation therapy. Radiation therapy is the main treatment modality for glioma lesions that cannot be safely resected. Whether or not the post-radiation microenvironment enhances invasiveness is inconclusive. It has been reported that radiotherapy coupled with temozolomide (TMZ) treatment has an additional effect of inhibiting the proliferation and migration of glioma spheroids [94]. It is thought that the radiation-induced tumor bed effect reduces blood flow, pH, and hypoxia, making the environment unsuitable for tumor cell survival [95,96]. However, it has been pointed out that radiation increases the invasiveness and motility of

glioma [97,98]. Tsuji et al. reported that the secretion of CXCL12, VEGF-A, TGF- β 1, and TNF α is enhanced in the brain after irradiation, and that the microenvironment in the brain in the chronic phase after irradiation is suitable for tumor cell growth and invasion [99]. In experiments using cell lines, various changes have been observed in invasiveness caused by radiation [100,101]. Radiation-induced damage of the tumor microenvironment may create a tumor-susceptible niche that promotes the proliferation and invasion of the residual glioma cells [102]. In a model experiment, multiple radiations altered glycosylated components (PG and GAG) in normal brain tissue, reduced CSPG expression and CS in normal brain tissue, and promoted residual glioma cell adhesion and proliferation [103]. In molecular biology, radiation has been reported to activate MMP-2 and MMP-9 through p53, resulting in increased invasiveness [104,105]. It was also suggested that radiation increases the activity of MMP-2 and MMP-9 through the expression of integrin α v β 3 [106]. PI3K-mediated activation of the Rho signaling pathway is associated with radiation-induced invasion [98]. HIF-1 α is also an important molecule that contributes to radiation-induced enhancement of invasiveness. It has been reported that irradiation stabilizes HIF-1 α by destabilizing prolyl hydroxylases (PHD)-2 and protein von Hippel-Lindau (pVHL) [107]. Ionizing radiation enhances the invasive capacity of GSCs through stabilization of HIF-1 α and activation of junction-mediated protein [108].

However, although radiation therapy may change the tumor microenvironment to increase the invasiveness of tumors, radiation is still an important modality for the treatment of tumors. It has been reported that high linear energy transfer (LET) irradiation, such as alpha and carbon radiation, suppresses migration, and future development of radiotherapy is expected [109,110].

7.2. Temozolomide (TMZ)

TMZ is an alkylating oral anticancer drug that has been used in conjunction with postoperative radiation therapy as the standard treatment for glioma [2]. It is one of few anticancer drugs that can pass through the blood-brain barrier (BBB) and is the mainstay of postoperative chemoradiotherapy in the current treatment of glioma. It is unclear whether TMZ enhances the invasion of glioma. MMP-2 secretion and invadopodia formation is enhanced by radiation and TMZ therapy [111,112]. There are reports that the expression of CXCR4 and VEGF and the activity of MMP-2 and MMP-9 were reduced by TMZ [113,114].

7.3. Anti-VEGF Therapy

VEGF is a stimulator of angiogenesis that is frequently expressed in glioblastoma; it is commonly attributed to the autocrine and paracrine production of VEGF-A. Inhibiting VEGF signaling suppresses the tumor growth of glioma xenografts in model mice [115,116]. Anti-VEGF antibody is a monoclonal antibody to VEGF and has a certain effect on the tumor control of primary or relapsed glioblastoma [117–119]. Although it improved PFS in primary and recurrent glioblastoma, it was not effective in improving OS.

There is some preclinical evidence that antiangiogenic therapies promote glioma cell invasiveness. Anti-VEGF therapy induces a vascular gradient, which, in turn, induces tumor hypoxia, macrophage infiltration, mesenchymal transition, stem cell marker expression, and increased invasiveness [120]. It has been reported that hypoxia induced by anti-VEGF enhances angiogenesis, tumor survival, invasion, and resistance to therapy. Keunen et al. reported that, in a rat-patient-derived xenograft model, bevacizumab treatment resulted in a decrease in tumor volume and tumor blood flow, but a 68% increase in infiltrating cells, which was associated with the enhanced expression of HIF-1 and activation of the PI3K pathway and Wnt-signaling pathway [121]. Shimizu et al. also reported that bevacizumab upregulates δ -catenin in glioma cells and increases invasiveness [116]. It has been reported that suppression of VEGF increased CD44 expression and that GSCs became invasive [122]. Administration of bevacizumab causes the dose-dependent accumulation of collagen, MMP-2, and MMP-9, which play important roles in the adhesion process of tumor cell invasion and degradation of the cellular matrix [123]. Although invasiveness is

perhaps enhanced by anti-VEGF therapy, the prognosis is not necessarily poor [118,119,124]. Combination with drugs that suppress invasion, such as γ -secretase inhibitor, has been used in an attempt to mitigate the bevacizumab-induced invasive effect [125].

7.4. Glucocorticoid

Glioma is often associated with prominent cerebral edema, which can cause mass effect and elevated intracranial pressure, affecting the prognosis [126]. Glioblastoma-induced cerebral edema has been conventionally treated with dexamethasone (DEX). Glioblastoma-induced brain edema is associated with vasogenic edema due to extravasation by disruption of the BBB, and DEX improves edema by increasing the expression of tight junction genes that regulate the endothelial permeability of the BBB [127]. The effect of DEX on the invasive properties of glioma is not well understood. Luedi et al. reported that DEX increases invasion, proliferation, and angiogenesis in GSCs, and that patients with a high DEX-regulated gene signature derived from DEX-treated GSCs showed worse prognosis [128]. It has also been reported that glucocorticoid receptor- β interacts with β -catenin and is involved in proliferation and migration [129]. DEX also affects the tumor microenvironment. The combination of TMZ and DEX affects proteoglycan structure and composition in normal brain tissue, resulting in worsened brain ECM, which is favorable for the progression of residual glioma cells; a high DEX dose results in downregulation of the transcription of PG-coding genes, whereas a high DEX dose and TMZ predominantly affects the polysaccharide GAG chains of the molecules [130]. In contrast, DEX inhibits migration via the suppression of glucocorticoid receptor-dependent ERK1/2 MAPK pathway and MMP-2 secretion [131,132]. Guan et al. reported that DEX inhibits cell proliferation and promotes migration and invasion by upregulating aquaporin-1 (AQP1) in C6 cells [133].

8. Treatment of Invasive Glioma and Its Future Development

The suppression of glioma invasion is one of the therapeutic approaches in gliomas that spread invasively to the brain and offer limited resection. However, treatments that inhibit invasion are still being studied at present. In this section, we will discuss treatments for invasion that are undergoing clinical trials and therapeutic development.

8.1. Tumor-Treating Fields (TTF)

Tumor-treating fields (TTF) is a non-invasive treatment that uses electrode pads on the scalp to deliver a weak, sustained 100 to 300 kHz mid-frequency current to brain tumors. TTF works by selectively inhibiting the mitosis of brain tumor cells and can prolong survival by 4.9 months [134]. In addition to inhibiting cell proliferation, TTF has also been reported to inhibit EMT, endothelial cell angiogenesis, and migration by downregulating PI3K/Akt/NF- κ B pathways [135].

8.2. Molecular Target Drugs

As our knowledge of the invasion of various cancers increases, therapies that target the molecular mechanisms that lead to cancer invasion are being developed. The major therapeutic agents that are currently in development are summarized in Table 1.

MMP inhibitor: Degradation of the ECM has been well observed in tumor tissues, and MMPs have been considered a good target for tumor invasion. However, the selectivity, low bioavailability, and low metabolic profile of broad-spectrum MMP inhibitors limited the efficacy of MMP inhibitors and did not justify continuation of the clinical trial [136]. MMP inhibitors were expected to have an effect on the invasiveness of tumor cells, but clinical trials for gliomas to date have not shown positive results. In a mouse model of colorectal carcinoma, AB0041 and AB0046, which are monoclonal anti-MMP-9 antibodies, were found to inhibit tumor growth and metastasis [137]. Since bevacizumab increases the expression of MMP-9 [138], anti-MMP-9 therapy may be effective against bevacizumab-induced resistance and invasiveness. Clinical trials of GS5745, a monoclonal antibody of MMP-9, are in progress.

Integrin inhibitor: Cilengitide was one of the earliest integrin antagonists to enter clinical trials [139]. In a rat model, bevacizumab treatment caused tumor cells to invade the brain parenchyma along with blood vessels, but cilengitide administration suppressed the invasion of tumor borders, suggesting the involvement of integrin in bevacizumab-induced glioma invasion [140]. The phase 2 study of cilengitide showed prolongation of median OS by adding cilengitide to standard treatment, and development was expected [141]; however, phase 3 studies such as CENTRIC failed to show OS prolongation [142] and development was discontinued. The addition of cilengitide to oncolytic virus therapy has been shown to enhance antitumor effects, and cilengitide may undergo re-evaluation as virus therapy develops [143].

Notch inhibitor: The expression of Notch is increased in GSCs, and Notch inhibition by γ -secretase inhibitor has been attempted. γ -secretase cleaves Notch to form the NICD, which translocates to the nucleus. γ -secretase inhibitors can inhibit Notch signaling. Jin et al. showed that MRK-003, an inhibitor of Notch and Akt phosphorylation, suppresses invasion but not mitosis when combined with MK-2206, an Akt phosphorylation inhibitor [144]. The Notch pathway blockade by γ -secretase inhibitor inhibited tumor growth and neurosphere formation in culture, and also prolonged survival in xenograft mice [145]. However, in a phase 2 study, RO4929097, a γ -secretase inhibitor, was evaluated for 6 month PFS and neurosphere formation in patients with recurrent glioblastoma, but failed to demonstrate efficacy [146]. Although no effective treatment for GSCs has been established yet, their treatment may remain an attractive strategy.

