

The Mechanical Rigidity of the Extracellular Matrix Regulates the Structure, Motility, and Proliferation of Glioma Cells

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Abstract

Glioblastoma multiforme (GBM) is a malignant astrocytoma of the central nervous system associated with a median survival time of 15 months, even with aggressive therapy. This rapid progression is due in part to diffuse infiltration of single tumor cells into the brain parenchyma, which is thought to involve aberrant interactions between tumor cells and the extracellular matrix (ECM). Here, we test the hypothesis that mechanical cues from the ECM contribute to key tumor cell properties relevant to invasion. We cultured a series of glioma cell lines (U373-MG, U87-MG, U251-MG, SNB19, C6) on fibronectin-coated polymeric ECM substrates of defined mechanical rigidity and investigated the role of ECM rigidity in regulating tumor cell structure, migration, and proliferation. On highly rigid ECMs, tumor cells spread extensively, form prominent stress fibers and mature focal adhesions, and migrate rapidly. As ECM rigidity is lowered to values comparable with normal brain tissue, tumor cells appear rounded and fail to productively migrate. Remarkably, cell proliferation is also strongly regulated by ECM rigidity, with cells dividing much more rapidly on rigid than on compliant ECMs. Pharmacologic inhibition of nonmuscle myosin II–based contractility blunts this rigidity-sensitivity and rescues cell motility on highly compliant substrates. Collectively, our results provide support for a novel model in which ECM rigidity provides a transformative, microenvironmental cue that acts through actomyosin contractility to regulate the invasive properties of GBM tumor cells. [Cancer Res 2009;69(10):4167–74]

Introduction

Glioblastoma multiforme (GBM) is a high-grade astrocytoma associated with a median survival time of 15 months, even with surgical care, chemotherapy, and radiotherapy (1). This uncommon aggressiveness is partly derived from diffuse infiltration of single tumor cells into the surrounding brain parenchyma before diagnosis, making complete tumor debulking virtually impossible. A central therapeutic goal has been to develop strategies to limit invasion, thereby rendering the tumor addressable by local therapies. This has led to an expansive effort to identify key molecular regulators of GBM tumor cell motility *in vitro* and *in vivo* (1–4).

Note: Supplementary data for this article are available at Cancer Research Online (<http://cancerres.aacrjournals.org/>).

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doi:10.1158/0008-5472.CAN-08-4859

Among the key regulators of cell motility are the extracellular matrix (ECM) and the cellular components needed to recognize and process ECM-derived cues, including adhesion proteins and molecular motors. Several *in vitro* studies have shown the importance of fibronectin, laminin, collagen, and other ECM proteins in stimulating a migratory phenotype in both GBM cell lines and biopsy explants (5). Strong correlations between matrix metalloproteinase (MMP) activation, GBM invasion, and poor prognosis indicate that tumor cells can extensively remodel the surrounding matrix during invasion (1). This remodeling is frequently accompanied by secretion of ECM proteins, such as tenascin-C, which has been associated with angiogenesis and enhanced cell motility (6). Because these behaviors are central to tumor progression, a growing body of work has begun addressing the functional contributions of key mediators of cell-ECM interactions, including integrins (7), focal adhesion proteins, such as vinculin and focal adhesion kinase (FAK; refs. 8, 9), and molecular motors, such as nonmuscle myosin II (NMMII; ref. 2). These interactions have taken on new significance in light of the recent Cancer Genome Atlas (TCGA) sequencing effort, which has revealed a preponderance of genomic lesions across GBM tumors in the epidermal growth factor receptor (EGFR)/Ras/phosphatidylinositol 3-kinase (PI3K) pathway (10), which has been previously linked at multiple levels to ECM-based signaling in the context of glioma invasion (11).

However, whereas it is clear that biochemical signaling from the ECM is an important regulator of GBM invasion, the biophysical components of this crosstalk are comparatively poorly understood, particularly in light of the recent explosion of work showing the powerful influence of biophysical inputs, such as the density, rigidity, and geometry of the ECM on cell fate, migration, and morphogenesis (12, 13). For example, recent studies have shown that manipulating substrate elasticity in a two-dimensional cell culture system can strongly influence lineage specification of naive human mesenchymal stem cells (14), the migration, adhesion, and cytoarchitecture of smooth muscle cells (15), and the outgrowth of neurons versus glia in mixed cortical cultures (16). A growing literature indicates that the biomechanical properties of cells and the surrounding ECM directly influence and are influenced by the progression of neoplastic disease (17, 18). For example, a modest change in substrate elasticity during *in vitro* culture of mammary epithelial cells is enough to cause otherwise normal cells to develop early hallmarks of a growing tumor (19). With respect to invasion, ECM rigidity can control the motility of human prostate carcinoma cells in three-dimensional ECMs (20) and the density and activity of tumor cell invadopodia, which spatially focus proteolytic secretion (21). Promising new chemotherapeutics have already begun targeting components of the contractility and adhesion machinery, including the integrin antagonist Cilengitide (7) and small molecule inhibitors of FAK (8).

Several lines of evidence indirectly suggest that ECM-derived biomechanical cues may play an important role in GBM

specifically, although the pathophysiologic significance of these cues remains poorly understood. Neurosurgeons anecdotally report that GBM tumors are stiffer than the surrounding parenchyma, consistent with the efficacy of ultrasound elastography in guiding surgical resection (22). Moreover, the tremendous anatomic variation in stiffness within the brain (23) may feature prominently in invasion; for example, the infiltrative path of GBM cells tends to favor interfaces between mechanically distinct structures, such as the basement membrane of blood vessels and white matter tracts (24). Recent work suggests that the mechanical properties of the cellular microenvironment may fundamentally alter the migration of glioblastoma cells *in vitro* and *in vivo* (2, 25, 26). For example, the migration rate of SNB19 cells cultured on elastomeric films correlates with substrate mechanical properties (controlled by altering the duration of heating and distance from a Bunsen burner; ref. 25), and several three-dimensional studies have shown strong correlations between matrix density and invasion from tumor spheroids (26, 27). Glioma cell migration depends on actomyosin-generated contractile forces and involves dynamic, spatially regulated changes to the cytoskeleton and cell-matrix adhesion complexes. Many of these motility-mediating interactions are shaped by ECM mechanics, and the expression levels of several contractility-mediating signaling molecules, including RhoA and RhoB, are thought to correlate with tumor malignancy (28, 29). Indeed, Rosenfeld and colleagues recently showed that NMMIII is

needed to deform the nuclei of glioma cells to enable amoeboid motion through ECM pores, and invading tumor cells *in vivo* significantly up-regulate NMMII expression relative to endogenous brain cells (2).

