Host epithelial geometry regulates breast cancer cell invasiveness

Eline Boghaert[a], Jason P. Gleghorn[a], KangAe Lee[a,b], Nikolce Gjorevski[a], Derek C. Radisky[c], and Celeste M. Nelson[a,b,1]

Departments of [a]Chemical and Biological Engineering and [b]Molecular Biology, Princeton University, Princeton, NJ 08544; and [c]Department of Cancer Biology, Mayo Clinic Cancer Center, Jacksonville, FL 32224

Edited by Joan S. Brugge, Harvard Medical School, Boston, MA, and approved October 15, 2012 (received for review November 15, 2011)

Breast tumor development is regulated in part by cues from the local microenvironment, including interactions with neighboring nontumor cells as well as the ECM. Studies using homogeneous populations of breast cancer cell lines cultured in 3D ECM have shown that increased ECM stiffness stimulates tumor cell invasion. However, at early stages of breast cancer development, malignant cells are surrounded by normal epithelial cells, which have been shown to exert a tumor-suppressive effect on cocultured cancer cells. Here we explored how the biophysical characteristics of the host microenvironment affect the proliferative and invasive tumor phenotype of the earliest stages of tumor development, by using a 3D microfabrication-based approach to engineer ducts composed of normal mammary epithelial cells that contained a single tumor cell. We found that the phenotype of the tumor cell was dictated by its position in the duct: proliferation and invasion were enhanced at the ends and blocked when the tumor cell was located elsewhere within the tissue. Regions of invasion correlated with high endogenous mechanical stress, as shown by finite element modeling and bead displacement experiments, and modulating the contractility of the host epithelium controlled the subsequent invasion of tumor cells. Combining microcomputed tomographic analysis with finite element modeling suggested that predicted regions of high mechanical stress correspond to regions of tumor formation in vivo. This work suggests that the mechanical tone of nontumorigenic host epithelium directs the phenotype of tumor cells and provides additional insight into the instructive role of the mechanical tumor microenvironment.

host–tumor interactions | mechanotransduction | focal adhesion kinase | integrin clustering

More than 90% of all human mammary carcinomas originate in the epithelial ducts rather than the surrounding connective tissue (1), and the majority of these arise from the terminal ductal lobular unit (2). In mice, strains with robust lateral branching in the ductal tree show high incidence of spontaneous mammary tumors (3–5). Moreover, the specific location where a tumor develops in the breast can have a profound effect on the resulting breast cancer outcome: patients with tumors in the upper lateral quadrant of the breast have a better prognosis than those with tumors that develop in one of the other three quadrants (6, 7). These architecture-dependent variations in tumor development underscore the notion that the microenvironment of the tumor in vivo plays an important role in determining the phenotypic outcome of genetic mutations (8, 9).

In culture and in vivo, the tumor microenvironment can suppress or induce a malignant phenotype in cells with a preexisting malignant genotype (10–13). Indeed, many people harbor potentially malignant tumors that remain dormant for several years (14–16). Recent findings suggest that whereas the microenvironment surrounding a tumor normally provides tumor-suppressive signals (10, 17–19), the loss of tissue homeostasis can induce the development of an aberrant tumor microenvironment that can act as a potent tumor promoter (19–23). Thus, genetic mutations that have the potential to lead to the initiation of tumors can be restrained by a nonpermissive tissue microenvironment (19).

A developing tumor can affect the mechanical properties of its microenvironment in ways that drive tumor progression (24, 25). Normally, cells exert contractile forces against their surrounding microenvironment (26, 27). Failure to maintain a balance between these exerted forces and the opposing forces from the microenvironment causes aberrations that promote the progression of disease, including cancer (28). Cells recognize an increase in ECM stiffness and respond by generating increased traction forces on their surroundings; this in turn enhances growth, survival, and invasion of tumor cells by promoting focal adhesion maturation and signaling through actomyosin contractility (29). Motility, invasion, and metastatic dissemination are assisted by the disruption of cell–cell junctional integrity and cytoskeletal remodeling (28–31). The signaling molecule Rho GTPase has been identified as a key effector of these processes: Rho activity is frequently elevated in tumors (32), and elevated signaling through Rho can regulate cell proliferation (32) and invasion (33–35). Increased Rho signaling can also affect the alignment of collagen fibers and prime the microenvironment for subsequent invasion by tumor cells (35).

Here we used a 3D microlithography-based approach to examine how the phenotype of tumor cells varies with their location within an engineered epithelial host tissue. Our results show that mammary tumor cells proliferate or invade preferentially in regions of endogenously generated mechanical stress. We show that the tumor cell phenotype can be controlled by altering the contractility of the host epithelial tissue through the expression of dominant-negative or constitutively active RhoA. We further show that at regions of high mechanical stress that can activate the tumor phenotype, tumor cells require signaling through focal adhesion kinase (FAK) to invade. In regions of lower mechanical stress that inhibit tumor cell invasion, artificially inducing the assembly of focal adhesions by promoting integrin clustering is sufficient to drive the invasive phenotype.

Results

Tumorigenic Phenotype Is Suppressed Within Engineered Mammary Ducts. To explore whether the normal microenvironment of the host could alter the phenotype of tumor cells, we used a microlithography-based approach to engineer surrogate ducts composed of normal mammary epithelial cells that contained a single tumor cell (Fig. 1*A* and Table S1). We varied the initial position of the tumor cell within the engineered ducts and monitored its resulting phenotype (Fig. 1*B*). We found that the proliferation of several breast cancer cell lines depended on their initial location in the tissue. In particular, tumor cell lines previously shown to be noninvasive, including SKBR3, MDA-MB-361, and MDA-MB-453, proliferated at a significantly higher rate when they were located at the ends of the tissue surrogates, compared with when the tumor cells were located elsewhere within the duct (Fig. 1*C*).