TGF- β inhibitor: TGF- β inhibitor has been reported to have inhibitory effects on the metastasis of breast, colon, pancreatic, and gastric cancers [147–150]. LY2109761, a TGF- β receptor inhibitor, not only enhanced the effects of radiotherapy but also inhibited cell migration via the SMAD4 signaling pathway [150]. In glioblastoma treatment, Zhang et al. reported that LY2109761 suppressed migration in vitro, and LY2109761 added to RT + TMZ significantly inhibited tumor growth in model mice [151]. Since it is not an invasive model, however, the inhibition of invasion in vivo was inconclusive. A phase 2b study of AP-12009 (trabedersen), a phosphorothioate antisense oligodeoxynucleotide, a specific target for the mRNA of TGF β 2, showed safety against chemotherapy in recurrent high-grade glioma and significant improvement in the 14-month tumor control rate in anaplastic astrocytoma. However, the phase 3 study, SAPHIRE, was discontinued due to a lack of patients [152]. Compared with chemoradiotherapy, galunisertib, a TGF- β receptor inhibitor, had a higher disease control rate but shorter PFS and no difference in efficacy [153].

PI3K inhibitor: Tumor metastasis and invasion are enhanced by activating the PI3K/Akt pathway through regulating the expression of MMP [154]. In glioblastoma, the PI3K pathway is activated by changes in epidermal growth factor receptor (EGFR) amplification and phosphatase and tensin homolog (PTEN) mutation; and PTEN changes are a poor prognostic factor in glioblastoma [155]. It has been reported that a number of inhibitory agents of PI3K were preclinically effective in inhibiting cell proliferation and invasion [156–159]. The PI3K inhibitor PX-866 was well tolerated in a phase 1 trial, but failed to meet its predefined efficacy endpoint in a phase 2 trial in patients with recurrent glioblastoma [160]. A phase 1 study of voxalisib, the PI3K/mTOR inhibitor, plus TMZ with or without radiotherapy, in patients with high-grade gliomas demonstrated favorable safety; however, no conclusion could be drawn regarding the efficacy because of the small number of patients and short follow-up [161]. Buparlisib, an oral pan-PI3K inhibitor, has high penetration across the BBB. A phase 2 study of buparlisib in recurrent glioblastoma patients showed minimal efficacy. The lack of tumor response was explained by incomplete PI3K inhibition in the tumor tissue [162].

Table 1. Molecular-targeted drugs and clinical trials related to glioma invasion.

Inhibitor	Target Molecule	Clinical Trial Phase	Reference	
MMP inhibitor	AG3340 (prinomastat)	MMP	Phase 2	NCT00004200
	GS5745 (andecaliximab)	MMP-9	Phase 1, ongoing	NCT03631836
Integrin inhibitor	cilengitide	integrin	Phase 3	Stupp et al. (2014) [142]
Notch inhibitor	RO4929097	γ -secretase inhibitor	Phase 2	Peereboom et al. (2021) [146]
TGF- β inhibitor	AP-12009 (trabedersen)	TGF- β 2	Phase 3	Bogdahn et al. (2011) [152]
	LY2157299 (galunisertib)	TGF- β receptor I	Phase 1b/2a	Wick et al. (2020) [153]
PI3K inhibitor	PX-866	PI3K	Phase 2	Pitz et al. (2015) [160]
	XL-765, SAR245409 (voxtalisib)	PI3K/mTOR	Phase 1	Wen et al. (2015) [161]
	NVP-BKM120 (buparlisib)	PI3K	Phase 2	Wen et al. (2019) [162]

8.3. Stem Cell Therapy

In recent years, research has been conducted on therapies using stem cells for drug delivery. Neural stem cells, mesenchymal stem cells, and induced pluripotent stem cells all accumulate in tumors [163,164]. Radioisotope transporters, tumor lytic viruses, suicide genes, immunomodulatory agents, anti-angiogenic factors apoptosis-inducing agents, etc., are placed on the stem cells, injected locally or intravenously, and accumulate in the tumor to produce a therapeutic effect [165–168].

In suicide gene therapy, tumor cells expressing genes such as herpes simplex virus thymidine kinase (HSV-TK) and cytosine deaminase (CD) can metabolize the prodrugs, resulting in apoptosis [169]. In phase 3 clinical trial using fibroblasts with suicide genes incorporated, the significant improvement in PFS, median survival and survival rate was not observed, suggesting that the low diffusibility of suicide genes is a problem [170]. Therefore, the use of stem cells, which have a high ability to accumulate in tumors, as a vehicle for the delivery of suicide genes to glioma cells infiltrating the brain parenchyma, is being attempted for therapeutic development [165,171].

8.4. Viral Therapy

Antitumor therapy using oncolytic viruses (viral therapy) is a field derived from gene therapy. Proliferative viruses selectively proliferate in the tumor cells and exhibit antitumor effects through tumor lysis and inducing tumor immunity. It has been reported that the oncolytic virus has antitumor effects in mouse models of invasive tumors using GSCs due to its extensive distribution and infectivity [67]. Microenvironmental changes such as increased tumor vascular permeability and elevated expression of inflammatory cytokine genes induced by viral administration induce the resistance to viral therapy [172]. Therefore, there has been an attempt to modify the microenvironment and enhance the antitumor effects of viral therapy [143,173,174]. It is also known that tumor lytic virus activates Notch signaling in non-infected cells, and it has been reported that the combination of oncolytic virus and Notch inhibitor suppressed the cell proliferation of non-infected cells and enhanced the effect of tumor lytic virus [175]. In the future, viral therapy will continue to evolve with various studies and improvements in the approach to invasive lesions.

9. Conclusions

The high invasiveness of gliomas is due to a complex combination of factors, including hypoxia, ECM, cancer stem cells, EMT, etc. The impact of glioma treatment on invasiveness is not yet fully understood, and further research is needed in this area. Establishing a treatment for glioma invasion will be one of the main topics of therapeutic development in the future.

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References

- Louis, D.N.; Perry, A.; Reifenberger, G.; von Deimling, A.; Figarella-Branger, D.; Cavenee, W.K.; Ohgaki, H.; Wiestler, O.D.; Kleihues, P.; Ellison, D.W. The 2016 World Health Organization Classification of Tumors of the Central Nervous System: A summary. *Acta Neuropathol.* **2016**, *131*, 803–820. [[CrossRef](#)]
- Stupp, R.; Mason, W.P.; van den Bent, M.J.; Weller, M.; Fisher, B.; Taphoorn, M.J.B.; Belanger, K.; Brandes, A.A.; Marosi, C.; Bogdahn, U.; et al. Radiotherapy plus Concomitant and Adjuvant Temozolomide for Glioblastoma. *N. Engl. J. Med.* **2005**, *352*, 987–996. [[CrossRef](#)]
- Sanai, N.; Polley, M.Y.; McDermott, M.W.; Parsa, A.T.; Berger, M.S. An extent of resection threshold for newly diagnosed glioblastomas. *J. Neurosurg.* **2011**, *115*, 3–8. [[CrossRef](#)]
- Stummer, W.; Pichlmeier, U.; Meinel, T.; Wiestler, O.D.; Zanella, F.; Reulen, H.-J.; ALA-Glioma Study Group. Fluorescence-guided surgery with 5-aminolevulinic acid for resection of malignant glioma: A randomised controlled multicentre phase III trial. *Lancet Oncol.* **2006**, *7*, 392–401. [[CrossRef](#)]
- Kuhnt, D.; Ganslandt, O.; Schlaffer, S.-M.; Buchfelder, M.; Nimsy, C. Quantification of Glioma Removal by Intraoperative High-Field Magnetic Resonance Imaging: An Update. *Neurosurgery* **2011**, *69*, 852–863. [[CrossRef](#)] [[PubMed](#)]
- Hua, X.; Huang, M.; Deng, X.; Xu, J.; Luo, Y.; Xie, Q.; Xu, J.; Tian, Z.; Li, J.; Zhu, J.; et al. The inhibitory effect of compound ChIA-F on human bladder cancer cell invasion can be attributed to its blockage of SOX2 protein. *Cell Death Differ.* **2020**, *27*, 632–645. [[CrossRef](#)] [[PubMed](#)]
- Onishi, M.; Ichikawa, T.; Kurozumi, K.; Date, I. Angiogenesis and invasion in glioma. *Brain Tumor Pathol.* **2011**, *28*, 13–24. [[CrossRef](#)]
- Shimizu, T.; Kurozumi, K.; Ishida, J.; Ichikawa, T.; Date, I. Adhesion molecules and the extracellular matrix as drug targets for glioma. *Brain Tumor Pathol.* **2016**, *33*, 97–106. [[CrossRef](#)] [[PubMed](#)]
- Fayzullin, A.; Sandberg, C.J.; Spreadbury, M.; Saberniak, B.M.; Grieg, Z.; Skaga, E.; Langmoen, I.A.; Vik-Mo, E.O. Phenotypic and Expressional Heterogeneity in the Invasive Glioma Cells. *Transl. Oncol.* **2019**, *12*, 122–133. [[CrossRef](#)] [[PubMed](#)]
- Lagerweij, T.; Dusoswa, S.; Negrean, A.; Hendrikx, E.M.L.; De Vries, H.E.; Kole, J.; Garcia-Vallejo, J.J.; Mansvelter, H.; Vander-top, W.P.; Noske, D.P.; et al. Optical clearing and fluorescence deep-tissue imaging for 3D quantitative analysis of the brain tumor microenvironment. *Angiogenesis* **2017**, *20*, 533–546. [[CrossRef](#)] [[PubMed](#)]
- Jabouille, A.; Delugin, M.; Pineau, R.; Dubrac, A.; Soulet, F.; Lhomond, S.; Pallares-Lupon, N.; Prats, H.; Bikfalvi, A.; Chevet, E.; et al. Glioblastoma invasion and cooption depend on IRE1 α endoribonuclease activity. *Oncotarget* **2015**, *6*, 24922–24934. [[CrossRef](#)] [[PubMed](#)]
- Monzo, P.; Chong, Y.K.; Guetta-Terrier, C.; Krishnasamy, A.; Sathe, S.R.; Yim, E.; Ng, W.H.; Ang, B.T.; Tang, C.; Ladoux, B.; et al. Mechanical confinement triggers glioma linear migration dependent on formin FHOD3. *Mol. Biol. Cell* **2016**, *27*, 1246–1261. [[CrossRef](#)]
- Tamura, R.; Miyoshi, H.; Sampetean, O.; Shinozaki, M.; Morimoto, Y.; Iwasawa, C.; Fukaya, R.; Mine, Y.; Masuda, H.; Maruyama, T.; et al. Visualization of spatiotemporal dynamics of human glioma stem cell invasion. *Mol. Brain* **2019**, *12*, 45. [[CrossRef](#)] [[PubMed](#)]
- Farin, A.; Suzuki, S.O.; Weiker, M.; Goldman, J.E.; Bruce, J.N.; Canoll, P. Transplanted glioma cells migrate and proliferate on host brain vasculature: A dynamic analysis. *Glia* **2006**, *53*, 799–808. [[CrossRef](#)]
- Prahl, L.; Stanslaski, M.R.; Vargas, P.; Piel, M.; Odde, D.J. Predicting Confined 1D Cell Migration from Parameters Calibrated to a 2D Motor-Clutch Model. *Biophys. J.* **2020**, *118*, 1709–1720. [[CrossRef](#)]
- Chaichana, K.L.; Jusue-Torres, I.; Lemos, A.M.; Gokaslan, A.; Cabrera-Aldana, E.E.; Ashary, A.; Olivi, A.; Quinones-Hinojosa, A. The butterfly effect on glioblastoma: Is volumetric extent of resection more effective than biopsy for these tumors? *J. Neuro-Oncol.* **2014**, *120*, 625–634. [[CrossRef](#)]
- Shen, S.; Feng, S.; Liu, H.; Jiang, J.; Yu, X. Associations of histological and molecular alterations with invasion of the corpus callosum in gliomas. *Acta Neurochir.* **2020**, *162*, 1691–1699. [[CrossRef](#)]

