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Rapid disorganization of mechanically interacting systems of mammary acini

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Cells and multicellular structures can mechanically align and concentrate fibers in their ECM environment and can sense and respond to mechanical cues by differentiating, branching, or disorganizing. Here we show that mammary acini with compromised structural integrity can interconnect by forming long collagen lines. These collagen lines then coordinate and accelerate transition to an invasive phenotype. Interacting acini begin to disorganize within 12.5 ± 4.7 h in a spatially coordinated manner, whereas acini that do not interact mechanically with other acini disorganize more slowly (in 21.8 ± 4.1 h) and to a lesser extent (P < 0.0001). When the directed mechanical connections between acini were cut with a laser, the acini reverted to a slowly disorganizing phenotype. When acini were fully mechanically isolated from each other and also from the bulk gel by box-cuts with a side length <900 μm, transition to an invasive phenotype was blocked in 20 of 20 experiments, regardless of waiting time. Thus, pairs or groups of mammary acini can interact mechanically over long distances through the collagen matrix, and these directed mechanical interactions facilitate transition to an invasive phenotype.

Significance

Tissue mechanics are important in differentiation and development but also in diseases like breast cancer. Most breast cancers start in mammary acini, which are basic anatomical units of the mammary gland. We found in a model system that mammary acini can coordinate their disorganization toward a malignant phenotype through long-range mechanical interactions. When two or more contractile acini are sufficiently close together, they can interact via collagen lines that form between them due to acinar contractility and the nonlinearity of collagen mechanics. Disorganization of interacting acini is more probable, rapid, and extensive than that of noninteracting acini. The results may help to better understand how extrinsic factors such as tissue architecture and mechanics contribute to tumor initiation and progression.


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remove the rBM. The wash procedure was developed to preserve overall acinar morphology but to mimic conditions intrinsic to a premalignant acinus, by compromising the acinar BM, as judged by the thickness of lamactin surrounding the acini, and weakening cadherin-based adherens junctions, as judged by reduction of β-catenin signal from cell-cell interfaces (Fig. S1 A and B). Thinning of the BM enables the acini to sense and engage the collagen matrix and weakening of cadherin-based adherens junctions destabilizes tissue integrity to increase lamellipodia activity (29) and actomyosin traction-driven cell scattering (30), which mirrors a genetically primed acinus that precedes transition to an invasive and metastatic tumor. Thus, treated acini deposited on rBM remained intact, as expected, because rBM supports normal development of the cells into polarized and growth-arrested structures (27, 28). However, acini allowed to settle on collagen 1 disorganized within several hours (Fig. 1 A and B), a process involving disruption of basal tissue polarity (11). The fraction of acini that disorganized depended on the duration of the Tris/EDTA wash step and the degree of disorganization depended weakly on bulk collagen concentration, consistent with previous reports (11) (Fig. S1 C and D).

To relate acinar morphology to collagen organization, we labeled the collagen with a novel reagent: photoactivatable CNA35-mEos2 collagen binding protein. This reagent can be photo-activated where and when desired, allowing collagen pulling and alignment, as well as large-scale substrate deformation to be visualized. We seeded about 200 acini on a 1-cm² block of 2 mg/mL collagen 1 and followed the acini-collagen system for up to 40 h (Fig. 1 C and D and Movie S1). As expected based on the previous literature (8, 10), the acini concentrated the collagen around and among them (Movies S2–S6), yielding pairs and clusters of acini interconnected by lines of intense collagen signal. By about 10 h, some of the acini began to disorganize, and by 20 h, many acini had lost their regular, spherical morphology, and single cells were leaving the acini and scattering on the collagen.

A closer look at the interface between collagen and acinar protrusions shows extensive alignment of the actin network among multiple cells, and in turn, this multicellular patch of aligned actin runs parallel to the adjacent extracellular collagen network, suggesting a tension generating actomyosin network acting on an elastic collagen gel (Fig. S2 and Movie S7). Indeed, the Y27632 Rho-associated protein kinase (ROCK) inhibitor (31) and the blebbistatin (32) nonmuscle myosin inhibitor significantly reduced acinar disorganization (Fig. S3). In addition, the inhibitors had a strong effect on the collagen lines. Line formation was reduced 54% by 0.5 μM blebbistatin, a concentration that is expected to reduce the ATPase rate of myosin II by only ~10% (33). The sensitivity of the system to impairment of myosin II contractility suggests that line formation requires very high contractility. The tensions generated by the acini are transmitted to the collagen by integrins, because inhibition of focal adhesion kinase (FAK) and Src kinase by PP1 attenuated mechanical collagen remodeling (P values in Fig. S3).