Author contributions: E.B., D.C.R., and C.M.N. designed research; E.B., J.P.G., K.L., N.G., and D.C.R. performed research; and E.B. and C.M.N. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

[1]To whom correspondence should be addressed. E-mail: celesten@princeton.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1118872109/-/DCSupplemental.

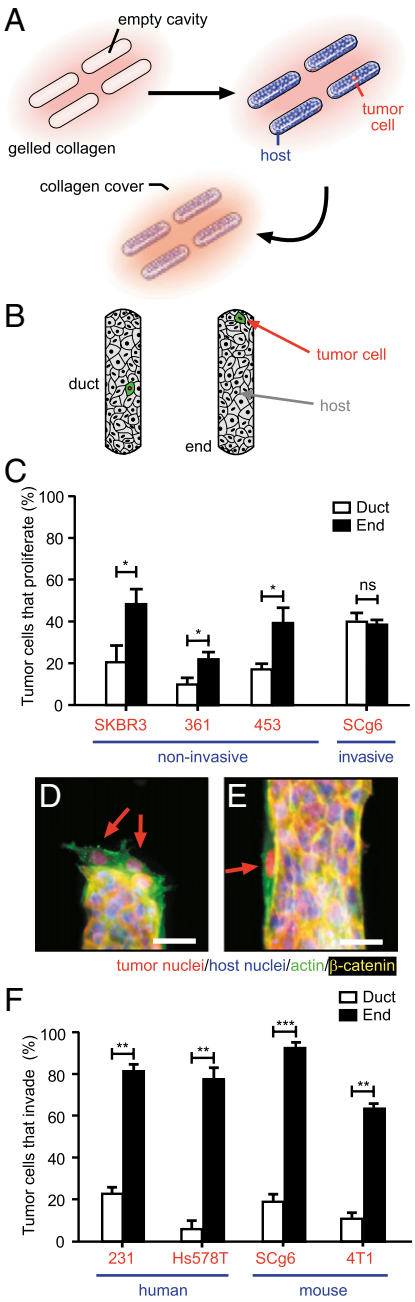

Fig. 1. Normal host microenvironment reduces tumor cell proliferation and suppresses invasion from the duct. (*A*) Schematic of 3D microlithography-based approach to engineer epithelial tissues. (*B*) Schematic depicting duct vs. end locations in engineered epithelial tissues. (*C*) Noninvasive tumor cells exhibit increased proliferation at the ends compared with the duct; invasive tumor cells show no preference as quantified by EdU (5-ethynl-2′-deoxyuridine) incorporation. Tumor cells (nuclei in red) (*D*) invading from the end of a tissue and (*E*) suppressed from invading from the duct. (Scale bars, 25 μm.) (*F*) Quantification of invasion using different combinations of normal (host) cells and tumor cell lines reveals that the spatial regulation of invasive phenotype is not cell line-dependent. Error bars represent SEM ($n = 3$). Paired t test: $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

Conversely, whereas the proliferation rates of invasive breast tumor cell lines, including SCg6, 4T1, MDA-MB-231, and Hs578T, were independent of their initial location within the tissue (Fig. 1*C* and Fig. S1), these same cells showed dramatic differences in invasiveness depending on their location. When grown as homogeneous cultures, the cells invaded randomly into the surrounding collagen gel, as would be expected for tumor cell lines characterized as invasive (Fig. S2). However, when individual tumor cells were incorporated into nonmalignant host tissue surrogates, they invaded much more readily when initially located at the end rather than in the duct (Fig. 1 *D–F* and Fig. S3). Tumor cell invasion required signaling through epidermal growth factor receptor and the catalytic activity of matrix metalloproteinases, because inhibiting these with AG1478 and GM6001, respectively, blocked invasion (Fig. S4). Breast tumor cell lines previously shown to be noninvasive remained noninvasive when incorporated within the engineered ducts, regardless of their location (Fig. S5). The end region thus selectively promotes proliferation or invasion of mammary tumor cells, suggesting the presence of instructive cues in the host microenvironment.

Tumor Phenotype Corresponds with Endogenous Mechanical Stress of the Host Tissue. Tissue geometry can affect cellular phenotype by establishing regional differences in endogenous mechanical stress or concentration gradients of diffusible molecules, including TGF-β (36, 37). We used the finite element method (FEM) to simulate two tissue geometries that could distinguish between these signals and reveal which regulated tumor cell invasion. As previously described (36, 38), we simulated contraction of an epithelial tissue within a collagenous matrix and used FEM to compute the resulting maximum principal stress within the tissue, which represents a coordinate-invariant description of the stress at each point (Fig. 2*A*); full details of the model can be found in *SI Methods*. For adjacent pairs of ducts, this model predicted that the ends of the tissue experience high mechanical stress, with higher stress predicted at the proximal ends than the distal ends. To test our simple computational model, calculated displacements (Fig. 2*B*) were compared with those measured experimentally (Fig. 2*C*) by tracking the movement of beads embedded within the surrounding collagen before and after relaxing the tissue. We found that our computational models generated displacement fields that were similar in magnitude to the experimental system. Similarly, our model predicted regions of high displacement at the tips and correctly predicted lower displacements at the proximal ends than at the distal ends (because the tissues are in opposition to each other and thus pulling on the matrix between them in opposite directions) but failed to capture some of the larger spatial patterns of displacement in the matrix. We then engineered pairs of adjacent ducts that contained a single tumor cell (Fig. 2*D*). Invasion occurred at regions of high mechanical stress, as tumor cells invaded from both the proximal and distal ends but were prevented from invading when in the duct region (Fig. 2 *E* and *F*). Similarly, tissues with a central bump were predicted to have high mechanical stress and displacements at the ends and at the bump (Fig. 2 *G–I*), and tumor cells invaded preferentially from these high-stress regions (Fig. 2 *J–L*). Tumor cell invasion thus correlates with regions of high endogenous mechanical stress calculated within the engineered host epithelium. Surprisingly, the levels of invasion at the end and the bump regions were not significantly different, despite the distinct levels of predicted mechanical stress. This suggests that there is a threshold level of stress within the host at which invasion occurs.