18. Sadahiro, H.; Yoshikawa, K.; Ideguchi, M.; Kajiwara, K.; Ishii, A.; Ikeda, E.; Owada, Y.; Yasumoto, Y.; Suzuki, M. Pathological features of highly invasive glioma stem cells in a mouse xenograft model. *Brain Tumor Pathol.* **2014**, *31*, 77–84. [[CrossRef](#)] [[PubMed](#)]
19. Jafri, N.F.; Clarke, J.L.; Weinberg, V.; Barani, I.J.; Cha, S. Relationship of glioblastoma multiforme to the subventricular zone is associated with survival. *Neuro-Oncology* **2013**, *15*, 91–96. [[CrossRef](#)] [[PubMed](#)]
20. Mistry, A.M.; Dewan, M.C.; White-Dzuro, G.A.; Brinson, P.R.; Weaver, K.D.; Thompson, R.C.; Ihrle, R.A.; Chambless, L.B. Decreased survival in glioblastomas is specific to contact with the ventricular-subventricular zone, not subgranular zone or corpus callosum. *J. Neuro-Oncol.* **2017**, *132*, 341–349. [[CrossRef](#)]
21. Yamaki, T.; Shibahra, I.; Matsuda, K.-I.; Kanemura, Y.; Konta, T.; Kanamori, M.; Yamakawa, M.; Tominaga, T.; Sonoda, Y. Relationships between recurrence patterns and subventricular zone involvement or CD133 expression in glioblastoma. *J. Neuro-Oncol.* **2020**, *146*, 489–499. [[CrossRef](#)] [[PubMed](#)]
22. Qin, E.Y.; Cooper, D.D.; Abbott, K.; Lennon, J.; Nagaraja, S.; Mackay, A.; Jones, C.; Vogel, H.; Jackson, P.K.; Monje, M. Neural Precursor-Derived Pleiotrophin Mediates Subventricular Zone Invasion by Glioma. *Cell* **2017**, *170*, 845–859.e819. [[CrossRef](#)]
23. Lu, K.V.; Jong, K.A.; Kim, G.Y.; Singh, J.; Dia, E.Q.; Yoshimoto, K.; Wang, M.Y.; Cloughesy, T.F.; Nelson, S.F.; Mischel, P.S. Differential Induction of Glioblastoma Migration and Growth by Two Forms of Pleiotrophin. *J. Biol. Chem.* **2005**, *280*, 26953–26964. [[CrossRef](#)]
24. Wang, X. Pleiotrophin: Activity and mechanism. *Adv. Clin. Chem.* **2020**, *98*, 51–89. [[CrossRef](#)] [[PubMed](#)]
25. Ryan, E.; Shen, D.; Wang, X. Pleiotrophin interacts with glycosaminoglycans in a highly flexible and adaptable manner. *FEBS Lett.* **2021**, *595*, 925–941. [[CrossRef](#)]
26. Goffart, N.; Kroonen, J.; Di Valentin, E.; Dedobbeleer, M.; Denne, A.; Martinive, P.; Rogister, B. Adult mouse subventricular zones stimulate glioblastoma stem cells specific invasion through CXCL12/CXCR4 signaling. *Neuro-Oncology* **2015**, *17*, 81–94. [[CrossRef](#)]
27. Shi, Y.; Riese, D.J.I.; Shen, J. The Role of the CXCL12/CXCR4/CXCR7 Chemokine Axis in Cancer. *Front. Pharmacol.* **2020**, *11*, 574667. [[CrossRef](#)] [[PubMed](#)]
28. Ehtesham, M.; A Winston, J.; Kabos, P.; Thompson, R.C. CXCR4 expression mediates glioma cell invasiveness. *Oncogene* **2006**, *25*, 2801–2806. [[CrossRef](#)] [[PubMed](#)]
29. Zhang, J.; Sarkar, S.; Yong, V. The chemokine stromal cell derived factor-1 (CXCL12) promotes glioma invasiveness through MT2-matrix metalloproteinase. *Carcinogenesis* **2005**, *26*, 2069–2077. [[CrossRef](#)]
30. Chen, L.; Zhu, M.; Yu, S.; Hai, L.; Zhang, L.; Zhang, C.; Zhao, P.; Zhou, H.; Wang, S.; Yang, X. Arg kinase mediates CXCL12/CXCR4-induced invadopodia formation and invasion of glioma cells. *Exp. Cell Res.* **2020**, *389*, 111893. [[CrossRef](#)]
31. Paz, H.; Pathak, N.; Yang, J. Invading one step at a time: The role of invadopodia in tumor metastasis. *Oncogene* **2014**, *33*, 4193–4202. [[CrossRef](#)]
32. Artym, V.V.; Zhang, Y.; Seillier-Moiseiwitsch, F.; Yamada, K.; Mueller, S.C. Dynamic Interactions of Cortactin and Membrane Type 1 Matrix Metalloproteinase at Invadopodia: Defining the Stages of Invadopodia Formation and Function. *Cancer Res.* **2006**, *66*, 3034–3043. [[CrossRef](#)] [[PubMed](#)]
33. Plasswilm, L.; Tannapfel, A.; Cordes, N.; Demir, R.; Höper, K.; Bauer, J.; Höper, J. Hypoxia-Induced Tumour Cell Migration in an in vivo Chicken Model. *Pathobiology* **2000**, *68*, 99–105. [[CrossRef](#)] [[PubMed](#)]
34. Semenza, G.L.; Wang, G.L. A nuclear factor induced by hypoxia via de novo protein synthesis binds to the human erythropoietin gene enhancer at a site required for transcriptional activation. *Mol. Cell. Biol.* **1992**, *12*, 5447–5454. [[CrossRef](#)]
35. Semenza, G.L. Targeting HIF-1 for cancer therapy. *Nat. Rev. Cancer* **2003**, *3*, 721–732. [[CrossRef](#)]
36. Kaur, B.; Khwaja, F.W.; Severson, E.A.; Matheny, S.L.; Brat, D.J.; Van Meir, E.G. Hypoxia and the hypoxia-inducible-factor pathway in glioma growth and angiogenesis. *Neuro-Oncology* **2005**, *7*, 134–153. [[CrossRef](#)] [[PubMed](#)]
37. Grassi, E.S.; Pantazopoulou, V.; Pietras, A. Hypoxia-induced release, nuclear translocation, and signaling activity of a DLK1 intracellular fragment in glioma. *Oncogene* **2020**, *39*, 4028–4044. [[CrossRef](#)] [[PubMed](#)]
38. Qiang, L.; Wu, T.; Zhang, H.-W.; Lu, N.; Hu, R.; Wang, Y.-J.; Zhao, L.; Chen, F.-H.; Wang, X.-T.; You, Q.-D.; et al. HIF-1 α is critical for hypoxia-mediated maintenance of glioblastoma stem cells by activating Notch signaling pathway. *Cell Death Differ.* **2012**, *19*, 284–294. [[CrossRef](#)]
39. Sahlgren, C.; Gustafsson, M.V.; Jin, S.; Poellinger, L.; Lendahl, U. Notch signaling mediates hypoxia-induced tumor cell migration and invasion. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 6392–6397. [[CrossRef](#)]
40. Huang, W.; Ding, X.; Ye, H.; Wang, J.; Shao, J.; Huang, T. Hypoxia enhances the migration and invasion of human glioblastoma U87 cells through PI3K/Akt/mTOR/HIF-1 α pathway. *NeuroReport* **2018**, *29*, 1578–1585. [[CrossRef](#)]
41. Smith, B.N.; Bhowmick, N.A. Role of EMT in Metastasis and Therapy Resistance. *J. Clin. Med.* **2016**, *5*, 17. [[CrossRef](#)] [[PubMed](#)]
42. Wang, M.; Wang, T.; Liu, S.; Yoshida, D.; Teramoto, A. The expression of matrix metalloproteinase-2 and-9 in human gliomas of different pathological grades. *Brain Tumor Pathol.* **2003**, *20*, 65–72. [[CrossRef](#)]
43. Sincevičiūtė, R.; Vaitkienė, P.; Urbanavičiūtė, R.; Steponaitis, G.; Tamašauskas, A.; Skiriūtė, D. MMP2 is associated with glioma malignancy and patient outcome. *Int. J. Clin. Exp. Pathol.* **2018**, *11*, 3010–3018. [[PubMed](#)]
44. Ferrer, V.P.; Moura-Neto, V.; Mentlein, R. Glioma infiltration and extracellular matrix: Key players and modulators. *Glia* **2018**, *66*, 1542–1565. [[CrossRef](#)]