Having confirmed the basic molecular and cellular aspects of line formation, we asked whether there was a correlation between the collagen lines and the rate of acinar disorganization. Specifically, we asked whether the presence of a directed collagen line between two acini affected their disorganization. We studied \( n = 162 \) contractile acini. All acini gradually concentrated the collagen and aligned it (Fig. 2 A–C and Fig. S4). Of the 162 acini, \( n = 104 \) interacted with other acini and \( n = 58 \) noninteracting acini were well separated from other acini and did not extend collagen lines to other acini. We used the acinar surface area \( A \) as our primary descriptor of acinar state; initially, acini had a mean area of \( A = 0.046 ± 0.025 \) mm². We compared the time to disorganization for the interacting and noninteracting acini and found that interacting acini began to disorganize earlier than noninteracting acini (time to 20% area increase, 12.5 ± 4.7 h (interacting) vs. 21.8 ± 4.1 h (noninteracting); two-sided \( t \) test, \( P < 0.0001 \)), resulting in markedly distinct distribution functions in a Kaplan–Meier survival analysis, with the events defined as acinar disorganization (Fig. 2D; log-rank \( P \) value for difference, \( P < 0.0001 \)). The area of interacting acini increased more rapidly than that of noninteracting acini (Fig. S2; log-rank \( P \) value for difference, \( P < 0.0001 \)). Finally, interacting acini disorganized to a greater extent than noninteracting acini ([total area increase within 24 h: 1.62 ± 0.33 (interacting) vs. 1.09 ± 0.11 h (noninteracting); two-sided \( t \) test, \( P < 0.0001 \)). Therefore, mechanically interacting acini disorganize earlier, faster, and to a greater extent than noninteracting acini. These conclusions are robust toward changes of event definition, such as use of other morphological features, for example, sphericity to follow disorganization, or use of a phenotypic metric, such as the time to onset of cell streaming (22.1 ± 9.3 h (interacting) vs. 35.0 ± 7.3 h (noninteracting); Fig. S5).

Next, we asked whether the dynamics of line formation, rather than binary presence or absence of a line connecting two acini, were correlated with the dynamics of acinar disorganization. Acini began to mechanically remodel their matrix at \( t ∼ 3 \) h (Fig. 2 E and F), lines formed when contractile acini were within about 1.2 mm of one another, and thus interacting acini began to spread as early as \( t = 5 \) h. Two of 58 noninteracting acini (Fig. 2E, stars) also disorganized rapidly despite not visibly interacting with other acini through the collagen substrate; we attribute those two exceptions to the presence of one or more nearby contractile acini that are outside of the imaging region of interest. The ability of interacting acini to contract their substrate was inherently self-limiting, because the acini began to scatter at \( t > 10 \) h (which necessarily reduces acinar contractility; note plateau of collagen velocity at \( t = 7–11 \) h; Fig. 2F, dashed line), and in some very rare cases, the interacinar tensions were high enough to tear the collagen line (Movie S8, lower left corner).

Fig. 1. Mechanical remodeling of collagen substrates by mammary acini. (A) Schematic of experiment. Acini are placed on collagen 1 gels and subsequent disorganization is quantified. (B) Acini allowed to settle on collagen gels gradually disorganize as shown by changes in acinar morphology (nuclei stained blue) and actin cytoskeleton (red). (C) Low-magnification overview of a system of ~200 acini (red) on collagen 1 (green). Initially, the collagen is uniformly distributed and the acini are intact. (D) System of ~200 acini after 20 h. Many acini (red) have disorganized into single cells (tiny red dots), which are scattering. The collagen has been extensively reorganized; the average green signal has dropped and bright green collagen lines run along geodesics between acini.
which immediately reduces the tensions within the material. Interacinar interaction resulted in more rapid collagen pulling visualized by embedded bead movements compared with non-interacting acini (P < 0.001 between 3 and 13 h; Fig. 2F). Indeed, the rapidity of early bead pulling was weakly correlated (r ~ 0.35) with the time at which cells began to stream from an acinus (ANOVA P value for interacting acini: P = 0.00059; Fig. S6A), despite cell streaming occurring many hours after the time of maximum bead pulling. Interacting acini disorganized in a spatially correlated manner, because their protrusions pointed toward one another (Movies S8–S12), and on disorganization, the majority of cells and cell aggregates streamed along the collagen line from one acinus toward its partner(s) (Fig. S6B and Movies S9, S11, and S12). For example, as shown in Movie S12, at frame 00:29, 24 of 28 streaming cells are moving along lines connecting acini. Therefore, interacting acini manipulate the collagen in a manner that is quantitatively distinct from noninteracting acini, and these differences are correlated with phenotypic differences at the acinar level, such as morphology and the rapidity with which an invasive phenotype is seen.