Altering Host Tissue Contractility Directs Tumor Cell Invasiveness. Mechanical stress is generated by the actin cytoskeleton and transmitted between cells through cadherin-mediated intercellular adhesions (39). Reducing mechanical stress by inhibiting the Rho effector, Rho kinase (ROCK) blocked invasion of the tumor cells from the ends of the tissues (Fig. 3 *A*, *B*, and *L*). Similarly, inhibiting actomyosin-mediated contractility using blebbistatin, a selective inhibitor of nonmuscle myosin II ATPase activity, blocked tumor cell invasion from the tissue ends (Fig. 3 *C* and *L*). However, increasing cytoskeletal contractility and mechanical stress using the phosphatase inhibitor calyculin A did not further increase invasion from the ends (Fig. S6), suggesting that a maximum level of

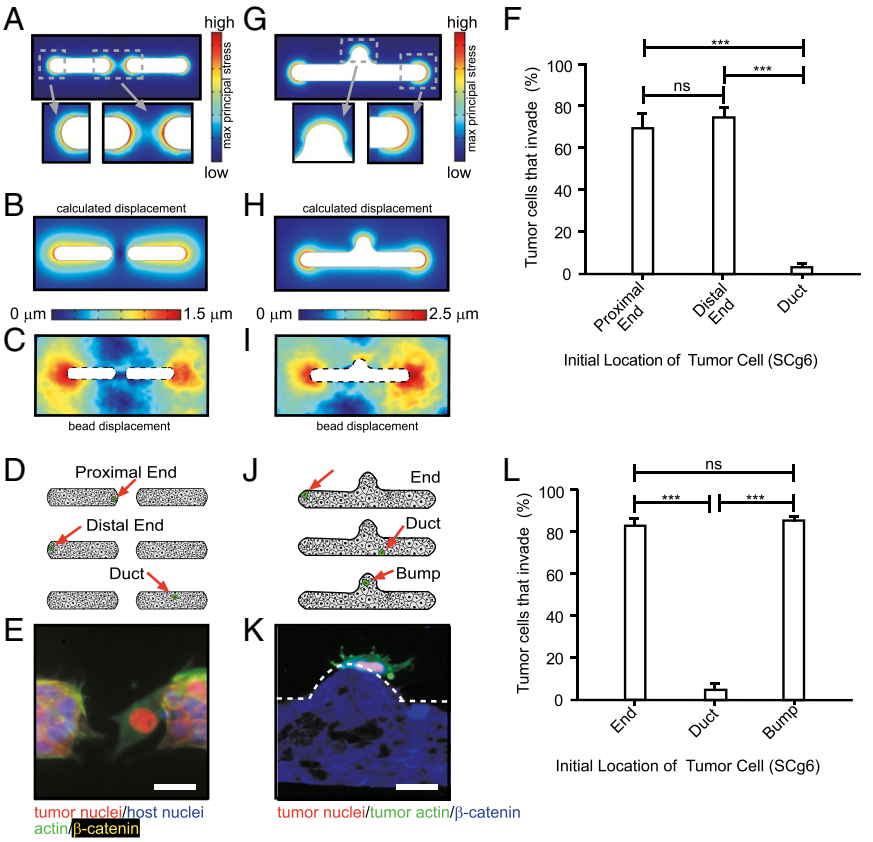

Fig. 2. Regions of high endogenous mechanical stress are permissive to tumor cell invasion. (*A* and *G*) Predicted endogenous mechanical stress and (*B* and *H*) displacement. (*C* and *I*) Experimental bead displacement in culture. (*D*) Schematic showing proximal end, distal end, and duct regions of adjacent tissues. (*E*) Fluorescence image of SCg6 tumor cell invading from the proximal end of a tissue. (Scale bar, 25 μm.) (*F*) Quantification of invasion from adjacent tissues. Error bars represent SEM (n = 3). One-way ANOVA and Tukey-Kramer posttest: ***$P < 0.001$. (*J*) Schematic showing end, duct, and bump regions of a tissue. (*K*) Fluorescence image of SCg6 tumor cell invading from the bump region of a tissue. (Scale bar, 25 μm.) (*L*) Quantification of invasion from ducts with a bump. Error bars represent SEM (n = 3). One-way ANOVA and Tukey-Kramer posttest: ***$P < 0.001$.

invasion was already induced by the microenvironment of this region of the surrogate tissues. This finding is again consistent with a threshold level of stress required for invasion.