45. Santibanez, J.F.; Obradović, H.; Kukolj, T.; Krstić, J. Transforming growth factor- β , matrix metalloproteinases, and urokinase-type plasminogen activator interaction in the cancer epithelial to mesenchymal transition. *Dev. Dyn.* **2018**, *247*, 382–395. [[CrossRef](#)]
46. Baumann, F.; Leukel, P.; Doerfelt, A.; Beier, C.P.; Dettmer, K.; Oefner, P.J.; Kastenberger, M.; Kreutz, M.; Nickl-Jockschat, T.; Bogdahn, U.; et al. Lactate promotes glioma migration by TGF- β 2-dependent regulation of matrix metalloproteinase-2. *Neuro-Oncology* **2009**, *11*, 368–380. [[CrossRef](#)] [[PubMed](#)]
47. Seliger, C.; Leukel, P.; Moeckel, S.; Jachnik, B.; Lottaz, C.; Kreutz, M.; Brawanski, A.; Proescholdt, M.; Bogdahn, U.; Bossert, A.; et al. Lactate-Modulated Induction of THBS-1 Activates Transforming Growth Factor (TGF)- β 2 and Migration of Glioma Cells In Vitro. *PLoS ONE* **2013**, *8*, e78935. [[CrossRef](#)]
48. Sanderson, R.D.; Elkin, M.; Rapraeger, A.C.; Ilan, N.; Vlodavsky, I. Heparanase regulation of cancer, autophagy and inflammation: New mechanisms and targets for therapy. *FEBS J.* **2017**, *284*, 42–55. [[CrossRef](#)]
49. Bello, L.; Francolini, M.; Marthyn, P.; Zhang, J.; Carroll, R.S.; Nikas, D.C.; Strasser, J.F.; Villani, R.; Cheresch, D.A.; Black, P.M. α v β 3 and α v β 5 Integrin Expression in Glioma Periphery. *Neurosurgery* **2001**, *49*, 380–389. [[CrossRef](#)]
50. Platten, M.; Wick, W.; Bode, C.W.; Aulwurm, S.; Dichgans, J.; Weller, M. Transforming Growth Factors β 1 (TGF- β 1) and TGF- β 2 Promote Glioma Cell Migration via Up-Regulation of α v β 3 Integrin Expression. *Biochem. Biophys. Res. Commun.* **2000**, *268*, 607–611. [[CrossRef](#)]
51. Levental, K.; Yu, H.; Kass, L.; Lakins, J.N.; Egeblad, M.; Erler, J.; Fong, S.F.; Csiszar, K.; Giaccia, A.; Wengler, W.; et al. Matrix Crosslinking Forces Tumor Progression by Enhancing Integrin Signaling. *Cell* **2009**, *139*, 891–906. [[CrossRef](#)]
52. Ulrich, T.A.; de Juan Pardo, E.M.; Kumar, S. The Mechanical Rigidity of the Extracellular Matrix Regulates the Structure, Motility, and Proliferation of Glioma Cells. *Cancer Res.* **2009**, *69*, 4167–4174. [[CrossRef](#)]
53. Grzeszkiewicz, T.M.; Kirschling, D.J.; Chen, N.; Lau, L.F. CYR61 Stimulates Human Skin Fibroblast Migration through Integrin α v β 5 and Enhances Mitogenesis through Integrin α v β 3, Independent of Its Carboxyl-terminal Domain. *J. Biol. Chem.* **2001**, *276*, 21943–21950. [[CrossRef](#)]
54. Walsh, C.T.; Radeff-Huang, J.; Matteo, R.; Hsiao, A.; Subramaniam, S.; Stupack, D.; Brown, J.H. Thrombin receptor and RhoA mediate cell proliferation through integrins and cysteine-rich protein 61. *FASEB J.* **2008**, *22*, 4011–4021. [[CrossRef](#)] [[PubMed](#)]
55. Ishida, J.; Kurozumi, K.; Ichikawa, T.; Otani, Y.; Onishi, M.; Fujii, K.; Shimazu, Y.; Oka, T.; Shimizu, T.; Date, I. Evaluation of extracellular matrix protein CCN1 as a prognostic factor for glioblastoma. *Brain Tumor Pathol.* **2015**, *32*, 245–252. [[CrossRef](#)] [[PubMed](#)]
56. Xie, D.; Yin, N.; Wang, H.-J.; Liu, G.-T.; Elashoff, R.; Black, K.; Koeffler, H.P. Levels of expression of CYR61 and CTGF are prognostic for tumor progression and survival of individuals with gliomas. *Clin. Cancer Res.* **2004**, *10*, 2072–2081. [[CrossRef](#)]
57. Uneda, A.; Kurozumi, K.; Fujimura, A.; Fujii, K.; Ishida, J.; Shimazu, Y.; Otani, Y.; Tomita, Y.; Hattori, Y.; Matsumoto, Y.; et al. Differentiated glioblastoma cells accelerate tumor progression by shaping the tumor microenvironment via CCN1-mediated macrophage infiltration. *Acta Neuropathol. Commun.* **2021**, *9*, 29. [[CrossRef](#)]
58. Silver, D.J.; Siebzehnrubl, F.; Schildts, M.J.; Yachnis, A.T.; Smith, G.M.; Smith, A.A.; Scheffler, B.; Reynolds, B.A.; Silver, J.; Steindler, D.A. Chondroitin Sulfate Proteoglycans Potently Inhibit Invasion and Serve as a Central Organizer of the Brain Tumor Microenvironment. *J. Neurosci.* **2013**, *33*, 15603–15617. [[CrossRef](#)]
59. Wade, A.; Robinson, A.E.; Engler, J.R.; Petritsch, C.; James, C.D.; Phillips, J.J. Proteoglycans and their roles in brain cancer. *FEBS J.* **2013**, *280*, 2399–2417. [[CrossRef](#)] [[PubMed](#)]
60. Naganuma, H.; Satoh, E.; Asahara, T.; Amagasaki, K.; Watanabe, A.; Satoh, H.; Kuroda, K.; Zhang, L.; Nukui, H. Quantification of thrombospondin-1 secretion and expression of α v β 3 and α 3 β 1 integrins and syndecan-1 as cell-surface receptors for thrombospondin-1 in malignant glioma cells. *J. Neuro-Oncol.* **2004**, *70*, 309–317. [[CrossRef](#)]
61. Ramani, V.C.; Purushothaman, A.; Stewart, M.D.; Thompson, C.A.; Vlodavsky, I.; Au, J.L.-S.; Sanderson, R.D. The heparanase/syndecan-1 axis in cancer: Mechanisms and therapies. *FEBS J.* **2013**, *280*, 2294–2306. [[CrossRef](#)] [[PubMed](#)]
62. Shi, S.; Zhong, D.; Xiao, Y.; Wang, B.; Wang, W.; Zhang, F.; Huang, H. Syndecan-1 knockdown inhibits glioma cell proliferation and invasion by deregulating a c-src/FAK-associated signaling pathway. *Oncotarget* **2017**, *8*, 40922–40934. [[CrossRef](#)] [[PubMed](#)]
63. Dwyer, C.A.; Bi, W.L.; Viapiano, M.S.; Matthews, R.T. Brevican knockdown reduces late-stage glioma tumor aggressiveness. *J. Neuro-Oncol.* **2014**, *120*, 63–72. [[CrossRef](#)]
64. Hong, X.; Jiang, F.; Kalkanis, S.N.; Zhang, Z.G.; Zhang, X.; Zheng, X.; Jiang, H.; Mikkelsen, T.; Chopp, M. Increased chemotactic migration and growth in heparanase-overexpressing human U251n glioma cells. *J. Exp. Clin. Cancer Res.* **2008**, *27*, 23–28. [[CrossRef](#)] [[PubMed](#)]
65. Kundu, S.; Xiong, A.; Spyrou, A.; Wicher, G.; Marinescu, V.D.; Edqvist, P.-H.D.; Zhang, L.; Essand, M.; Dimberg, A.; Smits, A.; et al. Heparanase Promotes Glioma Progression and Is Inversely Correlated with Patient Survival. *Mol. Cancer Res.* **2016**, *14*, 1243–1253. [[CrossRef](#)]
66. Gimple, R.C.; Bhargava, S.; Dixit, D.; Rich, J.N. Glioblastoma stem cells: Lessons from the tumor hierarchy in a lethal cancer. *Genes Dev.* **2019**, *33*, 591–609. [[CrossRef](#)]
67. Wakimoto, H.; Kesari, S.; Farrell, C.J.; Curry, W.T., Jr.; Zaupa, C.; Aghi, M.; Kuroda, T.; Stemmer-Rachamimov, A.; Shah, K.; Liu, T.-C.; et al. Human Glioblastoma-Derived Cancer Stem Cells: Establishment of Invasive Glioma Models and Treatment with Oncolytic Herpes Simplex Virus Vectors. *Cancer Res.* **2009**, *69*, 3472–3481. [[CrossRef](#)]