Motivated by the growing evidence that mechanobiological cues are present in human gliomas, by the limited existing information regarding the potential pathophysiologic role of ECM elasticity, and by the significant implications that this knowledge could have for the creation of mechanobiologically-inspired therapeutics, we sought to test the hypothesis that micromechanical cues from the ECM influence fundamental properties of GBM tumor cells relevant to growth and invasion. We fabricated ECM substrates with independently defined mechanical and biochemical properties and with rigidities spanning the range between normal and tumor tissue. Our studies reveal for the first time that ECM elasticity strongly affects GBM cell structure, motility, and proliferation and that this mechanosensing requires a competent actin cytoskeleton, Rho GTPase-based signaling, and NMMIII.

Materials and Methods

Synthesis and characterization of ECM substrates. We followed a previously established method for fabricating defined rigidity polyacrylamide ECMs (15, 30) with minor modifications (see Supplementary Materials and Methods). All substrates were functionalized with human plasma fibronectin (Millipore Corp.) to achieve a nominal surface density of

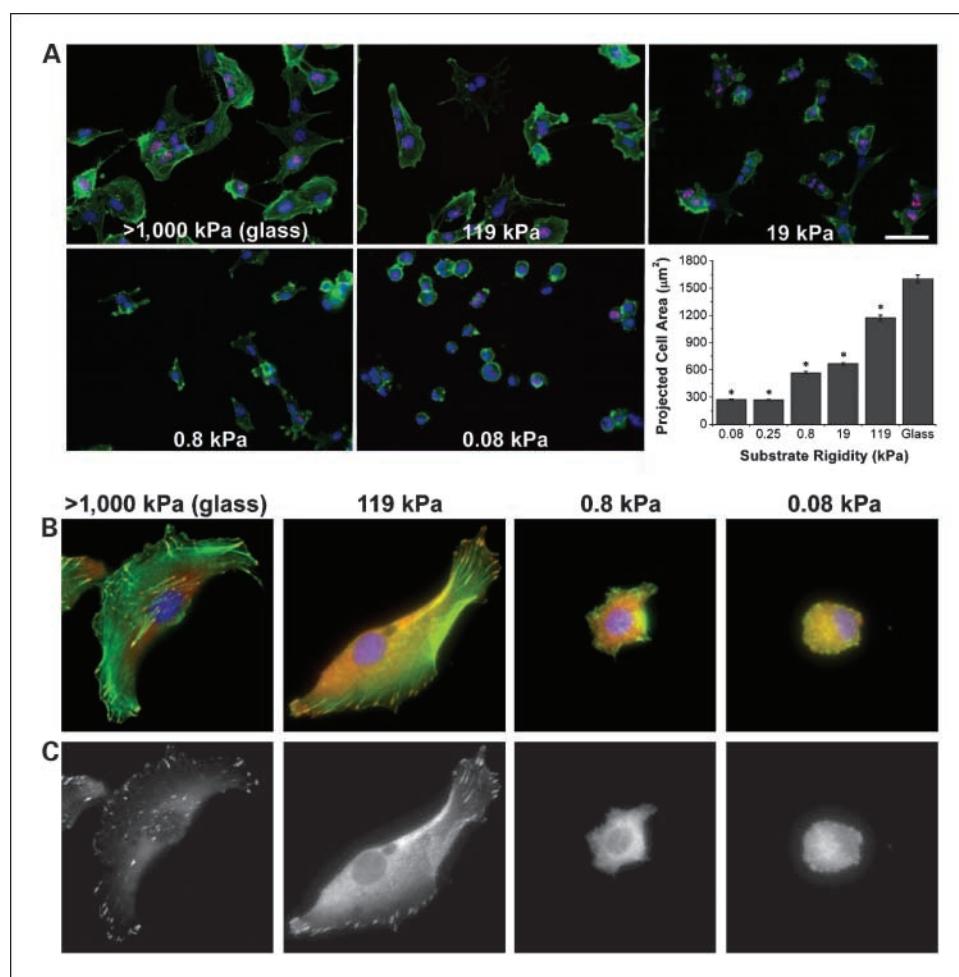
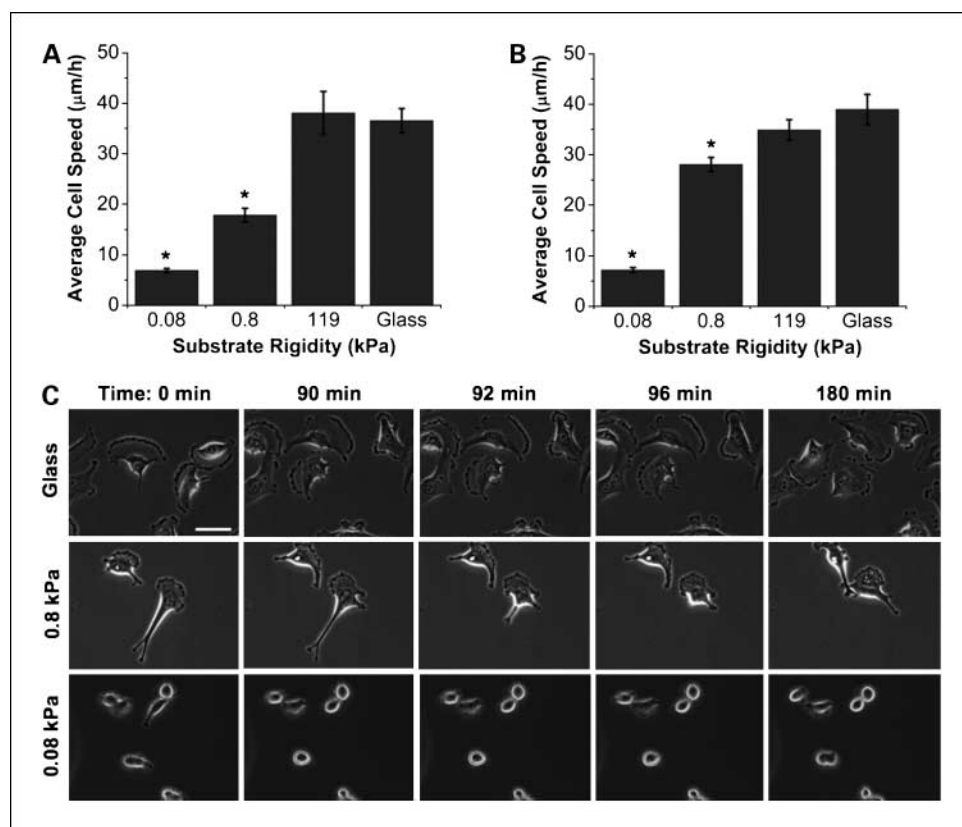


Figure 1. ECM rigidity alters glioma cell morphology and cytoskeletal organization. **A**, rigidity-dependent changes in cell structure. U373-MG cells cultured on fibronectin-conjugated glass and polyacrylamide gels over a range of stiffnesses were stained for F-actin (green), nuclear DNA (blue), and the nuclear antigen Ki67 (red). Note that a subset of cells on all substrates stained positive for Ki67. Bar, 50 µm. *, $P < 0.01$ with respect to glass; $n > 450$ cells for each condition. **B**, high-magnification imaging of cytoskeletal and adhesive structures. U87-MG cells were stained for F-actin (green), nuclear DNA (blue), and the focal adhesion protein vinculin (red). Bar, 25 µm. **C**, isolated view of vinculin signal only, showing structure and distributions of cell-ECM adhesions.