We next selectively modulated the contractility of the nonmalignant host epithelial tissue without altering that of the embedded tumor cell. Low levels of Rho activity prevent myosin light chain phosphorylation and cytoskeletal contraction (40). Transducing host epithelial cells with an adenovirus encoding dominant-negative RhoA ($RhoA^{N19}$) reduced the levels of endogenous contractility generated within the host tissue (Fig. S7*A*) without causing the tissues to dissociate (Fig. S7*B*). Host expression of $RhoA^{N19}$ also reduced the subsequent invasion of tumor cells from the ends of the tissue (Fig. 3 *D* and *L*). Conversely, transducing host epithelial cells with an adenovirus encoding constitutively active RhoA ($RhoA^{L63}$) resulted in an increase in the levels of endogenous contractility generated by the tissues (Fig. S7*A*), which again remained intact (Fig. S7*B*). We found that when embedded within $RhoA^{L63}$-expressing host tissue surrogates, tumor cells were able to invade from all locations (Fig. 3 *E* and *L*). Intercellular transmission of mechanical stress can be disrupted by expressing a dominant-negative mutant of E-cadherin that lacks the β-catenin-binding domain (EΔ) and thereby prevents coupling to the actin cytoskeleton (36, 41, 42). Disrupting intercellular transmission of mechanical stress in the host epithelial cells using an adenovirus encoding EΔ (Fig. S7 *A* and *B*) significantly reduced invasion of tumor cells (Fig. 3 *F* and *L*) and prevented preferential proliferation of noninvasive tumor cell lines (Fig. S8). The effects of the adenovirus encoding EΔ did not result from a loss of apicobasal polarity within the host, as shown by staining for ZO-1 (Fig. S7*C*), and could not be rescued by simultaneously expressing $RhoA^{L63}$ (Fig. 3 *G* and *L*). These data suggest that the tumorigenic phenotype is modulated by variations in mechanical stress that are generated by actomyosin-mediated contractility of the normal host epithelium and transmitted through intercellular adhesions within the host tissue.

Tumor Cell Invasion Is Regulated Through Focal Adhesions and Integrin Clustering. It has been shown that mechanical stress results in increased integrin expression, activation, and focal adhesion formation, ultimately leading to tumor cell invasion (29, 43). Furthermore, the phosphorylation and activation of FAK has been found to be enhanced in high-stress regions of mammary epithelial tissues (36). To determine whether FAK regulates the response of tumor cells to host tissue contractility, we expressed a dominant-negative mutant that lacks the kinase domain (FAK-Dter) (44) (Fig. S7*D*). Transducing tumor cells with an adenovirus encoding FAK-Dter significantly inhibited their ability to invade (Fig. 3 *H* and *L*). Conversely, forcing the assembly of focal adhesions specifically in tumor cells by selectively expressing an autoclustering mutant of β1-integrin ($β1^{V737N}$) (Fig. S7 *E*–*G*) induced invasion from all locations within the tissue surrogates (Fig. 3 *I* and *L*). However, inducing focal adhesion assembly in tumor cells did not rescue the inhibition of invasion resulting from expression of EΔ in the host cells (Fig. 3 *J* and *L*) or treatment with blebbistatin (Fig. 3 *K* and *L*). These data suggest that integrin clustering and FAK activation are required, but not sufficient, for invasion from the high-stress ends. Whereas promoting the assembly of focal adhesions can induce invasion in regions of lower mechanical stress, it does not induce tumor cells to invade when the intercellular transmission of mechanical stress between host cells is disrupted or when contractility is inhibited throughout the tissue. These data are consistent with the notion that tumor cell invasion requires a threshold level of mechanical stress within the host tissue, as inferred from the tissue geometry experiments (Fig. 2).

Predictions of Mechanical Stress Correspond with Tumor Development in Vivo. To determine whether regions of high mechanical stress correspond with those preferential for tumor development in vivo, we compared qualitatively the endogenous stress profiles in a simple contractile model of the mammary gland with the spatial patterns