68. Zhang, J.; Cai, H.; Sun, L.; Zhan, P.; Chen, M.; Zhang, F.; Ran, Y.; Wan, J. LGR5, a novel functional glioma stem cell marker, promotes EMT by activating the Wnt/ β -catenin pathway and predicts poor survival of glioma patients. *J. Exp. Clin. Cancer Res.* **2018**, *37*, 225. [[CrossRef](#)]
69. Yi, L.; Zhou, X.; Li, T.; Liu, P.; Hai, L.; Tong, L.; Ma, H.; Tao, Z.; Xie, Y.; Zhang, C.; et al. Notch1 signaling pathway promotes invasion, self-renewal and growth of glioma initiating cells via modulating chemokine system CXCL12/CXCR4. *J. Exp. Clin. Cancer Res.* **2019**, *38*, 339. [[CrossRef](#)]
70. Teodorczyk, M.; Schmidt, M.H.H. Notching on Cancer's™ Door: Notch Signaling in Brain Tumors. *Front. Oncol.* **2014**, *4*, 341. [[CrossRef](#)]
71. Wang, J.; Xu, S.-L.; Duan, J.-J.; Yi, L.; Guo, Y.-F.; Shi, Y.; Li, L.; Yang, Z.-Y.; Liao, X.-M.; Cai, J.; et al. Invasion of white matter tracts by glioma stem cells is regulated by a NOTCH1–SOX2 positive-feedback loop. *Nat. Neurosci.* **2019**, *22*, 91–105. [[CrossRef](#)]
72. Zhang, X.; Chen, T.; Zhang, J.; Mao, Q.; Li, S.; Xiong, W.; Qiu, Y.; Xie, Q.; Ge, J. Notch1 promotes glioma cell migration and invasion by stimulating β -catenin and NF- κ B signaling via AKT activation. *Cancer Sci.* **2011**, *103*, 181–190. [[CrossRef](#)]
73. Li, L.; Tang, P.; Li, S.; Qin, X.; Yang, H.; Wu, C.; Liu, Y. Notch signaling pathway networks in cancer metastasis: A new target for cancer therapy. *Med. Oncol.* **2017**, *34*, 180. [[CrossRef](#)] [[PubMed](#)]
74. Calinescu, A.-A.; Yadav, V.N.; Carballo, E.; Kadiyala, P.; Tran, D.; Zamler, D.; Doherty, R.; Srikanth, M.; Lowenstein, P.R.; Castro, M.G. Survival and Proliferation of Neural Progenitor-Derived Glioblastomas Under Hypoxic Stress is Controlled by a CXCL12/CXCR4 Autocrine-Positive Feedback Mechanism. *Clin. Cancer Res.* **2017**, *23*, 1250–1262. [[CrossRef](#)]
75. Xu, R.; Shimizu, F.; Hovinga, K.; Beal, K.; Karimi, S.; Droms, L.; Peck, K.K.; Gutin, P.; Iorgulescu, J.B.; Kaley, T.; et al. Molecular and Clinical Effects of Notch Inhibition in Glioma Patients: A Phase 0/I Trial. *Clin. Cancer Res.* **2016**, *22*, 4786–4796. [[CrossRef](#)] [[PubMed](#)]
76. Bourguignon, L.Y.; Earle, C.; Shiina, M. Hyaluronan-CD44 interaction promotes HPV 16 E6 oncogene-mediated oropharyngeal cell carcinoma survival and chemoresistance. *Matrix Biol.* **2019**, *78–79*, 180–200. [[CrossRef](#)]
77. Radotra, B.; McCormick, D. Glioma invasion in vitro is mediated by CD44-hyaluronan interactions. *J. Pathol.* **1997**, *181*, 434–438. [[CrossRef](#)]
78. Sherpa, A.D.; Guilfoyle, D.N.; Naik, A.A.; Isakovic, J.; Irie, F.; Yamaguchi, Y.; Hrabe, J.; Aoki, C.; Hrabetova, S. Integrity of White Matter is Compromised in Mice with Hyaluronan Deficiency. *Neurochem. Res.* **2020**, *45*, 53–67. [[CrossRef](#)]
79. Park, M.J.; Kim, M.S.; Park, I.C.; Kang, H.S.; Yoo, H.; Park, S.H.; Rhee, C.H.; Hong, S.I.; Lee, S.H. PTEN sup-presses hyaluronic acid-induced matrix metalloproteinase-9 expression in U87MG glioblastoma cells through focal adhesion kinase dephosphorylation. *Cancer Res.* **2002**, *62*, 6318–6322. [[PubMed](#)]
80. Kim, M.-S.; Park, M.-J.; Moon, E.-J.; Kim, S.-J.; Lee, C.-H.; Yoo, H.; Shin, S.-H.; Song, E.-S.; Lee, S.-H. Hyaluronic acid induces osteopontin via the phosphatidylinositol 3-kinase/Akt pathway to enhance the motility of human glioma cells. *Cancer Res.* **2005**, *65*, 686–691.
81. Pibuel, M.A.; Poodts, D.; Díaz, M.; Hajos, S.E.; Lompardía, S.L. The scrambled story between hyaluronan and glioblastoma. *J. Biol. Chem.* **2021**, *296*, 100549. [[CrossRef](#)]
82. Lim, E.-J.; Suh, Y.; Yoo, K.-C.; Lee, J.-H.; Kim, I.-G.; Kim, M.-J.; Chang, J.H.; Kang, S.-G.; Lee, S.-J. Tumor-associated mesenchymal stem-like cells provide extracellular signaling cue for invasiveness of glioblastoma cells. *Oncotarget* **2017**, *8*, 1438–1448. [[CrossRef](#)] [[PubMed](#)]
83. Kalluri, R.; Weinberg, R.A. The basics of epithelial-mesenchymal transition. *J. Clin. Investig.* **2009**, *119*, 1420–1428. [[CrossRef](#)] [[PubMed](#)]
84. Fedele, M.; Cerchia, L.; Pegoraro, S.; Sgarra, R.; Manfioletti, G. Proneural-Mesenchymal Transition: Phenotypic Plasticity to Acquire Multitherapy Resistance in Glioblastoma. *Int. J. Mol. Sci.* **2019**, *20*, 2746. [[CrossRef](#)] [[PubMed](#)]
85. Iwadate, Y. Epithelial-mesenchymal transition in glioblastoma progression. *Oncol. Lett.* **2016**, *11*, 1615–1620. [[CrossRef](#)]
86. Lu, Y.-B.; Sun, T.-J.; Chen, Y.-T.; Cai, Z.-Y.; Zhao, J.-Y.; Miao, F.; Yang, Y.-N.; Wang, S.-X. Targeting the Epithelial-to-Mesenchymal Transition in Cancer Stem Cells for a Better Clinical Outcome of Glioma. *Technol. Cancer Res. Treat.* **2020**, *19*, 1533033820948053. [[CrossRef](#)]
87. Jordà, M.; Olmeda, D.; Vinyals, A.; Valero, E.; Cubillo, E.; Llorens, A.; Cano, A.; Fabra, A. Upregulation of MMP-9 in MDCK epithelial cell line in response to expression of the Snail transcription factor. *J. Cell Sci.* **2005**, *118*, 3371–3385. [[CrossRef](#)]
88. Moustakas, A.; Heldin, C.-H. Mechanisms of TGF β -Induced Epithelial–Mesenchymal Transition. *J. Clin. Med.* **2016**, *5*, 63. [[CrossRef](#)]
89. Bruna, A.; Darken, R.S.; Rojo, F.; Ocana, A.; Peñuelas, S.; Arias, A.; Paris, R.; Tortosa, A.; Mora, J.; Baselga, J.; et al. High TGF β -Smad Activity Confers Poor Prognosis in Glioma Patients and Promotes Cell Proliferation Depending on the Methylation of the PDGF-B Gene. *Cancer Cell* **2007**, *11*, 147–160. [[CrossRef](#)]
90. Massague, J. TGFbeta in Cancer. *Cell* **2008**, *134*, 215–230. [[CrossRef](#)]
91. Yamahana, H.; Terashima, M.; Takatsuka, R.; Asada, C.; Suzuki, T.; Uto, Y.; Takino, T. TGF- β 1 facilitates MT1-MMP-mediated proMMP-9 activation and invasion in oral squamous cell carcinoma cells. *Biochem. Biophys. Rep.* **2021**, *27*, 101072. [[CrossRef](#)]
92. Iwadate, Y.; Matsutani, T.; Hirono, S.; Shinozaki, N.; Saeki, N. Transforming growth factor- β and stem cell markers are highly expressed around necrotic areas in glioblastoma. *J. Neuro-Oncol.* **2016**, *129*, 101–107. [[CrossRef](#)]