Figure 2. ECM rigidity regulates glioma cell motility. Effect of ECM rigidity on the random migration speed of U373-MG (A) and U87-MG (B) cells. Results represent the average migration rate from at least 15 cells per condition over 6 to 12 h. Qualitatively similar dependences of migration speed on substrate stiffness were observed for SNB19, U251-MG, and C6 cells. *, $P < 0.01$ with respect to glass. C, high-magnification imaging of U373-MG cell migration on ECMs of varying rigidity over both long time scales (columns 1 and 2 and columns 4 and 5) and short time scales (columns 2–4). Cells on glass (top row) migrate quickly, smoothly, and with broad, stable lamellipodia. Cells on 0.8-kPa ECMs (middle row) form smaller, less stable lamellipodia and migrate in a “stick-slip” fashion, in which the cell thins and extends as it advances and then abruptly contracts as adhesions at the trailing edge rupture. Cells on 0.08-kPa ECMs (bottom row) continuously extend thin filopodia and fail to productively migrate. Bar, 50 μm .



2.6 $\mu\text{g}/\text{cm}^2$. The macroscopic elastic shear modulus of each gel formulation was measured at 37°C using an Anton Paar Physica MCR 301 rheometer with 25-mm parallel plate geometry. Amplitude sweeps over the range $\gamma = 0.1$ –10% were used to identify the linear regime; frequency sweeps at 5% strain over 0.1 to 10 Hz were then used to extract storage, loss, and complex moduli of each sample. Three measurements were made on each sample, and at least three independent samples were measured per condition. Elastic moduli of 0.08, 0.25, 0.8, 19, and 119 kPa were measured for gels containing final acrylamide/bis-acrylamide (A/B) percentages of 3% A/0.05% B, 4% A/0.075% B, 5% A/0.1% B, 8% A/0.6% B, and 15% A/1.2% B, respectively, as described in detail elsewhere.³

Cell culture. U373-MG human glioma cells were obtained from the University of California, Berkeley Tissue Culture Facility, U87-MG and U251-MG human glioma cells were kindly provided by Dr. C. David James (University of California, San Francisco), and human SNB19 and rat C6 glioma cells were kindly provided by Dr. Andrew Wurmser (University of California, Berkeley). U373-MG and U87-MG cells were cultured in DMEM (Life Technologies) supplemented with 10% calf serum advantage (J.R. Scientific) and 1% penicillin/streptomycin, MEM nonessential amino acids, and sodium pyruvate (Life Technologies). SNB19, U251-MG, and C6 cells were cultured in DMEM supplemented with 10% calf serum and 1% penicillin/streptomycin.

Microscopy, fluorescence staining, and morphometric analysis. All live-cell and fluorescence imaging was performed using an inverted Nikon TE2000-E2 microscope equipped with a motorized, programmable stage (Prior Scientific, Inc.), an incubator chamber to maintain constant temperature, humidity, and CO₂ levels (*In vivo* Scientific), a digital camera (Photometrics Coolsnap HQ II, Roper Scientific), and SimplePCI software

(Hamamatsu Corporation). Cells were fixed and stained for filamentous actin (F-actin) and vinculin, as described in detail in Supplementary Materials and Methods. Cell spreading measurements were obtained by quantifying the area of phalloidin-stained cells using ImageJ software (NIH). High-magnification epifluorescence images acquired through polyacrylamide gels in Figs. 1 and 5 were enhanced by applying a uniform background subtraction to the entire image; subsequent adjustments to brightness and contrast were applied as necessary.

Measurement and analysis of cell migration. Cells were plated at a subconfluent density of 1,000 cells/cm² at least 10 h before the start of imaging in at least three independent experiments. In each experiment, 10 \times phase contrast timelapse images were acquired every 15 min over a 12-h period for at least 10 representative fields of view per substrate and at least two substrates per condition. A representative subset of timelapse videos was analyzed using SimplePCI software, where the periphery of each cell in each frame was used to define an object, and the Motion Tracking and Analysis module of SimplePCI was used to track the centroid of each object throughout the time sequence.

Measurement of cell proliferation. Cell proliferation was measured with a bromodeoxyuridine (BrdUrd) assay, as described in Supplementary Materials and Methods.

Inhibition of cell contractility. Rho-associated kinase (ROCK) inhibitor Y-27632 (Calbiochem), NMMII inhibitor blebbistatin (Sigma-Aldrich), and actin polymerization inhibitor cytochalasin D (Sigma-Aldrich) were added to the cell culture media in relevant timelapse and immunofluorescence experiments after the cells had been allowed to adhere for at least 10 h.

Statistical analysis. Data are reported as mean \pm SE, unless otherwise noted. Statistical comparisons between three or more sets of data were performed with a one-way ANOVA, followed by a Tukey-Kramer HSD (honestly significant difference) test for pair-wise comparisons. A Student's unpaired *t* test was performed if statistical comparisons were made between two sets of data. *P* values of <0.01 denote statistical significance.

³ A.J. Keung, E.M. de Juan Pardo, D.V. Schaffer, and S. Kumar. Matrix rigidity and Rho-family GTPase activation coregulate neural stem cell behavior, in preparation.

Results

To test the hypothesis that ECM rigidity influences the behavior of cultured glioma cells, we fabricated a series of fibronectin-coated polyacrylamide ECMs of variable stiffness, as we and others have done previously (15, 30, 31). Here, ECM stiffness is dictated by the ratio of monomer (acrylamide) to crosslinker (*bis*-acrylamide), and fibronectin is covalently grafted at fixed density to the gel surface. Because polyacrylamide does not support appreciable passive protein adsorption, this system enables independent control of ECM stiffness and ligand density. The rigidity of our ECMs ranged from one order of magnitude below normal brain tissue (0.08 kPa) to three orders of magnitude above (119 kPa).