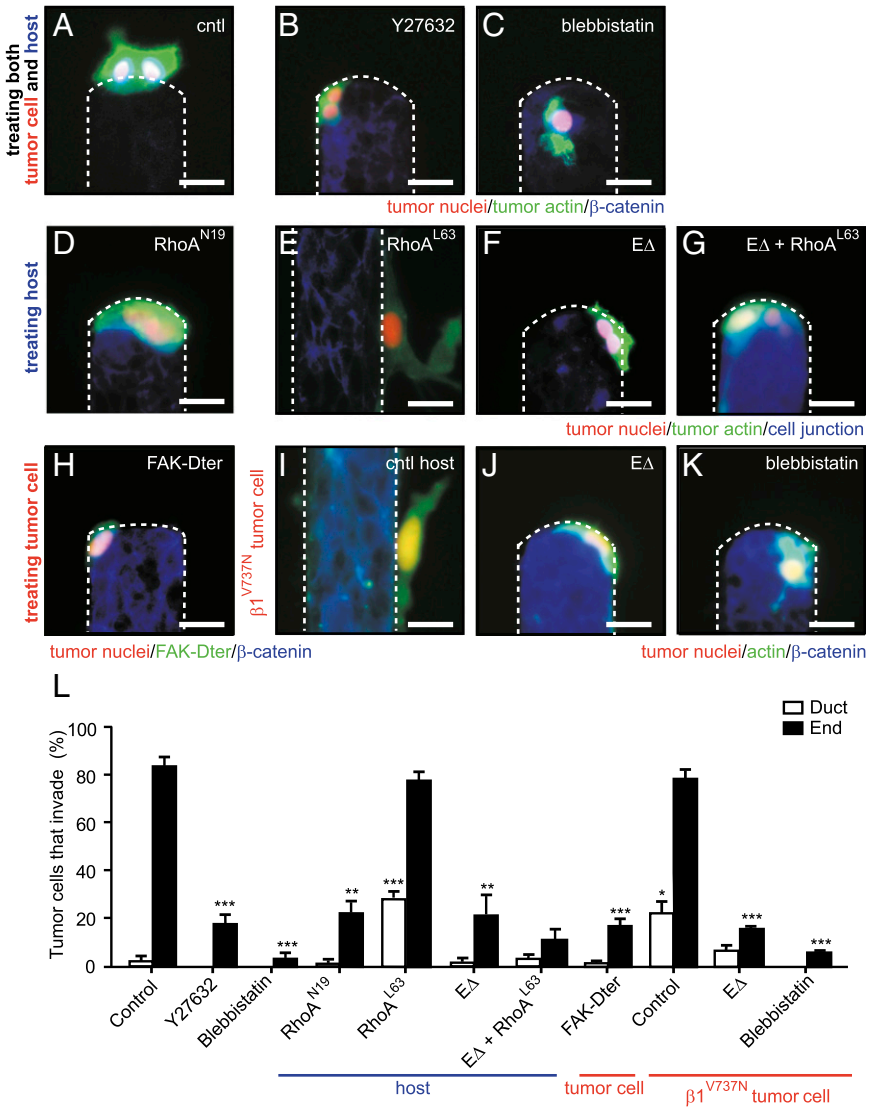

Fig. 3. Endogenous contractility of the host epithelium regulates tumor cell invasion. Fluorescence images of EpH4 host tissue with SCg6 tumor cell (*A*) invading at the end or inhibited from invading when tissues are treated with (*B*) Y27632 or (*C*) blebbistatin. (*D*) Expression of dominant-negative RhoA ($RhoA^{N19}$) in host epithelial cells inhibits invasion from the end. (*E*) Expression of constitutively active RhoA ($RhoA^{L63}$) in host epithelial cells induces invasion from the duct. (*F*) Disrupting the intercellular transmission of mechanical stress by expressing EΔ in host epithelial cells inhibits invasion of tumor cells from the end, even when (*G*) constitutively active RhoA is expressed. (*H*) Expression of FAK-Dter in tumor cells inhibits invasion from the end. Autoclustering of β1-integrin through expression of $\beta1^{V737N}$ in tumor cells (*I*) induces invasion from the duct but fails to induce invasion in tissues (*J*) containing EΔ-expressing host cells or (*K*) treated with blebbistatin. (Scale bars, 25 μm.) (*L*) Quantification of invasion of tumor cells from experiments depicted in *A*–*K*. Error bars represent SEM ($n = 3$). Paired *t* test: $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

of tumor formation in an inducible transgenic mouse. Microcomputed tomography (μCT) was used to create a 3D rendering of the mouse mammary gland (Fig. 4*A*). μCT generated serial cross-sectional images of the 3D mammary epithelial ductal tree. The data generated by μCT were converted to a solid model that recapitulated the native architecture of the gland (Fig. 4*B*), consisting of a hollow epithelial tree embedded in a 3D ECM. As a first approximation, the ECM was modeled as a homogeneous linearly elastic solid with the material properties of collagen. We used FEM to calculate the maximum principal stress throughout this geometry. This qualitative model of endogenous contractility in the 3D mammary renderings predicted elevated mechanical stress at the ends of the epithelial tree compared with the ducts (Fig. 4 *C* and *D*).

To investigate whether tumors develop preferentially at these predicted high-stress regions within the murine mammary gland, we created mice transgenic for an inducible form of the kRas oncogene, under the control of the mouse mammary tumor virus (MMTV) promoter. Using an inducible oncogene allowed us to introduce expression of kRas in the mammary epithelium after the ductal tree had developed and thus to examine spatial variations in tumor formation in the context of the adult gland. When kRas was expressed in adult mammary glands, tumors developed preferentially at the ends of mammary epithelial ducts (Fig. 4 *G*–*I*), whereas control mice failed to develop tumors (Fig. 4 *E* and *F*). These data suggest that the phenotypic outcome of expression of the oncogene depends on the local microenvironment of the mammary gland. In particular, these data are consistent with a possible role for the mechanical environment of the host epithelium and suggest that low-stress regions such as the ducts may suppress the formation of tumors.

Discussion

The cellular, chemical, and physical properties of the tumor microenvironment have a profound effect on tumor progression (10,

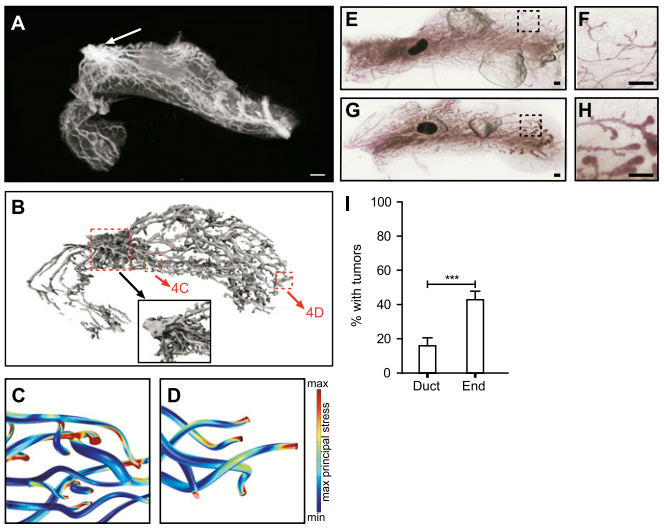

Fig. 4. Computational model shows that mechanical stress corresponds with regions of tumor development in vivo. (*A*) μCT unprocessed volume rendering of the inguinal mammary gland of an 8-wk-old CD-1 mouse. (*B*) 3D rendering of the network of mammary epithelial ducts. (*Inset*) Detailed view of the ductal network near the nipple region. Computational model of predicted maximum principal stress (*C*) along the ducts and (*D*) at the ends of a network of epithelial ducts embedded in collagen. (Scale bar, 500 μm.) Whole-mount of inguinal mammary gland from (*E* and *F*) control mouse, (*G* and *H*) MMTV-rtta/tet-kRas mouse. (Scale bar, 500 μm.) (*I*) Quantification of tumor location in kRas-expressing glands. Error bars represent SEM ($n = 4$). Paired t test: $^{***}P < 0.001$.