93. Anido, J.; Sáez-Borderías, A.; González-Juncà, A.; Rodón, L.; Folch, G.; Carmona, M.A.; Prieto-Sánchez, R.M.; Barba, I.; Martínez-Saez, E.; Prudkin, L.; et al. TGF- β Receptor Inhibitors Target the CD44^{high}/Id1^{high} Glioma-Initiating Cell Population in Human Glioblastoma. *Cancer Cell* **2010**, *18*, 655–668. [[CrossRef](#)] [[PubMed](#)]
94. Fehlauer, F.; Muench, M.; Richter, E.; Rades, D. The inhibition of proliferation and migration of glioma spheroids exposed to temozolomide is less than additive if combined with irradiation. *Oncol. Rep.* **2007**, *17*, 941–945.
95. Kim, I.H.; Lemmon, M.J.; Brown, J.M. The influence of irradiation of the tumor bed on tumor hypoxia: Measurements by radiation response, oxygen electrodes, and nitroimidazole binding. *Radiat. Res.* **1993**, *135*, 411–417. [[CrossRef](#)] [[PubMed](#)]
96. Baumann, M.; Würschmidt, F.; Twardy, A.; Beck-Bornholdt, H.-P. Impact of Tumor Stroma on Expression of the Tumor Bed Effect in R1H Rat Rhabdomyosarcoma. *Radiat. Res.* **1994**, *140*, 432–436. [[CrossRef](#)]
97. Hegedus, B.; Zach, J.; Czirik, A.; Lovey, J.; Vicsek, T. Irradiation and Taxol Treatment Result in Non-Monotonous, Dose-Dependent Changes in the Motility of Glioblastoma Cells. *J. Neuro-Oncol.* **2004**, *67*, 147–157. [[CrossRef](#)]
98. Zhai, G.G.; Malhotra, R.; Delaney, M.; Latham, D.; Nestler, U.; Zhang, M.; Mukherjee, N.; Song, Q.; Robe, P.; Chakravarti, A. Radiation Enhances the Invasive Potential of Primary Glioblastoma Cells via Activation of the Rho Signaling Pathway. *J. Neuro-Oncol.* **2006**, *76*, 227–237. [[CrossRef](#)] [[PubMed](#)]
99. Tsuji, Y.; Nonoguchi, N.; Okuzaki, D.; Wada, Y.; Motooka, D.; Hirota, Y.; Toho, T.; Yoshikawa, N.; Furuse, M.; Kawabata, S.; et al. Chronic pathophysiological changes in the normal brain parenchyma caused by radiotherapy accelerate glioma progression. *Sci. Rep.* **2021**, *11*, 22110. [[CrossRef](#)]
100. Cordes, N.; Hansmeier, B.; Beinke, C.; Meineke, V.; Van Beuningen, D. Irradiation differentially affects substratum-dependent survival, adhesion, and invasion of glioblastoma cell lines. *Br. J. Cancer* **2003**, *89*, 2122–2132. [[CrossRef](#)]
101. Nakamura, J.L.; Haas-Kogan, D.A.; Pieper, R.O. Glioma Invasiveness Responds Variably to Irradiation in a Co-Culture Model. *Int. J. Radiat. Oncol. Biol. Phys.* **2007**, *69*, 880–886. [[CrossRef](#)]
102. Grigorieva, E.V. Radiation Effects on Brain Extracellular Matrix. *Front. Oncol.* **2020**, *10*, 576701. [[CrossRef](#)] [[PubMed](#)]
103. Politko, M.O.; Tsidulko, A.Y.; Pashkovskaya, O.A.; Kuper, K.E.; Suhovskih, A.V.; Kazanskaya, G.M.; Klyushova, L.S.; Sokolov, D.K.; Volkov, A.M.; Kliver, E.E.; et al. Multiple Irradiation Affects Cellular and Extracellular Components of the Mouse Brain Tissue and Adhesion and Proliferation of Glioblastoma Cells in Experimental System In Vivo. *Int. J. Mol. Sci.* **2021**, *22*, 13350. [[CrossRef](#)]
104. Trog, D.; Yeghiazaryan, K.; Fountoulakis, M.; Friedlein, A.; Moenkemann, H.; Haertel, N.; Schueller, H.; Breipohl, W.; Schild, H.; Leppert, D.; et al. Pro-invasive gene regulating effect of irradiation and combined temozolomide-radiation treatment on surviving human malignant glioma cells. *Eur. J. Pharmacol.* **2006**, *542*, 8–15. [[CrossRef](#)]
105. Pei, J.; Park, I.-H.; Ryu, H.-H.; Li, S.-Y.; Li, C.-H.; Lim, S.-H.; Wen, M.; Jang, W.-Y.; Jung, S. Sublethal dose of irradiation enhances invasion of malignant glioma cells through p53-MMP 2 pathway in U87MG mouse brain tumor model. *Radiat. Oncol.* **2015**, *10*, 164. [[CrossRef](#)]
106. Wild-Bode, C.; Weller, M.; Rimmer, A.; Dichgans, J.; Wick, W. Sublethal irradiation promotes migration and invasiveness of glioma cells: Implications for radiotherapy of human glioblastoma. *Cancer Res.* **2001**, *612*, 744–2750.
107. Kim, Y.-H.; Yoo, K.-C.; Cui, Y.-H.; Uddin, N.; Lim, E.-J.; Kim, M.-J.; Nam, S.-Y.; Kim, I.-G.; Suh, Y.; Lee, S.-J. Radiation promotes malignant progression of glioma cells through HIF-1 α stabilization. *Cancer Lett.* **2014**, *354*, 132–141. [[CrossRef](#)]
108. Gauthier, L.R.; Saati, M.; Bensalah-Pigeon, H.; Ben M'Barek, K.; Gitton-Quent, O.; Bertrand, R.; Busso, D.; Mouthon, M.-A.; Collura, A.; Junier, M.-P.; et al. The HIF1 α /JMY pathway promotes glioblastoma stem-like cell invasiveness after irradiation. *Sci. Rep.* **2020**, *10*, 18742. [[CrossRef](#)] [[PubMed](#)]
109. Goetze, K.; Scholz, M.; Taucher-Scholz, G.; Mueller-Klieser, W. The impact of conventional and heavy ion irradiation on tumor cell migration in vitro. *Int. J. Radiat. Biol.* **2007**, *83*, 889–896. [[CrossRef](#)]
110. Wank, M.; Schilling, D.; Reindl, J.; Meyer, B.; Gempt, J.; Motov, S.; Alexander, F.; Wilkens, J.J.; Schlegel, J.; Schmid, T.E.; et al. Evaluation of radiation-related invasion in primary patient-derived glioma cells and validation with established cell lines: Impact of different radiation qualities with differing LET. *J. Neuro-Oncol.* **2018**, *139*, 583–590. [[CrossRef](#)] [[PubMed](#)]
111. Mao, L.; Whitehead, C.; Paradiso, L.; Kaye, A.H.; Morokoff, A.; Luwor, R.; Stylli, S.S. Enhancement of invadopodia activity in glioma cells by sublethal doses of irradiation and temozolomide. *J. Neurosurg.* **2018**, *129*, 598–610. [[CrossRef](#)]
112. Dinevska, M.; Gazibegovic, N.; Morokoff, A.P.; Kaye, A.H.; Drummond, K.J.; Mantamadiotis, T.; Stylli, S.S. Inhibition of Radiation and Temozolomide-Induced Glioblastoma Invadopodia Activity Using Ion Channel Drugs. *Cancers* **2020**, *12*, 2888. [[CrossRef](#)] [[PubMed](#)]
113. Khazaei, M.; Pazhouhi, M.; Sariri, R.; Khazaei, M.R.; Moradi, M.T. Synergistic effect of temozolomide and thymoquinone on human glioblastoma multiforme cell line (U87MG). *J. Cancer Res. Ther.* **2018**, *14*, 1023–1028. [[CrossRef](#)] [[PubMed](#)]
114. Mirabdaly, S.; Komi, D.E.A.; Shakiba, Y.; Moini, A.; Kiani, A. Effects of temozolomide on U87MG glioblastoma cell expression of CXCR4, MMP2, MMP9, VEGF, anti-proliferatory cytotoxic and apoptotic properties. *Mol. Biol. Rep.* **2020**, *47*, 1187–1197. [[CrossRef](#)] [[PubMed](#)]
115. Stefanik, D.F.; Fellows, W.K.; Rizkalla, L.R.; Rizkalla, W.M.; Stefanik, P.P.; DeLeo, A.B.; Welch, W.C. Monoclonal antibodies to vascular endothelial growth factor (VEGF) and the VEGF receptor, FLT-1, inhibit the growth of C6 glioma in a mouse xenograft. *J. Neuro-Oncol.* **2001**, *55*, 91–100. [[CrossRef](#)]
116. Shimizu, T.; Ishida, J.; Kurozumi, K.; Ichikawa, T.; Otani, Y.; Oka, T.; Tomita, Y.; Hattori, Y.; Uneda, A.; Matsumoto, Y.; et al. δ -Catenin Promotes Bevacizumab-Induced Glioma Invasion. *Mol. Cancer Ther.* **2019**, *18*, 812–822. [[CrossRef](#)]

117. Friedman, H.S.; Prados, M.D.; Wen, P.Y.; Mikkelsen, T.; Schiff, D.; Abrey, L.E.; Yung, W.A.; Paleologos, N.; Nicholas, M.K.; Jensen, R.; et al. Bevacizumab Alone and in Combination With Irinotecan in Recurrent Glioblastoma. *J. Clin. Oncol.* **2009**, *27*, 4733–4740. [[CrossRef](#)]
118. Chinot, O.L.; Wick, W.; Mason, W.; Henriksson, R.; Saran, F.; Nishikawa, R.; Carpentier, A.F.; Hoang-Xuan, K.; Kavan, P.; Cernea, D.; et al. Bevacizumab plus Radiotherapy–Temozolomide for Newly Diagnosed Glioblastoma. *N. Engl. J. Med.* **2014**, *370*, 709–722. [[CrossRef](#)]
119. Gilbert, M.R.; Dignam, J.J.; Armstrong, T.S.; Wefel, J.S.; Blumenthal, D.T.; Vogelbaum, M.A.; Colman, H.; Chakravarti, A.; Pugh, S.; Won, M.; et al. A Randomized Trial of Bevacizumab for Newly Diagnosed Glioblastoma. *N. Engl. J. Med.* **2014**, *370*, 699–708. [[CrossRef](#)]
120. Piao, Y.; Liang, J.; Holmes, L.; Zurita, A.J.; Henry, V.; Heymach, J.V.; De Groot, J.F. Glioblastoma resistance to anti-VEGF therapy is associated with myeloid cell infiltration, stem cell accumulation, and a mesenchymal phenotype. *Neuro Oncol.* **2012**, *14*, 1379–1392. [[CrossRef](#)]
121. Keunen, O.; Johansson, M.; Oudin, A.; Sanzey, M.; Rahim, S.A.A.; Fack, F.; Thorsen, F.; Taxt, T.; Bartoš, M.; Jirik, R.; et al. Anti-VEGF treatment reduces blood supply and increases tumor cell invasion in glioblastoma. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 3749–3754. [[CrossRef](#)] [[PubMed](#)]
122. Nishikawa, M.; Inoue, A.; Ohnishi, T.; Yano, H.; Kanemura, Y.; Kohno, S.; Ohue, S.; Ozaki, S.; Matsumoto, S.; Suehiro, S.; et al. CD44 expression in the tumor periphery predicts the responsiveness to bevacizumab in the treatment of recurrent glioblastoma. *Cancer Med.* **2021**, *10*, 2013–2025. [[CrossRef](#)]
123. Zhang, W.; Fulci, G.; Buhrman, J.S.; Stemmer-Rachamimov, A.O.; Chen, J.W.; Wojtkiewicz, G.; Weissleder, R.; Rabkin, S.; Martuza, R.L. Bevacizumab With Angiostatin-armed oHSV Increases Antiangiogenesis and Decreases Bevacizumab-induced Invasion in U87 Glioma. *Mol. Ther.* **2012**, *20*, 37–45. [[CrossRef](#)]
124. Nowosielski, M.; Wiestler, B.; Goebel, G.; Hutterer, M.; Schlemmer, H.P.; Stockhammer, G.; Wick, W.; Bendszus, M.; Radbruch, A. Progression types after antiangiogenic therapy are related to outcome in recurrent glioblastoma. *Neurology* **2014**, *82*, 1684–1692. [[CrossRef](#)] [[PubMed](#)]
125. Pan, E.; Supko, J.G.; Kaley, T.J.; Butowski, N.A.; Cloughesy, T.; Jung, J.; Desideri, S.; Grossman, S.; Ye, X.; Park, D.M. Phase I study of RO4929097 with bevacizumab in patients with recurrent malignant glioma. *J. Neuro-Oncol.* **2016**, *130*, 571–579. [[CrossRef](#)] [[PubMed](#)]
126. Stummer, W. Mechanisms of tumor-related brain edema. *Neurosurg. Focus* **2007**, *22*, E8. [[CrossRef](#)] [[PubMed](#)]
127. Hue, C.D.; Cho, F.S.; Cao, S.; Dale Bass, C.R.; Meaney, D.F.; Morrison, I.B., 3rd. Dexamethasone Potentiates in Vitro Blood-Brain Barrier Recovery after Primary Blast Injury by Glucocorticoid Receptor-Mediated Upregulation of ZO-1 Tight Junction Protein. *J. Cereb. Blood Flow Metab.* **2015**, *35*, 1191–1198. [[CrossRef](#)]
128. Luedi, M.M.; Singh, S.K.; Mosley, J.C.; Hassan, I.S.A.; Hatami, M.; Gumin, J.; Andereggen, L.; Sulman, E.P.; Lang, F.F.; Stueber, F.; et al. Dexamethasone-mediated oncogenicity in vitro and in an animal model of glioblastoma. *J. Neurosurg.* **2018**, *129*, 1446–1455. [[CrossRef](#)]
129. Yin, Y.; Zhang, X.; Li, Z.; Deng, L.; Jiao, G.; Zhang, B.; Xie, P.; Mu, H.; Qiao, W.; Zou, J. Glucocorticoid receptor β regulates injury-mediated astrocyte activation and contributes to glioma pathogenesis via modulation of β -catenin/TCF transcriptional activity. *Neurobiol. Dis.* **2013**, *59*, 165–176. [[CrossRef](#)]
130. Tsidulko, A.; Bezier, C.; De La Bourdonnaye, G.; Suhovskih, A.V.; Pankova, T.M.; Kazanskaya, G.M.; Aidagulova, S.; Grigorieva, E. Conventional Anti-glioblastoma Chemotherapy Affects Proteoglycan Composition of Brain Extracellular Matrix in Rat Experimental Model in vivo. *Front. Pharmacol.* **2018**, *9*, 1104. [[CrossRef](#)]
131. Lin, Y.-M.; Jan, H.-J.; Lee, C.-C.; Tao, H.-Y.; Shih, Y.-L.; Wei, H.-W.; Lee, H.-M. Dexamethasone reduced invasiveness of human malignant glioblastoma cells through a MAPK phosphatase-1 (MKP-1) dependent mechanism. *Eur. J. Pharmacol.* **2008**, *593*, 1–9. [[CrossRef](#)]
132. Piette, C.; Deprez, M.; Roger, T.; Noel, A.; Foidart, J.-M.; Munaut, C. The Dexamethasone-induced Inhibition of Proliferation, Migration, and Invasion in Glioma Cell Lines Is Antagonized by Macrophage Migration Inhibitory Factor (MIF) and Can Be Enhanced by Specific MIF Inhibitors. *J. Biol. Chem.* **2009**, *284*, 32483–32492. [[CrossRef](#)]
133. Guan, Y.; Chen, J.; Zhan, Y.; Lu, H. Effects of dexamethasone on C6 cell proliferation, migration and invasion through the upregulation of AQP1. *Oncol. Lett.* **2018**, *15*, 7595–7602. [[CrossRef](#)] [[PubMed](#)]
134. Stupp, R.; Taillibert, S.; Kanner, A.A.; Read, W.; Steinberg, D.M.; Lhermitte, B.; Toms, S.; Idbaih, A.; Ahluwalia, M.S.; Fink, K.; et al. Effect of Tumor-Treating Fields Plus Maintenance Temozolomide vs. Maintenance Temozolomide Alone on Survival in Patients With Glioblastoma: A randomized clinical Trial. *JAMA* **2017**, *318*, 2306–2316. [[CrossRef](#)] [[PubMed](#)]
135. Kim, E.H.; Song, H.S.; Yoo, S.H.; Yoon, M. Tumor treating fields inhibit glioblastoma cell migration, invasion and angiogenesis. *Oncotarget* **2016**, *7*, 65125–65136. [[CrossRef](#)] [[PubMed](#)]
136. Vandenbroucke, R.; Libert, C. Is there new hope for therapeutic matrix metalloproteinase inhibition? *Nat. Rev. Drug Discov.* **2014**, *13*, 904–927. [[CrossRef](#)]
137. Marshall, D.C.; Lyman, S.K.; McCauley, S.; Kovalenko, M.; Spangler, R.; Liu, C.; Lee, M.; O’Sullivan, C.; Barry-Hamilton, V.; Ghermazien, H.; et al. Selective Allosteric Inhibition of MMP9 Is Efficacious in Preclinical Models of Ulcerative Colitis and Colorectal Cancer. *PLoS ONE* **2015**, *10*, e0127063. [[CrossRef](#)]