ECM rigidity alters glioma cell morphology and cytoskeletal organization. We began by asking whether changes in ECM rigidity were sufficient to grossly and systematically alter glioma cell morphology and cytoskeletal organization. To answer this, we cultured cells on ECMs with varying rigidity and captured both cell-ECM adhesion area and cytoskeletal F-actin organization. The adhesive contact area of U373-MG cells decreased dramatically with decreasing substrate stiffness (Fig. 1), a finding that was qualitatively reproducible for U87-MG, U251-MG, SNB19, and C6 cells (Supplementary Fig. S1). U87-MG (Fig. 1B and C) and U373-MG (Supplementary Fig. S2) cells cultured on rigid substrates were typically well-spread with visible actin stress fibers and discrete, elongated vinculin-positive focal adhesions. Importantly, cells cultured on glass and the stiffest polyacrylamide substrates were similar in this respect, suggesting that conjugation chemistry does not significantly interfere with adhesion-based cytoskeletal assembly. Cells cultured on progressively softer substrates showed decreasing spreading area, along with a rigidity-dependent dissipation of stress fibers and focal adhesions. Cells on the softest substrates were uniformly rounded with cortical rings of F-actin and small, punctate vinculin-positive focal complexes. Interestingly, cell rounding on the softest substrates did not reflect apoptosis, as evidenced by positive staining for the nuclear antigen Ki67 (Fig. 1A).

ECM rigidity regulates the random motility of glioma cells. Given that productive cell motility is critical to invasion, we next asked whether changes in ECM rigidity could alter migration speed in culture (Fig. 2). To address this question, we used timelapse imaging to record the random motility of sparsely cultured cells over 12 hours. Mean migration speeds fell dramatically with decreasing substrate rigidity for both U373-MG and U87-MG cells, with statistically indistinguishable speeds observed on the most rigid substrates and glass (Fig. 2A and B; Supplementary Movies S1–S4). Cells on the glass surface adjacent to polyacrylamide substrates exhibited similar morphology and qualitatively similar motility to cells on fibronectin-coated glass substrates (not shown), effectively ruling out the possibility that rigidity-dependent changes in motility are related to altered paracrine signaling.

Concurrent with these reductions in cell speed, we observed a gradual transition in the mode of cell motility (Fig. 2C; Supplementary Movies S5–S8). Cells on glass moved in a smooth, gliding fashion with broad lamellipodia and continuous actin turnover at the leading edge. As ECM stiffness was reduced, this motility began transitioning to a “stick-slip” pattern, in which cells would thin and extend as the leading edge advanced, with the trailing edge abruptly detaching and snapping forward to catch up to the cell body. Whereas cells on glass and 119 kPa ECMs migrated with broad lamellipodia, the lamellipodia of cells on 0.8 kPa ECMs

were smaller and less stable. Cells on the most compliant ECMs (0.08 kPa), actively extended small, thin filopodial processes over periods of 6 to 12 hours but failed to establish lamellipodia capable of supporting migration.

Although the migration of all cell lines was highly sensitive to ECM rigidity, we observed variation between cell types. Specifically, on rigid substrates, U373-MG, SNB19, and U251-MG cells typically exhibited prominent broad, ruffled lamellipodia and a polygonal morphology, whereas the U87-MG and C6 cells exhibited a comparatively elongated spindle morphology (Supplementary Fig. S1), as reported by others (32, 33). However, all cell lines reduced to a mutually indistinguishable rounded morphology with largely nonproductive filopodial extension when cultured on the most compliant substrates (0.08 kPa).

ECM rigidity regulates glioma cell proliferation. The above results show that ECM rigidity can substantially regulate the structure and motility of cultured glioma cells. Given that alterations in shape and motility have been previously correlated with alterations in tumor growth (34), we reasoned that ECM rigidity might concurrently alter cell proliferation. We first observed that, in long-term cultures, cells on stiff substrates reached confluency more rapidly than cells on soft substrates and at a level that could not be solely attributed to differences in cell

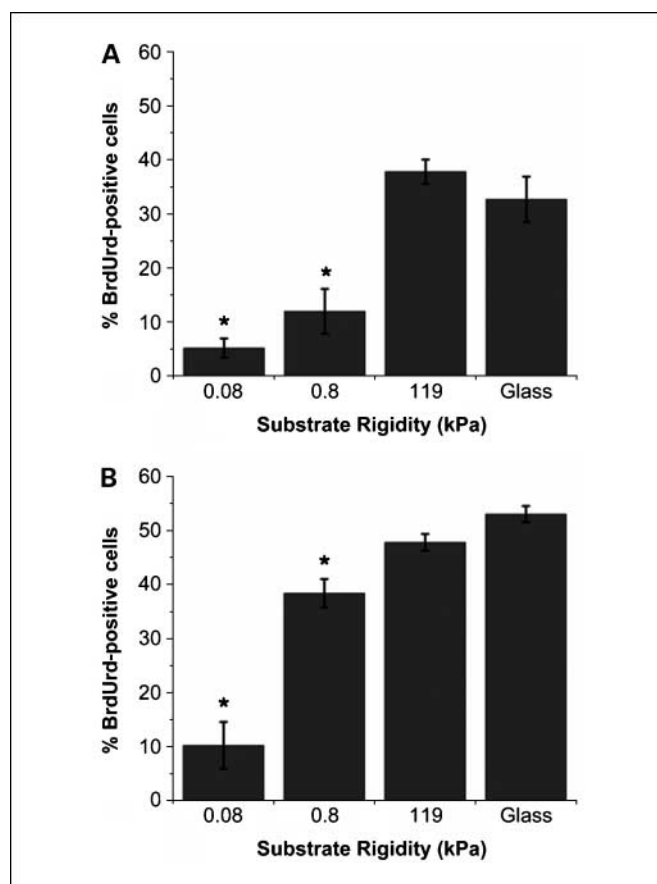
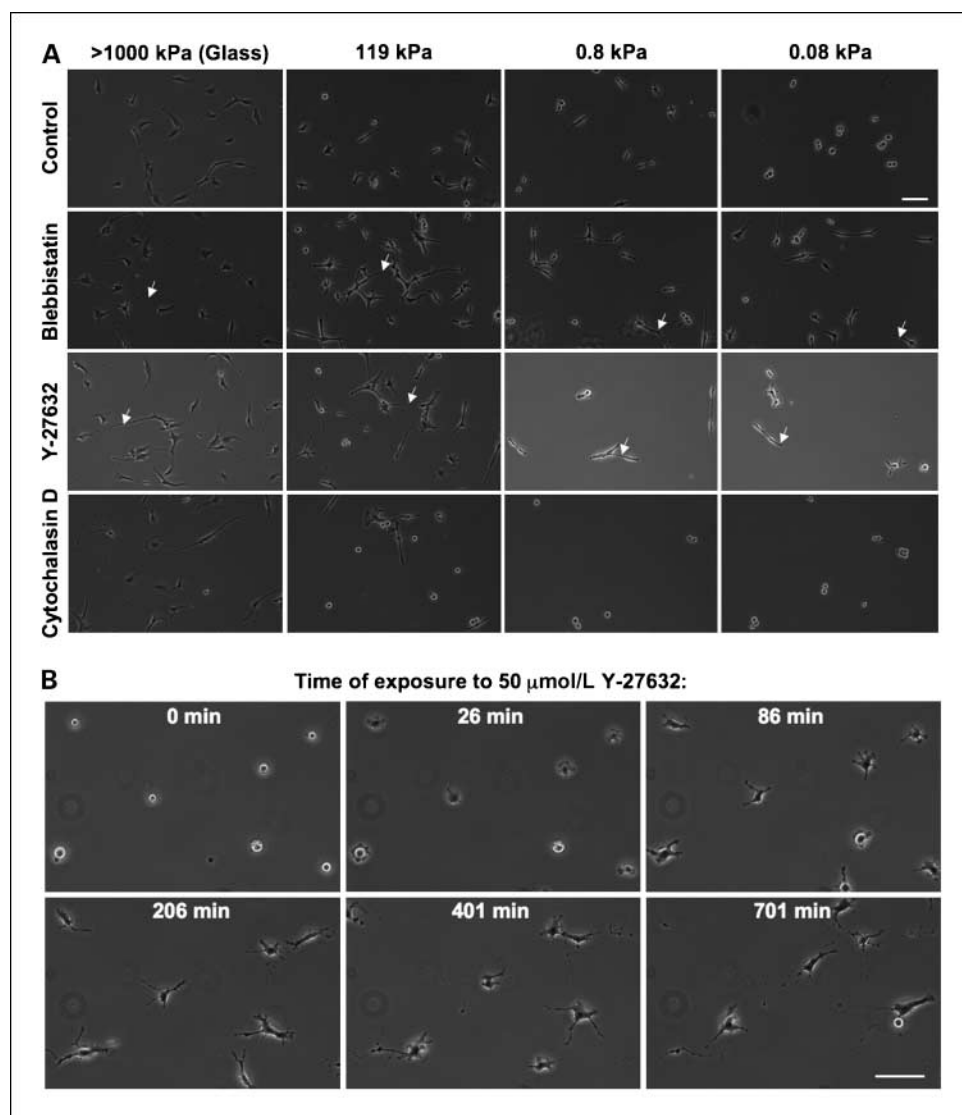