23, 29, 43, 45–48). Here we found that the mechanical environment of the host epithelium also plays a critical role in tumor cell phenotype. We determined that tumor cells embedded in nonmalignant tissues proliferate or invade preferentially when located in regions characterized by high endogenous mechanical stress. We further found that tuning the contractility of the host epithelium altered the dependence of tumor cell phenotype on location in the host tissue. We found similar behaviors for a variety of mouse and human mammary cancer cells; that these phenotypic effects are present even when using tumor cells containing a variety of genetic alterations illustrates the importance of these host-derived microenvironmental cues on tumor cell behavior.

It is becoming increasingly clear that mechanical cues from the tumor microenvironment alter tumor cell behavior. Tumors are appreciably stiffer than normal tissue (21, 49). During transformation of the mammary gland, the tumor epithelium and tumor-associated vasculature, as well as the surrounding ECM, undergo an increase in stiffness (49). The enzyme lysyl oxidase causes cross-linking and remodeling of collagen and stiffening of the ECM in mammary tumors; inhibiting lysyl oxidase was found to prevent tissue stiffening, reduce tumor incidence, and delay the progression of the tumors that did form (43). The associated changes in ECM stiffness can disrupt normal tissue architecture and induce a malignant phenotype through integrin clustering and activation of ERK (29, 43, 50). Indeed, alignment of collagen fibrils in the tumor stroma is an independent negative prognostic indicator for human breast carcinomas (51). In addition to these mechanical contributions from the ECM, our data suggest that the mechanical tone (that is, the intrinsic tissue-level contractility or tension) of the surrounding nonmalignant host epithelial tissue may be critical in establishing regions that modulate tumor phenotype. Remarkably, we found that changes in contractility of the surrounding host tissue control the subsequent invasion of tumor cells. Similar to mechanisms by which tumor cells sense changes in ECM stiffness, our data suggest that tumor cells sense alterations from the host epithelial environment in part through integrin activation and focal adhesion assembly.

Our data show that tumors develop in regions of the epithelium that experience higher mechanical stress: FEM analysis of our 3D rendering predicted higher mechanical stress at the distal regions of the epithelial tree, which is where we found tumors developing in response to kRas expression (Fig. 4). However, the mechanism by which the neighboring cells transmit the mechanical information to the tumor cell is likely to be complex. Indeed, it is important to note that both mechanical stress and mechanical strain are predicted to correlate with the tumor phenotypes examined here. It is difficult to uncouple stress from strain, because they are intimately related through the constitutive response of the tissue, and furthermore, it is as yet unclear whether cells in a given context sense one or the other or both (52–54). Thus, although we refer to the regions that induce tumor cell proliferation and invasion as "high stress," we do so without prejudice. From the perspective of the cell, it is probably more informative to focus on the molecular changes that result from spatial variations in mechanical tone, such as conformational changes in mechanically responsive proteins or activation of mechanically sensitive signaling cascades (26). Some insight into this can be gained from regional analyses of mouse mammary glands, which have found in distal growth regions increased expression of epithelial cell-specific factors that are critical for cancer development, including GATA3 (55) and FGFR2 (56). Another possibility is regional differences in the organization of ECM components, which could affect cell behavior in important ways (57).

Here we found that expression of constitutively active RhoA in the host tissue induced tumor cell invasion from regions that otherwise suppressed tumor phenotype, whereas dominant-negative RhoA inhibited invasion. Signaling through the RhoA pathway induces collagen alignment and matrix remodeling, which are dependent on contractility and can guide local tumor cell invasion in culture (35, 45) and in vivo (58). Collagen cross-linking and increasing tissue stiffness enhance integrin signaling and assembly of focal adhesions, thereby promoting a malignant phenotype (43). In the skin, expression of conditionally active ROCK has been found to increase collagen density and tissue stiffness, leading to activation of FAK and ultimately epidermal hyperplasia (47). We found here that FAK activity was required in the breast cancer cells for their invasion from regions of high mechanical stress, consistent with a possible role for RhoA-induced collagen remodeling and activation of FAK in the patterned behavior.

Regardless of the mechanism by which the host transmits this information to the tumor cell, it is clear from our data that the host contractility is a dominant feature. Although activation of FAK, and by inference focal adhesion formation, are required for tumor cell invasion, ectopic induction of integrin clustering was not sufficient to induce invasion of tumor cells residing in a flaccid or uncoupled host. Altogether, these data suggest that there is some minimum threshold of host contractility that is required for induction of an invasive phenotype in the tumor cell.

Conversely, we found that the duct region of mammary tissues has lower intrinsic mechanical tone and provides microenvironmental cues that are suppressive of tumor cell proliferation and invasion. These data add to our growing understanding that the microenvironment can provide important contextual cues that suppress tumorigenic behavior (10, 17–19). Indeed, occult tumors are surprisingly common (14–16); autopsies have revealed that 20% of young and middle-aged women have clinically occult breast tumors (16). However, it is unclear how these tumors are restrained from progressing to malignant cancers. Our results show that the mechanical properties of the normal host epithelium may be critical for suppressing tumorigenic phenotype in cells with a tumorigenic genotype. These differences in tumor cell behavior depending on location within the host epithelium strengthen the importance of studying tumorigenesis in the context of a tissue rather than in isolated individual cells (9) and reinforce the importance of using

3D culture models to recapitulate the natural architecture of tissues and complement studies in vivo (59).

Methods

Three-dimensional tissues of precise geometry were generated using microlithography as previously described (37, 60). To generate tissues that contained a single tumor cell, labeled tumor cells and functionally normal host cells were mixed in a 1:100 ratio. Detailed methods are available in *SI Methods*.