These experiments suggested a connection between collagen lines and rapid acinar disorganization, but a statistical analysis does not address causality. We therefore used a UV laser to cut deep grooves into the gel, severing specific collagen lines (Fig. 3A, dashed white line), inspired by the use of UV lasers to study and alter the mechanics in developing fly embryos (34, 35). Laser cutting of the collagen was performed at distances of >300 μm from any acini to avoid potential phototoxity. On severing the interconnecting collagen line between acini (Fig. 3A), they still disorganized, but more slowly and without directional bias. Although the simple line cut as shown in Fig. 3A reduced the rate of disorganization and directional preference, some interacting acini were able to ultimately bypass the defect in the gel and reconnect by new lines, which then ran along the geometrically shortest path around the cut region (Fig. 3B, arrows, gap bypass). We therefore turned to a different cutting geometry, in which the acini are fully mechanically isolated from other acini and the rest of the gel via a complete box cut with a side half-length r of 0.30 mm (Fig. 3C and D). After being isolated by a box cut, the acini remained contractile but, strikingly, did not spread or scatter at all: 20 of 20 acini remained intact even after a waiting period of t = 40 h. The mechanically isolated acini were still markedly contractile, as seen by a bright ring of concentrated collagen that formed around them (Fig. 3D, arrow) but they did not spread or scatter. This lack of spreading or scattering is surprising because the mechanically isolated acini concentrated the collagen more than noninteracting or interacting acini, resulting in very high collagen densities (Fig. 3E, green curve). Therefore, the bulk
Mechanical reprogramming of protrusion site and direction. Initially, Movie S12 Shi et al. and 7 h. Then at | 15 h, acinus 1 begins to pull more rapidly than t 200 μm dashed white line). (D) Mechanical control of transition to invasive phenotype. (10 h due to time needed to move acini from laser and C D 10 25 15.2 h (arrow, v) 20 experiments). r 0.30 mm, namely, 17.8 h), acinus 2 v − to 0.45 mm, all acini spread ∼ − > 0.45 and 0.60 mm. We assessed the acini for spreading/scattering and change of circularity. The latter measure is easier to quantify automatically on our high-throughput imaging system than the former. Indeed, inspection of three-acinus systems (Fig. 4) suggests that acini are particularly sensitive to the tensile stresses acting on them. In a typical three-acinus system, two of them interacted creating a collagen line between them, and then, after some delay, the third acinus began to pull collagen. We saw several cases in which the third acinus was able to partially erase the initial collagen line; then, new lines formed as the old line(s) faded. For example, although acinus 2 initially began to protrude toward acinus 3, acinus 2 ultimately disorganized and scattered toward acinus 1, which had the larger collagen pulling rates (Fig. 4, Fig. S7, and Movie S12). As shown in the time traces, acinus 1 began to pull more strongly than acinus 3 at t = 15.2 h (arrow, v1 > v2). In the following 2.6 h (15.2 < t < 17.8 h), acinus 2’s initial protrusion subsided and a new protrusion, now pointing toward acinus 1, developed (lower trace, arrow, reorientation of main protrusion). Thus, acini are sensitive to substrate mechanics throughout the disorganization process, and distant mechanical changes lead to subtle changes within tens of minutes and in large phenotypic changes within about 3 h.

Over which distances do the mechanical cues extend within the substrate? As quantified by tracking fluorescent beads within the gel, via fluorescent fiducial grids written into the collagen by gel, via fluorescent fiducial grids written into the collagen by...
localized activation of CNA35-mEos2 or polarization microscopy, acini deformed the collagen over hundreds of micrometers (Figs. S8 and S9 and Movies S14 and 15). Noninteracting acini concentrated and aligned the collagen over distances of at least 550 μm (Fig. S9B). When two or more contractile acini were within ~1.2 mm of one another, lines formed (Fig. S9 C and E–G), and they extended with little spatial decay over distances of hundreds of micrometers to millimeters (note flat central region of Fig. S9C).

We note that that basic mechanical and polymer-physical considerations indicate that the characteristics of the lines, including their length and width, where they will form, will be functions of multiple variables, such as acinar contractility, the strength of cell-cell adhesions, the substrate, and the spatial density and relative arrangement of acini. For example, multicellular structures with reduced cell-cell cohesion would be expected to have impaired ability to form collagen lines. We tested this idea by growing multicellular structures from Michigan Cancer Foundation-7 (MCF-7) cells and then quantifying the extent of line formation and disorganization. The MCF-7 cell line was originally derived from a patient with invasive ductal carcinoma, represents an advanced stage of tumor progression (37, 38), and has further compromised integrity of cell-cell adhesion (39, 40). When grown, extracted, and deposited on collagen I like the MCF10AT acini, the MCF-7 spheroids more readily spread as expected, although some MCF-7 spheroids were able to form collagen lines (Fig. S9D) along which streaming cells then traveled, just as in the MCF10AT experiments, the intense collagen lines were now very rare, with only ~10% of structures generating a line compared with more than 80% of the MCF10AT acini. Indeed, the majority of MCF-7 spheroids disorganized rapidly without strongly aligning the collagen around them, suggesting that substrate mechanics play a smaller role in their disorganization and/or that MCF-7 spheroids have a smaller critical tension/alignment needed to trigger disorganization.