Figure 3. ECM rigidity regulates glioma cell proliferation. Effect of ECM rigidity on proliferation of U373-MG (A) and U87-MG (B) cells. Results represent quantification of $n > 325$ cells in at least eight fields of view per substrate for at least five substrates per condition, where the percentage of dividing cells was determined as the average percentage of cells staining positive for BrdUrd incorporation. *, $P < 0.01$ with respect to glass.

Figure 4. Pharmacologic inhibition of cytoskeletal contractility reduces stiffness-dependent differences in cell morphology. **A**, U87-MG cells cultured on fibronectin-conjugated glass and polyacrylamide substrates in either the absence of drug (control) or 24 h after addition of 25 $\mu\text{mol/L}$ blebbistatin, 10 $\mu\text{mol/L}$ Y-27632, or 1 $\mu\text{mol/L}$ cytochalasin D. Cells began extending actin-rich processes (arrows) within an hour after addition of Y-27632 or blebbistatin. Cytochalasin D induced stellation and rounding of cells on stiff substrates but had no appreciable effect on the morphology or migration of cells on the softest substrates. *Bar*, 100 μm . **B**, U373-MG cells cultured on 0.08 kPa fibronectin-conjugated polyacrylamide substrates showed enhanced spreading and migration with addition of 50 $\mu\text{mol/L}$ Y-27632. *Bar*, 100 μm .



spreading area (not shown). To test this connection more rigorously, we used BrdUrd incorporation to measure percentages of dividing cells as a function of ECM rigidity (Fig. 3). These studies revealed a remarkable correlation between the proliferation rate of U373-MG and U87-MG cells and ECM stiffness, with ~ 5 -fold increase in the percentage of BrdUrd-positive cells on the stiffest substrates (119 kPa) compared with those on the softest substrates (0.08 kPa). Consistent with our previous measurements of cell structure and motility, BrdUrd incorporation on the stiffest substrates was comparable with glass.

Pharmacologic disruption of intracellular tension tempers mechanical regulation of glioma cell morphology, cytoskeletal architecture, and migration. Increasing ECM stiffness is associated with increased cell spreading and formation of actomyosin stress fiber bundles (Fig. 1), suggesting that ECM rigidity controls NMMII-mediated intracellular contractility. This relationship has been directly observed in other systems (14, 35) and has led to the hypothesis that NMMII and its upstream regulators are critical to processing rigidity-encoded cues. To test this hypothesis in our system, we asked whether glioma cells remained sensitive to ECM rigidity when actin cytoskeletal

assembly and contractility are disrupted. Direct pharmacologic inhibition of NMMII or ROCK blunted sensitivity of U87-MG (Fig. 4A) and U373-MG (Supplementary Fig. S3; Supplementary Movies S9–S12) cell morphology to ECM rigidity, with cells exhibiting a stellate morphology in all cases. Remarkably, inhibition of either NMMII or ROCK on the softest ECMs not only enhanced adhesion but rescued cell motility, with cells spreading and resuming migration within minutes of drug addition (Fig. 4B). For all ECMs, ROCK-inhibited and NMMII-inhibited cells lacked prominent stress fibers and vinculin-positive focal adhesions (Fig. 5). To confirm that this rescue of cell motility requires competent actin polymerization, we treated cells with cytochalasin D, which disrupts F-actin and inhibits new polymerization. Indeed, treatment with cytochalasin D caused cytoskeletal collapse and loss of motility on stiff substrates but failed to induce spreading or rescue migration on the softest substrates (Figs. 4 and 5).

Discussion

Although mechanistic studies of glioma growth and invasion have historically focused on biochemical and genetic factors,