ACKNOWLEDGMENTS. We thank Alexander Wright of the Radiology Department at the University of Pennsylvania School of Medicine for technical assistance with μCT scanning and image reconstruction. This work was supported in part by National Institutes of Health Grants CA128660, GM083997, and HL110335, Susan G. Koman for the Cure, the David & Lucile Packard Foundation, the Alfred P. Sloan Foundation, and the Camille & Henry Dreyfus Foundation. C.M.N. holds a Career Award at the Scientific Interface from the Burroughs Wellcome Fund. E.B. was supported in part by a predoctoral fellowship from the New Jersey Commission on Cancer Research. N.G. was supported in part by a Wallace Memorial Honorific Fellowship.

1. Silberstein GB (2001) Tumour-stromal interactions. Role of the stroma in mammary development. *Breast Cancer Res* 3(4):218–223.
2. Simpson PT, Reis-Filho JS, Gale T, Lakhani SR (2005) Molecular evolution of breast cancer. *J Pathol* 205(2):248–254.
3. Gardner WU, Strong LC (1935) The normal development of the mammary glands of virgin female mice of ten strains varying in susceptibility to spontaneous neoplasms. *Am J Cancer* 25:282–290.
4. Korteweg R (1940) The anatomy of the mammary gland in mice with regard to the degree of its disposition for cancer. *Akad V Wettenschappen* 43:891–900.
5. Huseby RA, Bittner JJ (1946) A comparative morphological study of the mammary glands with reference to the known factors influencing the development of mammary carcinoma in mice. *Cancer Res* 6:240–255.
6. Levi F, Randimbison L, Te VC, La Vecchia C (2003) Influence of tumor location on breast cancer prognosis. *Int J Cancer* 107(4):683–684.
7. Kroman N, Wohlfahrt J, Mouridsen HT, Melbye M (2003) Influence of tumor location on breast cancer prognosis. *Int J Cancer* 105(4):542–545.
8. Sonnenschein C, Soto AM (2000) Somatic mutation theory of carcinogenesis: Why it should be dropped and replaced. *Mol Carcinog* 29(4):205–211.
9. Soto AM, Sonnenschein C (2011) The tissue organization field theory of cancer: A testable replacement for the somatic mutation theory. *Bioessays* 33(5):332–340.
10. Weaver VM, et al. (1997) Reversion of the malignant phenotype of human breast cells in three-dimensional culture and in vivo by integrin blocking antibodies. *J Cell Biol* 137(1):231–245.
11. Kenny PA, Bissell MJ (2003) Tumor reversion: Correction of malignant behavior by microenvironmental cues. *Int J Cancer* 107(5):688–695.
12. Park CC, Bissell MJ, Barcellos-Hoff MH (2000) The influence of the microenvironment on the malignant phenotype. *Mol Med Today* 6(8):324–329.
13. Leung CT, Brugge JS (2012) Outgrowth of single oncogene-expressing cells from suppressive epithelial environments. *Nature* 482(7385):410–413.
14. Rich AR (2007) On the frequency of occurrence of occult carcinoma of the prostrate. 1934. *Int J Epidemiol* 36(2):274–277.
15. Sakr WA, Haas GP, Cassin BF, Pontes JE, Crissman JD (1993) The frequency of carcinoma and intraepithelial neoplasia of the prostate in young male patients. *J Urol* 150 (2 Pt 1):379–385.
16. Nielsen M, Thomsen JL, Primdahl S, Dyreborg U, Andersen JA (1987) Breast cancer and atypia among young and middle-aged women: A study of 110 medicolegal autopsies. *Br J Cancer* 56(6):814–819.
17. Dolberg DS, Bissell MJ (1984) Inability of Rous sarcoma virus to cause sarcomas in the avian embryo. *Nature* 309(5968):552–556.
18. Mintz B, Illmensee K (1975) Normal genetically mosaic mice produced from malignant teratocarcinoma cells. *Proc Natl Acad Sci USA* 72(9):3585–3589.
19. Bissell MJ, Hines WC (2011) Why don't we get more cancer? A proposed role of the microenvironment in restraining cancer progression. *Nat Med* 17(3):320–329.
20. Sieweke MH, Thompson NL, Sporn MB, Bissell MJ (1990) Mediation of wound-related Rous sarcoma virus tumorigenesis by TGF-beta. *Science* 248(4963):1656–1660.
21. Boyd NF, et al. (2007) Mammographic density and the risk and detection of breast cancer. *N Engl J Med* 356(3):227–236.
22. Thomasset N, et al. (1998) Expression of autoactivated stromelysin-1 in mammary glands of transgenic mice leads to a reactive stroma during early development. *Am J Pathol* 153(2):457–467.
23. Camps JL, et al. (1990) Fibroblast-mediated acceleration of human epithelial tumor growth in vivo. *Proc Natl Acad Sci USA* 87(1):75–79.
24. DuFort CC, Paszek MJ, Weaver VM (2011) Balancing forces: Architectural control of mechanotransduction. *Nat Rev Mol Cell Biol* 12(5):308–319.
25. Yu H, Mouw JK, Weaver VM (2011) Forcing form and function: Biomechanical regulation of tumor evolution. *Trends Cell Biol* 21(1):47–56.
26. Eyckmans J, Boudou T, Yu X, Chen CS (2011) A hitchhiker's guide to mechanobiology. *Dev Cell* 21(1):35–47.
27. Schwartz MA (2010) Integrins and extracellular matrix in mechanotransduction. *Cold Spring Harb Perspect Biol* 2(12):a005066.