138. Lucio-Eterovic, A.K.; Piao, Y.; De Groot, J.F. Mediators of Glioblastoma Resistance and Invasion during Antivascular Endothelial Growth Factor Therapy. *Clin. Cancer Res.* **2009**, *15*, 4589–4599. [[CrossRef](#)]
139. Kurozumi, K.; Ichikawa, T.; Onishi, M.; Fujii, K.; Date, I. Cilengitide Treatment for Malignant Glioma: Current Status and Future Direction. *Neurol. medico-chirurgica* **2012**, *52*, 539–547. [[CrossRef](#)]
140. Ishida, J.; Onishi, M.; Kurozumi, K.; Ichikawa, T.; Fujii, K.; Shimazu, Y.; Oka, T.; Date, I. Integrin Inhibitor Suppresses Bevacizumab-Induced Glioma Invasion. *Transl. Oncol.* **2014**, *7*, 292–302.e291. [[CrossRef](#)]
141. Nabors, L.B.; Fink, K.L.; Mikkelsen, T.; Grujicic, D.; Tarnawski, R.; Nam, D.H.; Mazurkiewicz, M.; Salacz, M.; Ashby, L.; Zagonel, V.; et al. Two cilengitide regimens in combination with standard treatment for patients with newly diagnosed glioblastoma and unmethylated MGMT gene promoter: Results of the open-label, controlled, randomized phase II CORE study. *Neuro-Oncology* **2015**, *17*, 708–717. [[CrossRef](#)] [[PubMed](#)]
142. Stupp, R.; Hegi, M.; Gorlia, T.; Erridge, S.C.; Perry, J.; Hong, Y.-K.; Aldape, K.D.; Lhermitte, B.; Pietsch, T.; Grujicic, D.; et al. Cilengitide combined with standard treatment for patients with newly diagnosed glioblastoma with methylated MGMT promoter (CENTRIC EORTC 26071-22072 study): A multicentre, randomised, open-label, phase 3 trial. *Lancet Oncol.* **2014**, *15*, 1100–1108. [[CrossRef](#)]
143. Fujii, K.; Kurozumi, K.; Ichikawa, T.; Onishi, M.; Shimazu, Y.; Ishida, J.; Chiocca, E.A.; Kaur, B.; Date, I. The integrin inhibitor cilengitide enhances the anti-glioma efficacy of vasculostatin-expressing oncolytic virus. *Cancer Gene Ther.* **2013**, *20*, 437–444. [[CrossRef](#)] [[PubMed](#)]
144. Jin, R.; Nakada, M.; Teng, L.; Furuta, T.; Sabit, H.; Hayashi, Y.; Demuth, T.; Hirao, A.; Sato, H.; Zhao, G.; et al. Combination therapy using Notch and Akt inhibitors is effective for suppressing invasion but not proliferation in glioma cells. *Neurosci. Lett.* **2013**, *534*, 316–321. [[CrossRef](#)] [[PubMed](#)]
145. Fan, X.; Khaki, L.; Zhu, T.S.; Soules, M.E.; Talsma, C.E.; Gul, N.; Koh, C.; Zhang, J.; Li, Y.-M.; Maciaczyk, J.; et al. NOTCH Pathway Blockade Depletes CD133-Positive Glioblastoma Cells and Inhibits Growth of Tumor Neurospheres and Xenografts. *Stem Cells* **2010**, *28*, 5–16. [[CrossRef](#)]
146. Peereboom, D.M.; Ye, X.; Mikkelsen, T.; Lesser, G.J.; Lieberman, F.S.; Robins, H.I.; Ahluwalia, M.S.; E Sloan, A.; A Grossman, S. A Phase II and Pharmacodynamic Trial of RO4929097 for Patients With Recurrent/Progressive Glioblastoma. *Neurosurgery* **2021**, *88*, 246–251. [[CrossRef](#)] [[PubMed](#)]
147. Ge, R.; Rajeev, V.; Ray, P.; Lattime, E.; Rittling, S.; Medicherla, S.; Protter, A.; Murphy, A.; Chakravarty, J.; Dugar, S.; et al. Inhibition of Growth and Metastasis of Mouse Mammary Carcinoma by Selective Inhibitor of Transforming Growth Factor- β Type I Receptor Kinase In vivo. *Clin. Cancer Res.* **2006**, *12*, 4315–4330. [[CrossRef](#)]
148. Melisi, D.; Ishiyama, S.; Sclabas, G.M.; Fleming, J.B.; Xia, Q.; Tortora, G.; Abbruzzese, J.L.; Chiao, P.J. LY2109761, a novel transforming growth factor β receptor type I and type II dual inhibitor, as a therapeutic approach to suppressing pancreatic cancer metastasis. *Mol. Cancer Ther.* **2008**, *7*, 829–840. [[CrossRef](#)]
149. Zhang, B.; Halder, S.K.; Zhang, S.; Datta, P.K. Targeting transforming growth factor- β signaling in liver metastasis of colon cancer. *Cancer Lett.* **2009**, *277*, 114–120. [[CrossRef](#)]
150. Yang, T.; Huang, T.; Zhang, D.; Wang, M.; Wu, B.; Shang, Y.; Sattar, S.; Ding, L.; Liu, Y.; Jiang, H.; et al. TGF- β receptor inhibitor LY2109761 enhances the radiosensitivity of gastric cancer by inactivating the TGF- β /SMAD4 signaling pathway. *Aging* **2019**, *11*, 8892–8910. [[CrossRef](#)]
151. Zhang, M.; Herion, T.W.; Timke, C.; Han, N.; Hauser, K.; Weber, K.J.; Peschke, P.; Wirkner, U.; Lahn, M.; Huber, P.E. Trimodal Glioblastoma Treatment Consisting of Concurrent Radiotherapy, Temozolomide, and the Novel TGF- β Receptor I Kinase Inhibitor LY2109761. *Neoplasia* **2011**, *13*, 537–IN14. [[CrossRef](#)] [[PubMed](#)]
152. Bogdahn, U.; Hau, P.; Stockhammer, G.; Venkataramana, N.K.; Mahapatra, A.K.; Suri, A.; Balasubramaniam, A.; Nair, S.; Oliushine, V.; Parfenov, V.; et al. Targeted therapy for high-grade glioma with the TGF-2 inhibitor trabedersen: Results of a randomized and controlled phase IIIb study. *Neuro-Oncology* **2011**, *13*, 132–142. [[CrossRef](#)]
153. Wick, A.; Desjardins, A.; Suarez, C.; Forsyth, P.; Gueorguieva, I.; Burkholder, T.; Cleverly, A.L.; Estrem, S.T.; Wang, S.; Lahn, M.M.; et al. Phase 1b/2a study of galunisertib, a small molecule inhibitor of transforming growth factor-beta receptor I, in combination with standard temozolomide-based radiochemotherapy in patients with newly diagnosed malignant glioma. *Investig. New Drugs* **2020**, *38*, 1570–1579. [[CrossRef](#)] [[PubMed](#)]
154. Dilly, A.-K.; Ekambaram, P.; Guo, Y.; Cai, Y.; Tucker, S.C.; Fridman, R.; Kandouz, M.; Honn, K.V. Platelet-type 12-lipoxygenase induces MMP9 expression and cellular invasion via activation of PI3K/Akt/NF- κ B. *Int. J. Cancer* **2013**, *133*, 1784–1791. [[CrossRef](#)] [[PubMed](#)]
155. Smith, J.S.; Tachibana, I.; Passe, S.M.; Huntley, B.K.; Borell, T.J.; Iturria, N.; O’Fallon, J.R.; Schaefer, P.L.; Scheithauer, B.W.; James, C.D.; et al. PTEN Mutation, EGFR Amplification, and Outcome in Patients With Anaplastic Astrocytoma and Glioblastoma Multiforme. *JNCI J. Natl. Cancer Inst.* **2001**, *93*, 1246–1256. [[CrossRef](#)]
156. Koul, D.; Shen, R.; Kim, Y.-W.; Kondo, Y.; Lu, Y.; Bankson, J.; Ronen, S.M.; Kirkpatrick, D.L.; Powis, G.; Yung, W.K.A. Cellular and in vivo activity of a novel PI3K inhibitor, PX-866, against human glioblastoma. *Neuro-Oncology* **2010**, *12*, 559–569. [[CrossRef](#)]
157. Nan, Y.; Guo, L.; Song, Y.; Wang, L.; Yu, K.; Huang, Q.; Zhong, Y. Combinatorial therapy with adenoviral-mediated PTEN and a PI3K inhibitor suppresses malignant glioma cell growth in vitro and in vivo by regulating the PI3K/AKT signaling pathway. *J. Cancer Res. Clin. Oncol.* **2017**, *143*, 1477–1487. [[CrossRef](#)]