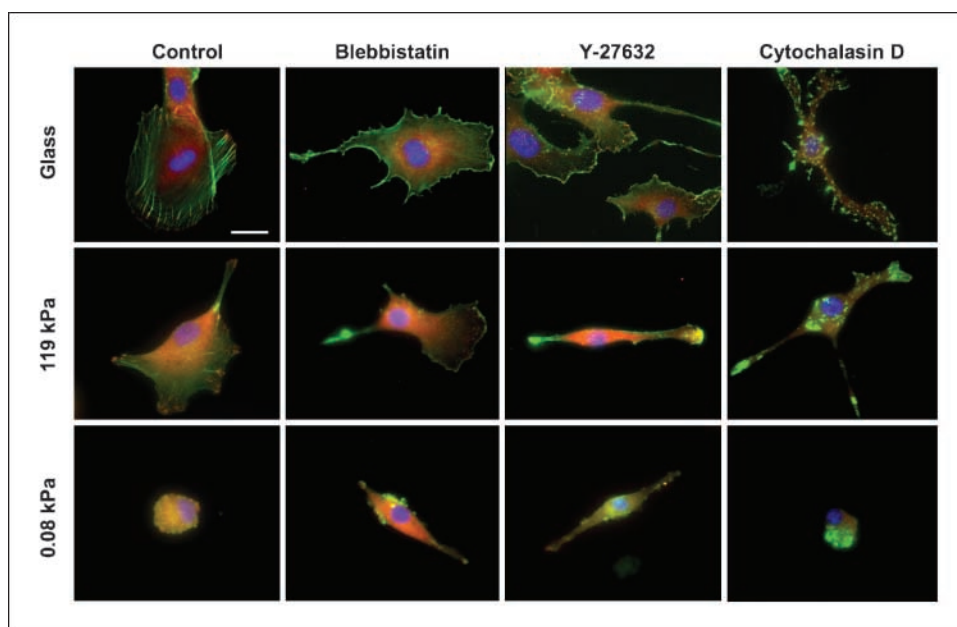


Figure 5. Pharmacologic inhibition of cell tension reduces stiffness-dependent differences in cytoskeletal and adhesive architecture. U87-MG cells cultured on fibronectin-coated glass and polyacrylamide substrates were treated with 25 $\mu\text{mol/L}$ blebbistatin, 10 $\mu\text{mol/L}$ Y-27632, or 1 $\mu\text{mol/L}$ cytochalasin D for 12 to 24 h before fixation and staining for nuclear DNA (blue), F-actin (green), and vinculin (red). In all cases, the number and size of vinculin-positive focal adhesions were reduced with inhibition of cell tension. Blebbistatin and Y-27632 both induced cell spreading on the softest substrates, whereas cytochalasin D induced collapse of the actin cytoskeleton. Bar, 25 μm .

studies with other cell types have revealed that biomechanical cues can also powerfully regulate cell behavior. Here, we have begun to explore the role of ECM-based mechanical cues in controlling cell behaviors central to GBM pathophysiology. Our studies reveal for the first time striking stiffness-dependent differences in glioma cell structure, migration, and proliferation. This mechanoregulation is especially significant in light of the contrasting mechanical microenvironments associated with normal and tumor brain tissue. Importantly, we were able to temper stiffness-dependent differences in cell structure and migration by inhibiting NMMII-dependent contractility, suggesting that mechanical features of the tumor microenvironment and the molecular systems that sense and process these features may serve as handles for understanding and manipulating glioma cell physiology.

The phenomenon of durotaxis (or mechanotaxis) was first defined by Wang and colleagues after they observed directed migration of fibroblasts *in vitro* from soft to stiff regions of ECM (36); other investigators have observed that changes in ECM rigidity can either increase or decrease cell migration speed, with the relationship depending strongly on cell type, degree of adhesion, and other factors (15, 25). High ECM stiffness enhances the expression and activity of contractility-mediating proteins, such as Rho and ROCK (19), which intuitively correlates with the enhanced expression of contractile proteins in many solid tumors (37). In the case of GBM, the role of Rho GTPases in mediating tumor growth and spread *in vivo* is complex and remains incompletely understood (28, 29). However, lysophosphatidic acid-mediated NMMII activation can strongly stimulate astrocytoma motility *in vitro* (3), and Rho/ROCK inhibition sensitizes glioma cells to apoptosis induced by radiation (38) and chemotherapy (39). We observe stiffness-dependent enhancement in the robustness of cytoskeletal and focal adhesion structures, cell spreading, and migration (Figs. 1 and 2), consistent with the predominant model of dynamic mechanical reciprocity, in which cells respond to rigidity-encoded cues through “inside-out” signaling that includes reinforcement of contractile and adhesive structures (13). How expression of contractility-mediating proteins in glioma cells varies

with substrate rigidity is an intriguing issue that has not yet been addressed.

Pharmacologic inhibition of NMMII or its upstream regulator ROCK blunts the sensitivity of glioma cells to ECM rigidity, with cells adopting a stellate morphology and becoming highly motile even on compliant ECMs (Figs. 4 and 5; Supplementary Movies S9–S12). Together, these results suggest that NMMII and its activators form a critical component of the ECM rigidity-sensing pathway in glioma cells, consistent with past observations in other cell types (14, 15, 19, 36). These results are also consistent with recently discovered contributions of NMMII isoforms (NMMIIA, NMMIIB, and NMMIIC) to cell motility, traction generation, and rigidity sensing. Specifically, NMMIIB-null fibroblasts rapidly alter cell shape by extending and retracting protrusions; analogous to our observations of glioma cells under NMMII inhibition, these fibroblasts migrate faster and are less morphologically sensitive to ECM rigidity than wild-type fibroblasts (40). Moreover, acute depletion of NMMIIA in mouse embryonic fibroblasts speeds cell spreading and slows retrograde flow of actin, suggesting that NMMIIA acts as a brake on cell spreading by globally retarding actin cytoskeletal remodeling (41). Additional mechanistic insights come from recent observations that glioma cell motility can be stimulated by inhibition of either NMMII (42) or ROCK (4); the latter effect may be blocked by concomitant inhibition of Rac GTPase, implying that the enhanced motility is due to Rac pathway disinhibition. Importantly, this balance between Rho and Rac activation may also be indirectly disturbed in glioma cells by pharmacologically inhibiting Ras (43), which offers an unexpected but potentially important mechanistic connection between Rho GTPase-based mechanosensing and the EGFR/Ras/PI3K pathway. Thus, in our studies, ROCK inhibition may have the dual effect of both releasing NMMII-based restrictions on cell spreading and enhancing Rac-mediated cell motility, explaining why ROCK inhibition rescues motility on compliant substrates more potently than direct inhibition of NMMII.

Finally, we observe that ECM rigidity strongly regulates glioma cell proliferation, with the stiffest ECMs supporting 5-fold more

proliferation than the softest ones (Fig. 3). Although the magnitude of this effect is somewhat surprising, ECM rigidity has been observed to modulate cell growth in other systems, including fibroblasts (44), hepatocytes (45), and neural stem cells (46). One potential explanation is that changes in ECM rigidity might alter the speed of progression through the cell cycle by altering mechanochemical feedback during mitosis. Indeed, direct application of mechanical force can slow cytokinesis and induce shape asymmetries, which cells can actively correct by mobilizing NMMII to produce a restoring force (47). Second, ECM rigidity might regulate mitosis by synergistically triggering mechanotransductive and mitogenic signaling pathways. As described earlier, ECM rigidity can transform cultured breast epithelial cells from a benign, highly differentiated phenotype into a dysplastic and proliferative one (19). This matrix-driven transformation is accompanied by activation of extracellular signal-regulated kinase (ERK), Rho GTPase, and NMMII-based contractility, is recreated by over-expressing constitutively active Rho or spontaneously clustering integrins, and is reversed by inhibition of ROCK or ERK. Importantly, many of these pathways have also been implicated in epithelial-mesenchymal transition (48). All of these are consistent with a paradigm in which tumor cells and their premalignant progenitors sense matrix rigidification through enhanced integrin clustering, which in turn activates ERK and mechanosensory signaling, thereby stiffening the cell and inducing proliferation. Suppression of these mitogenic pathways on compliant matrices may also explain why we fail to observe high proliferation in the face of low motility, as would be predicted by the “go or grow” hypothesis (34). The relationship between ECM rigidity, cellular mechanics, and EGFR/Ras/ERK signaling remains largely unexplored in GBM and other nonepithelial tumors, and given that 88% of clinical GBM tumors in the TCGA group bore mutations in the EGFR/Ras/PI3K pathway (10), it would be intriguing to ask if rigidity-dependent proliferation is accompanied by alterations in EGFR-based signaling or could be indirectly modulated by EGFR pathway manipulation.