28. Kumar S, Weaver VM (2009) Mechanics, malignancy, and metastasis: The force journey of a tumor cell. *Cancer Metastasis Rev* 28(1-2):113–127.
29. Paszek MJ, et al. (2005) Tensional homeostasis and the malignant phenotype. *Cancer Cell* 8(3):241–254.
30. Erler JT, Weaver VM (2009) Three-dimensional context regulation of metastasis. *Clin Exp Metastasis* 26(1):35–49.
31. Paszek MJ, Weaver VM (2004) The tension mounts: mechanics meets morphogenesis and malignancy. *J Mammary Gland Biol Neoplasia* 9(4):325–342.
32. Fritz G, Just I, Kaina B (1999) Rho GTPases are over-expressed in human tumors. *Int J Cancer* 81(5):682–687.
33. Schmitz AA, Govek EE, Böttner B, Van Aelst L (2000) Rho GTPases: Signaling, migration, and invasion. *Exp Cell Res* 261(1):1–12.
34. Itoh K, et al. (1999) An essential part for Rho-associated kinase in the transcellular invasion of tumor cells. *Nat Med* 5(2):221–225.
35. Provenzano PP, Inman DR, Eliceiri KW, Trier SM, Keely PJ (2008) Contact guidance mediated three-dimensional cell migration is regulated by Rho/ROCK-dependent matrix reorganization. *Biophys J* 95(11):5374–5384.
36. Gjorevski N, Nelson CM (2010) Endogenous patterns of mechanical stress are required for branching morphogenesis. *Integr Biol (Camb)* 2(9):424–434.
37. Nelson CM, Vanduijn MM, Inman JL, Fletcher DA, Bissell MJ (2006) Tissue geometry determines sites of mammary branching morphogenesis in organotypic cultures. *Science* 314(5797):298–300.
38. Gjorevski N, Nelson CM (2012) Mapping of mechanical strains and stresses around quiescent engineered three-dimensional epithelial tissues. *Biophys J* 103(1):152–162.
39. Adams CL, Nelson WJ (1998) Cytomechanics of cadherin-mediated cell-cell adhesion. *Curr Opin Cell Biol* 10(5):572–577.
40. Clark K, Langeslag M, Figdor CG, van Leeuwen FN (2007) Myosin II and mechanotransduction: A balancing act. *Trends Cell Biol* 17(4):178–186.
41. Gottardi CJ, Gumbiner BM (2001) Adhesion signaling: how beta-catenin interacts with its partners. *Curr Biol* 11(19):R792–R794.
42. Nelson CM, et al. (2005) Emergent patterns of growth controlled by multicellular form and mechanics. *Proc Natl Acad Sci USA* 102(33):11594–11599.
43. Levental KR, et al. (2009) Matrix crosslinking forces tumor progression by enhancing integrin signaling. *Cell* 139(5):891–906.
44. Chang F, Lemmon CA, Park D, Romer LH (2007) FAK potentiates Rac1 activation and localization to matrix adhesion sites: A role for betaPIX. *Mol Biol Cell* 18(1):253–264.
45. Provenzano PP, et al. (2006) Collagen reorganization at the tumor-stromal interface facilitates local invasion. *BMC Med* 4(1):38.
46. Radisky DC, Przybylo JA (2008) Matrix metalloproteinase-induced fibrosis and malignancy in breast and lung. *Proc Am Thorac Soc* 5(3):316–322.
47. Samuel MS, et al. (2011) Actomyosin-mediated cellular tension drives increased tissue stiffness and β-catenin activation to induce epidermal hyperplasia and tumor growth. *Cancer Cell* 19(6):776–791.
48. Nelson CM, Khauv D, Bissell MJ, Radisky DC (2008) Change in cell shape is required for matrix metalloproteinase-induced epithelial-mesenchymal transition of mammary epithelial cells. *J Cell Biochem* 105(1):25–33.
49. Lopez JI, Kang I, You WK, McDonald DM, Weaver VM (2011) In situ force mapping of mammary gland transformation. *Integr Biol (Camb)* 3(9):910–921.
50. Butcher DT, Alliston T, Weaver VM (2009) A tense situation: Forcing tumour progression. *Nat Rev Cancer* 9(2):108–122.
51. Conklin MW, et al. (2011) Aligned collagen is a prognostic signature for survival in human breast carcinoma. *Am J Pathol* 178(3):1221–1232.
52. Humphrey JD (2001) Stress, strain, and mechanotransduction in cells. *J Biomech Eng* 123(6):638–641.
53. De R, Zemel A, Safran SA (2008) Do cells sense stress or strain? Measurement of cellular orientation can provide a clue. *Biophys J* 94(5):L29–L31.
54. Tee SY, Bausch AR, Janmey PA (2009) The mechanical cell. *Curr Biol* 19(17):R745–R748.
55. Kouros-Mehr H, Slorach EM, Sternlicht MD, Werb Z (2006) GATA-3 maintains the differentiation of the luminal cell fate in the mammary gland. *Cell* 127(5):1041–1055.
56. Lu P, Ewald AJ, Martin GR, Werb Z (2008) Genetic mosaic analysis reveals FGF receptor 2 function in terminal end buds during mammary gland branching morphogenesis. *Dev Biol* 321(1):77–87.
57. Gjorevski N, Nelson CM (2011) Integrated morphodynamic signalling of the mammary gland. *Nat Rev Mol Cell Biol* 12(9):581–593.
58. Goetz JG, et al. (2011) Biomechanical remodeling of the microenvironment by stromal caveolin-1 favors tumor invasion and metastasis. *Cell* 146(1):148–163.
59. Yamada KM, Cukierman E (2007) Modeling tissue morphogenesis and cancer in 3D. *Cell* 130(4):601–610.
60. Nelson CM, Inman JL, Bissell MJ (2008) Three-dimensional lithographically defined organotypic tissue arrays for quantitative analysis of morphogenesis and neoplastic progression. *Nat Protoc* 3(4):674–678.