158. Zhong, S.; Xue, J.; Cao, J.-J.; Sun, B.; Sun, Q.-F.; Bian, L.-G.; Hu, L.-Y.; Pan, S.-J. The therapeutic value of XL388 in human glioma cells. *Aging* **2020**, *12*, 22550–22563. [[CrossRef](#)]
159. Omeljaniuk, W.J.; Krętowski, R.; Ratajczak-Wrona, W.; Jabłońska, E.; Cechowska-Pasko, M. Novel Dual PI3K/mTOR Inhibitor, Apatolisib (GDC-0980), Inhibits Growth and Induces Apoptosis in Human Glioblastoma Cells. *Int. J. Mol. Sci.* **2021**, *22*, 11511. [[CrossRef](#)]
160. Pitz, M.W.; Eisenhauer, E.A.; MacNeil, M.V.; Thiessen, B.; Easaw, J.C.; Macdonald, D.R.; Eisenstat, D.D.; Kakumanu, A.S.; Salim, M.; Chalchal, H.; et al. Phase II study of PX-866 in recurrent glioblastoma. *Neuro-Oncology* **2015**, *17*, 1270–1274. [[CrossRef](#)]
161. Wen, P.Y.; Omuro, A.; Ahluwalia, M.S.; Fathallah-Shaykh, H.M.; Mohile, N.; Lager, J.; Laird, A.D.; Tang, J.; Jiang, J.; Egile, C.; et al. Phase I dose-escalation study of the PI3K/mTOR inhibitor voxalisib (SAR245409, XL765) plus temozolomide with or without radiotherapy in patients with high-grade glioma. *Neuro-Oncology* **2015**, *17*, 1275–1283. [[CrossRef](#)]
162. Wen, P.Y.; Touat, M.; Alexander, B.M.; Mellinghoff, I.K.; Ramkissoon, S.; McCluskey, C.S.; Pelton, K.; Haidar, S.; Basu, S.S.; Gaffey, S.C.; et al. Buparlisib in Patients With Recurrent Glioblastoma Harboring Phosphatidylinositol 3-Kinase Pathway Activation: An Open-Label, Multicenter, Multi-Arm, Phase II Trial. *J. Clin. Oncol.* **2019**, *37*, 741–750. [[CrossRef](#)] [[PubMed](#)]
163. Koizumi, S.; Gu, C.; Amano, S.; Yamamoto, S.; Ihara, H.; Tokuyama, T.; Namba, H. Migration of mouse-induced pluripotent stem cells to glioma-conditioned medium is mediated by tumor-associated specific growth factors. *Oncol. Lett.* **2011**, *2*, 283–288. [[CrossRef](#)] [[PubMed](#)]
164. Yamazoe, T.; Koizumi, S.; Yamasaki, T.; Amano, S.; Tokuyama, T.; Namba, H. Potent tumor tropism of induced pluripotent stem cells and induced pluripotent stem cell-derived neural stem cells in the mouse intracerebral glioma model. *Int. J. Oncol.* **2015**, *46*, 147–152. [[CrossRef](#)]
165. Yamasaki, T.; Wakao, S.; Kawaji, H.; Koizumi, S.; Sameshima, T.; Dezawa, M.; Namba, H. Genetically Engineered Multilineage-Differentiating Stress-Enduring Cells as Cellular Vehicles against Malignant Gliomas. *Mol. Ther. Oncolytics* **2017**, *6*, 45–56. [[CrossRef](#)]
166. Krueger, T.E.G.; Thorek, D.L.J.; Denmeade, S.R.; Isaacs, J.T.; Brennen, W.N. Concise Review: Mesenchymal Stem Cell-Based Drug Delivery: The Good, the Bad, the Ugly, and the Promise. *STEM CELLS Transl. Med.* **2018**, *7*, 651–663. [[CrossRef](#)]
167. Chastkofsky, M.I.; Pituch, K.C.; Katagi, H.; Zannikou, M.; Ilut, L.; Xiao, T.; Han, Y.; Sonabend, A.M.; Curiel, D.T.; Bonner, E.R.; et al. Mesenchymal Stem Cells Successfully Deliver Oncolytic Virotherapy to Diffuse Intrinsic Pontine Glioma. *Clin. Cancer Res.* **2021**, *27*, 1766–1777. [[CrossRef](#)] [[PubMed](#)]
168. Tutter, M.; Schug, C.; Schmohl, K.A.; Urnauer, S.; Kitzberger, C.; Schwenk, N.; Petrini, M.; Zach, C.; Ziegler, S.; Bartenstein, P.; et al. Regional Hyperthermia Enhances Mesenchymal Stem Cell Recruitment to Tumor Stroma: Implications for Mesenchymal Stem Cell-Based Tumor Therapy. *Mol. Ther.* **2021**, *29*, 788–803. [[CrossRef](#)]
169. Kurozumi, K.; Tamiya, T.; Ono, Y.; Otsuka, S.; Kambara, H.; Adachi, Y.; Ichikawa, T.; Hamada, H.; Ohmoto, T. Apoptosis induction with 5-fluorocytosine/cytosine deaminase gene therapy for human malignant glioma cells mediated by adenovirus. *J. Neuro-Oncol.* **2004**, *66*, 117–127. [[CrossRef](#)]
170. Rainov, N.G. A Phase III Clinical Evaluation of Herpes Simplex Virus Type 1 Thymidine Kinase and Ganciclovir Gene Therapy as an Adjuvant to Surgical Resection and Radiation in Adults with Previously Untreated Glioblastoma Multiforme. *Hum. Gene Ther.* **2000**, *11*, 2389–2401. [[CrossRef](#)]
171. Kenmochi, H.; Yamasaki, T.; Koizumi, S.; Sameshima, T.; Namba, H. Nicotine does not affect stem cell properties requisite for suicide gene therapy against glioma. *Neurol. Res.* **2020**, *42*, 818–827. [[CrossRef](#)] [[PubMed](#)]
172. Kurozumi, K.; Hardcastle, J.; Thakur, R.; Yang, M.; Christoforidis, G.; Fulci, G.; Hochberg, F.H.; Weissleder, R.; Carson, W.; Chiocca, E.A.; et al. Effect of Tumor Microenvironment Modulation on the Efficacy of Oncolytic Virus Therapy. *JNCI J. Natl. Cancer Inst.* **2007**, *99*, 1768–1781. [[CrossRef](#)] [[PubMed](#)]
173. Hardcastle, J.; Kurozumi, K.; Dmitrieva, N.; Sayers, M.P.; Ahmad, S.; Waterman, P.; Weissleder, R.; Chiocca, E.A.; Kaur, B. Enhanced Antitumor Efficacy of Vasculostatin (Vstat120) Expressing Oncolytic HSV-1. *Mol. Ther.* **2010**, *18*, 285–294. [[CrossRef](#)]
174. Tomita, Y.; Kurozumi, K.; Yoo, J.Y.; Fujii, K.; Ichikawa, T.; Matsumoto, Y.; Uneda, A.; Hattori, Y.; Shimizu, T.; Otani, Y.; et al. Oncolytic Herpes Virus Armed with Vasculostatin in Combination with Bevacizumab Abrogates Glioma Invasion via the CCN1 and AKT Signaling Pathways. *Mol. Cancer Ther.* **2019**, *18*, 1418–1429. [[CrossRef](#)] [[PubMed](#)]
175. Otani, Y.; Yoo, J.Y.; Chao, S.; Liu, J.; Jaime-Ramirez, A.C.; Lee, T.J.; Hurwitz, B.; Yan, Y.; Dai, H.; Glorioso, J.C.; et al. Oncolytic HSV-Infected Glioma Cells Activate NOTCH in Adjacent Tumor Cells Sensitizing Tumors to Gamma Secretase Inhibition. *Clin. Cancer Res.* **2020**, *26*, 2381–2392. [[CrossRef](#)]