In summary, we have shown that increasing ECM rigidity can induce a suite of phenotypic changes in human glioma cells, which includes increased cell spreading, faster motility, and enhanced proliferation. As described earlier, bulk brain tissue has an elastic compliance of 0.5 to 1 kPa, similar to the most compliant matrices considered in this study. Whereas we are unaware of systematic

and definitive measurements of the mechanical rigidity of GBM tumor tissue, intraoperative ultrasound clearly shows that tumors and their surrounding stroma are stiffer than normal brain parenchyma. Placed in context of the notion that invasive glioma cells actively remodel their microenvironment from brain-like to tumor-like (1), this raises the intriguing hypothesis that GBM tumor cells stiffen their surroundings as they invade. We envision that this remodeling could occur through a combination of proteolytic degradation of existing matrix components, secretion of matrix components *de novo*, induction of strain-stiffening and contractility-dependent bundling, and alignment of ECM fibrils, as was recently observed for invading breast cancer cells (49, 50). The resulting microenvironmental stiffening may deliver reciprocal mechanobiological signals to tumor cells that act through integrins, focal adhesion proteins, Rho GTPases, and the cytoskeleton to promote shape plasticity, motility, and proliferation. If this is the case, then therapeutic interventions that either interfere with mechanotransductive signaling or mechanical remodeling may hold value in slowing or arresting GBM invasion, analogous to the use of integrin and FAK inhibitors (7, 8). Although challenging, revisiting these ideas in the setting of three-dimensional ECMs or *in vivo* platforms that allow precise tracking of cell-mediated mechanical remodeling during invasion should permit more direct evaluation of this hypothesis.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

Received 12/22/08; revised 2/10/09; accepted 3/16/09.

Grant support: University of California, Berkeley Graduate Division, National Science Foundation, and National Defense Science and Engineering Graduate Fellowships (T.A. Ulrich) and University of California, Berkeley, University of California Cancer Research Coordinating Committee, Arnold and Mabel Beckman Young Investigator Award, and NIH Director's New Innovator Award 1DP2OD004213, a part of the NIH Roadmap for Medical Research (S. Kumar).

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We thank Dr. A. Wurmser and Dr. C.D. James for helpful discussions and provision of cell lines, D. D'Sa for technical assistance with rheology, and J. Dabritz (Anton Paar) and D. Leong (Technical Instruments) for assistance with equipment and software.

References

- Nakada M, Nakada S, Demuth T, Tran NL, Hoelzinger DB, Berens ME. Molecular targets of glioma invasion. *Cell Mol Life Sci* 2007;64:458–78.
- Beadle C, Assanah MC, Monzo P, Vallee R, Rosenfeld SS, Canoll P. The Role of myosin II in glioma invasion of the brain. *Mol Biol Cell* 2008;19:3357–68.
- Manning TJ, Jr., Parker JC, Sontheimer H. Role of lysophosphatidic acid and rho in glioma cell motility. *Cell Motil Cytoskeleton* 2000;45:185–99.
- Salhia B, Rutten F, Nakada M, et al. Inhibition of Rho-kinase affects astrocytoma morphology, motility, and invasion through activation of Rac1. *Cancer Res* 2005;65:8792–800.
- Mahesparan R, Tysnes BB, Read TA, Enger PO, Bjerkvig R, Lund-Johansen M. Extracellular matrix-induced cell migration from glioblastoma biopsy specimens *in vitro*. *Acta Neuropathol* 1999;97:231–9.
- Deryugina EI, Bourdon MA. Tenascin mediates human glioma cell migration and modulates cell migration on fibronectin. *J Cell Sci* 1996;109:643–52.
- Reardon DA, Nabors LB, Stupp R, Mikkelsen T. Cilengitide: an integrin-targeting arginine-glycine-aspartic acid peptide with promising activity for glioblastoma multiforme. *Expert Opin Investig Drugs* 2008;17:1225–35.
- Shi Q, Hjelmeland AB, Keir ST, et al. A novel low-molecular weight inhibitor of focal adhesion kinase, TAE226, inhibits glioma growth. *Mol Carcinog* 2007;46:488–96.
- Magro AM, Magro AD, Cunningham C, Miller MR. Down-regulation of vinculin upon MK886-induced apoptosis in LN18 glioblastoma cells. *Neoplasma* 2007;54:517–26.
- The Cancer Genome Atlas Research Network. Comprehensive genomic characterization defines human glioblastoma genes and core pathways. *Nature* 2008;455:1061–8.
- Dey N, Crosswell HE, De P, et al. The protein phosphatase activity of PTEN regulates SRC family kinases and controls glioma migration. *Cancer Res* 2008;68:1862–71.
- Discher DE, Janmey P, Wang YL. Tissue cells feel and respond to the stiffness of their substrate. *Science* 2005;310:1139–43.
- Paszek MJ, Weaver VM. The tension mounts: mechanics meets morphogenesis and malignancy. *J Mammary Gland Biol Neoplasia* 2004;9:325–42.
- Engler AJ, Sen S, Sweeney HL, Discher DE. Matrix elasticity directs stem cell lineage specification. *Cell* 2006;126:677–89.
- Peyton SR, Putnam AJ. Extracellular matrix rigidity governs smooth muscle cell motility in a biphasic fashion. *J Cell Physiol* 2005;204:198–209.
- Georges PC, Miller WJ, Meaney DF, Sawyer ES, Janmey PA. Matrices with compliance comparable to that of brain tissue select neuronal over glial growth in mixed cortical cultures. *Biophys J* 2006;90:3012–8.
- Suresh S. Biomechanics and biophysics of cancer cells. *Acta Biomater* 2007;3:413–38.
- Bissell MJ, Radisky DC, Rizki A, Weaver VM, Petersen OW. The organizing principle: microenvironmental influences in the normal and malignant breast. *Differentiation* 2002;70:537–46.