We then turned our attention to the motile cells that were leaving the acini along the collagen lines formed by the MCF10AT acini. The single cells’ motility and morphology, including their long and thin projections, were reminiscent of mesenchymal cells, raising the possibility of an epithelial-to-mesenchymal transition (EMT). We used immuno-fluorescence mapping of intact acini and single spheroids from disorganizing acini to quantify the levels and subcellular distributions of three classic EMT markers: E-cadherin, β-catenin, and vimentin (Fig. 5 A–D). A primary step in acinar disorganization and appearance of motile single cells is the weakening of cell-cell junctions through reduction of E-cadherin levels (41) and the loss of cytoplasmic β-catenin. Although E-cadherin is a hallmark of the epithelial cell state, the intermediate filament protein vimentin is selectively up-regulated in mesenchymal cells (42). A combination of high vimentin, changes in the levels and/or location of E-cadherin and β-catenin, and accelerated mobility of disseminating cells have been equated with an EMT (43). As shown in Fig. 5 A–D, the cells at the top and the sides of the acini had the expected epithelial signatures, including high levels of E-cadherin and β-catenin and low or no vimentin. By contrast, cells at the collagen/acini interface, especially the single migratory cells on the collagen lines, had reduced E-cadherin and β-catenin but high vimentin (Fig. S9). Together with the phenotypic changes, the molecular changes in the cells at the collagen/acini boundary and in the streaming cells are consistent with the possibility of an EMT occurring as the cells leave their parent acini and travel along the collagen lines. Additional work, especially studies of the dynamics and reversibility of the transition, will be needed to formally prove a classical EMT.

How might cells at the substrate-acinus interface sense mechanical cues and what might those cues be? The collagen lines resisted lateral deformation by an atomic force microscope (AFM) cantilever eightfold more than unaligned control regions (Fig. S10 A–E), suggesting that the lines were mechanically loaded by contractile acini at either end. Cells leaving the acini along lines had nuclear localization of the Yap/Taz mechano-transducer (44), indicating tension on the cells’ actomyosin cytoskeleton (Fig. 5E, Fig. S10, and Movie S16) and showing that the cells were sensing the altered environment.

The phenomena reported here constitute a collective biological signaling mechanism where the polymer-physical properties of the extracellular material are fundamental to signal generation and its spatial propagation and duration. When two or more contractile acini are within a material’s dependent distance (in our conditions, typically ~1.2 mm) of one another, their collagen pulling fields overlap; lines then form and mechanically interconnect the acini. It is already known that acini disorganize in a dose-dependent manner on inappropriately hard matrices (11). Here, the acini themselves mechanically remodel the matrix, resulting in several fundamentally connected changes within the gel (tensile stresses; alignment; and directional stiffening), which then drive and coordinate changes in acinar behavior, morphology, and protein localization (Fig. S11). One simple explanation for our observations is that the decision of an acinus to transition to an invasive phenotype is significantly influenced by the magnitude of the tensile stress acting on it and that there is a threshold beyond which tensile stress drives a malignant transformation, although a response to collagen alignment is also compatible with all observations. The relative contributions of collagen alignment and the tensile stress to disorganization remain unclear and await further study. The possible importance of the tensile stress in our system is consistent with the broader mechanobiology literature, such as the finding that scattering of epithelial cell monolayers is regulated by integrin-dependent actomyosin contraction (30). Interestingly, the box-cut experiments show that spreading/scattering can be entirely blocked by suitable mechanical intervention (Fig. 3), whereas small
molecule inhibition of actomyosin contractility and Rho-ROCK signaling reduces but does not entirely block spreading/scattering (Fig. S3). Therefore, there must exist at least one more presently unknown mechanosensitive mechanism for acinar transition to an invasive phenotype, which awaits further study.

**Methods**

A detailed description of methods and materials is given in the SI Methods. Briefly, cell line maintenance, acini preparation, and immunostaining followed standard protocols (28, 45). Collagen gels were prepared according to the manufacturer's instructions. Acini were isolated from Matrigel using ice-cold Tris buffer/EDTA (45). The CNA35 collagen binding protein cDNA (a gift of the manufacturer) allowed standard protocols (28, 45). Collagen gels were prepared according to methods and materials is given in the SI Methods. Briefly, cell line maintenance, acini preparation, and immunostaining followed standard protocols (28, 45). Collagen gels were prepared according to the manufacturer’s instructions. Acini were isolated from Matrigel using ice-cold Tris buffer/EDTA (45). The CNA35 collagen binding protein cDNA (a gift of the manufacturer) allowed standard protocols (28, 45). Collagen gels were prepared according to

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