19. Paszek MJ, Zahir N, Johnson KR, et al. Tensional homeostasis and the malignant phenotype. *Cancer Cell* 2005;8:241–54.
20. Zaman MH, Trapani LM, Sieminski AL, et al. Migration of tumor cells in 3D matrices is governed by matrix stiffness along with cell-matrix adhesion and proteolysis. *Proc Natl Acad Sci U S A* 2006;103:10889–94.
21. Alexander NR, Branch KM, Parekh A, et al. Extracellular Matrix Rigidity Promotes Invadopodia Activity. *Curr Biol* 2008;18:1295–9.
22. Unsgaard G, Rygh OM, Selbekk T, et al. Intra-operative 3D ultrasound in neurosurgery. *Acta Neurochir (Wien)* 2006;148:235–53.
23. Elkin BS, Azeloglu EU, Costa KD, Morrison B, III. Mechanical heterogeneity of the rat hippocampus measured by atomic force microscope indentation. *J Neurotrauma* 2007;24:812–22.
24. Lefranc F, Brotchi J, Kiss R. Possible future issues in the treatment of glioblastomas: special emphasis on cell migration and the resistance of migrating glioblastoma cells to apoptosis. *J Clin Oncol* 2005;23:2411–22.
25. Thomas TW, DiMilla PA. Spreading and motility of human glioblastoma cells on sheets of silicone rubber depend on substratum compliance. *Med Biol Eng Comput* 2000;38:360–70.
26. Hegedus B, Marga F, Jakab K, Sharpe-Timms KL, Forgacs G. The interplay of cell-cell and cell-matrix interactions in the invasive properties of brain tumors. *Biophys J* 2006;91:2708–16.
27. Kaufman LJ, Brangwynne CP, Kasza KE, et al. Glioma expansion in collagen I matrices: analyzing collagen concentration-dependent growth and motility patterns. *Biophys J* 2005;89:635–50.
28. Forget MA, Desrosiers RR, Del M, et al. The expression of Rho proteins decreases with human brain tumor progression: potential tumor markers. *Clin Exp Metastasis* 2002;19:9–15.
29. Yan B, Chour HH, Peh BK, Lim C, Salto-Tellez M. RhoA protein expression correlates positively with degree of malignancy in astrocytomas. *Neurosci Lett* 2006;407:124–6.
30. Pelham RJ, Jr., Wang Y. Cell locomotion and focal adhesions are regulated by substrate flexibility. *Proc Natl Acad Sci U S A* 1997;94:13661–5.
31. Kumar S, Maxwell IZ, Heisterkamp A, et al. Viscoelastic retraction of single living stress fibers and its impact on cell shape, cytoskeletal organization, and extracellular matrix mechanics. *Biophys J* 2006;90:3762–73.
32. Yap CT, Simpson TI, Pratt T, Price DJ, Maciver SK. The motility of glioblastoma tumour cells is modulated by intracellular cofilin expression in a concentration-dependent manner. *Cell Motil Cytoskeleton* 2005;60:153–65.
33. Tas PW, Gambaryan S, Roewer N. Volatile anesthetics affect the morphology of rat glioma C6 cells via RhoA, ERK, and Akt activation. *J Cell Biochem* 2007;102:368–76.
34. Giese A, Loo MA, Tran N, Haskett D, Coons SW, Berens ME. Dichotomy of astrocytoma migration and proliferation. *Int J Cancer* 1996;67:275–82.
35. Yeung T, Georges PC, Flanagan LA, et al. Effects of substrate stiffness on cell morphology, cytoskeletal structure, and adhesion. *Cell Motil Cytoskeleton* 2005;60:24–34.
36. Lo CM, Wang HB, Dembo M, Wang YL. Cell movement is guided by the rigidity of the substrate. *Biophys J* 2000;79:144–52.
37. Itoh K, Yoshioka K, Akedo H, Uehata M, Ishizaki T, Narumiya S. An essential part for Rho-associated kinase in the transcellular invasion of tumor cells. *Nat Med* 1999;5:221–5.
38. Ader I, Delmas C, Bonnet J, et al. Inhibition of Rho pathways induces radiosensitization and oxygenation in human glioblastoma xenografts. *Oncogene* 2003;22:8861–9.
39. Rattan R, Giri S, Singh AK, Singh I. Rho/ROCK pathway as a target of tumor therapy. *J Neurosci Res* 2006;83:243–55.
40. Lo CM, Buxton DB, Chua GC, Dembo M, Adelstein RS, Wang YL. Nonmuscle myosin IIb is involved in the guidance of fibroblast migration. *Mol Biol Cell* 2004;15:982–9.
41. Cai Y, Biais N, Giannone G, et al. Nonmuscle myosin IIA-dependent force inhibits cell spreading and drives F-actin flow. *Biophys J* 2006;91:3907–20.
42. Sahlia B, Hwang JH, Smith CA, et al. Role of myosin II activity and the regulation of myosin light chain phosphorylation in astrocytomas. *Cell Motil Cytoskeleton* 2008;65:12–24.
43. Goldberg L, Kloog Y. A Ras inhibitor tilts the balance between Rac and Rho and blocks phosphatidylinositol 3-kinase-dependent glioblastoma cell migration. *Cancer Res* 2006;66:11709–17.
44. Wang HB, Dembo M, Wang YL. Substrate flexibility regulates growth and apoptosis of normal but not transformed cells. *Am J Physiol Cell Physiol* 2000;279:C1345–50.
45. Semler EJ, Ranucci CS, Moghe PV. Mechanochemical manipulation of hepatocyte aggregation can selectively induce or repress liver-specific function. *Biotechnol Bioeng* 2000;69:359–69.
46. Saha K, Keung AJ, Irwin EF, et al. Substrate modulus directs neural stem cell behavior. *Biophys J* 2008;95:4426–38.
47. Efler JC, Kee YS, Berk JM, Tran MN, Iglesias PA, Robinson DN. Mitosis-specific mechanosensing and contractile-protein redistribution control cell shape. *Curr Biol* 2006;16:1962–7.
48. Turley EA, Veisoh M, Radisky DC, Bissell MJ. Mechanisms of disease: epithelial-mesenchymal transition—does cellular plasticity fuel neoplastic progression? *Nat Clin Pract Oncol* 2008;5:280–90.
49. Wolf K, Wu YL, Liu Y, et al. Multi-step pericellular proteolysis controls the transition from individual to collective cancer cell invasion. *Nat Cell Biol* 2007;9:893–904.
50. Provenzano PP, Inman DR, Eliceiri KW, Trier SM, Keely PJ. Contact guidance mediated three-dimensional cell migration is regulated by Rho/ROCK-dependent matrix reorganization. *Biophys J* 2008;95:5374–84.