Extracellular matrix stiffness causes systematic variations in proliferation and chemosensitivity in myeloid leukemias

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Extracellular matrix stiffness influences biological functions of some tumors. However, it remains unclear how cancer subtypes with different oncogenic mutations respond to matrix stiffness. In addition, the relevance of matrix stiffness to in vivo tumor growth kinetics and drug efficacy remains elusive. Here, we designed 3D hydrogels with physical parameters relevant to hematopoietic tissues and adapted them to a quantitative high-throughput screening format to facilitate mechanistic investigations into the role of matrix stiffness on myeloid leukemias. Matrix stiffness regulates proliferation of some acute myeloid leukemia types, including *MLL-AF9*$^+$ MOLM-14 cells, in a biphasic manner by autocrine regulation, whereas it decreases that of chronic myeloid leukemia *BCR-ABL*$^+$ K-562 cells. Although Arg-Gly-Asp (RGD) integrin ligand and matrix softening confer resistance to a number of drugs, cells become sensitive to drugs against protein kinase B (PKB or AKT) and rapidly accelerated fibrosarcoma (RAF) proteins regardless of matrix stiffness when *MLL-AF9* and *BCR-ABL* are overexpressed in K-562 and MOLM-14 cells, respectively. By adapting the same hydrogels to a xenograft model of extramedullary leukemias, we confirm the pathological relevance of matrix stiffness in growth kinetics and drug sensitivity against standard chemotherapy in vivo. The results thus demonstrate the importance of incorporating 3D mechanical cues into screening for anticancer drugs.

matrix stiffness | systems pharmacology | biomaterials | drug screening | cancer

Myeloid leukemias originate from the hematopoietic stem cell compartment in bone marrow (BM) after oncogenic mutations. For instance, a translocation between parts of the human chromosome 22 and 9 results in the *BCR-ABL* fusion gene that causes chronic myeloid leukemia (CML) (1). Some translocations involving the mixed lineage leukemia (*MLL*) gene in the human chromosome 11, band q23, such as the *MLL-AF9* fusion gene, are involved in acute myeloid leukemia (AML) (2). In addition to mutations, hematopoietic microenvironments can contribute to pathogenesis and progression of myeloid leukemias (3). Both oncoproteins and cell-extrinsic factors are known to perturb various signaling pathways that regulate key biological processes in cancer. For instance, AKT/PKB (protein kinase B) is a major signaling node downstream of activated tyrosine kinases and phosphatidylinositol 3-kinase and has been targeted by a number of drugs to inhibit cancer cell survival and growth (4). Recently, physical cues from microenvironments have emerged as important regulators of tumor biology, such as extracellular matrix stiffness and collagen architecture (5, 6). Matrix stiffness also regulates normal hematopoiesis (7, 8). However, the relevance of physical cues to blood cancer remains largely unclear. Importantly, how different cancer subtypes with distinct oncogenic mutations respond to matrix stiffness also remains to be investigated.

Recent studies highlight the utility of adapting 3D culture into a high-throughput screening assay to better predict in vivo efficacy of anticancer drugs compared with conventional 2D culture (9, 10). However, physical properties of microenvironments were not considered in this assay format for cancer drug discovery. Effects of matrix stiffness on chemosensitivity were previously evaluated with breast cancer (11) and hepatocellular carcinoma cells (12) on 2D hydrogel systems, and with melanoma cells in 3D hydrogel systems (13). However, it is not clear whether these in vitro results inform in vivo drug efficacy. In general, it is largely unknown whether 3D matrix stiffness systematically influences responses of cancer cells to different drugs and potentially contributes to a failure to eradicate residual disease.

Here, we introduce a niche-based quantitative biophysical screen to evaluate the impact of 3D matrix stiffness on proliferation and drug sensitivity of different human myeloid leukemia subtypes. First, we altered mechanical properties of hydrogels so that they can closely mimic a range of physiological tissue stiffness relevant to the hematopoietic system. Leukemia cells were then encapsulated in the hydrogels and dispensed into a 96-multiwell assay format. Mechanistic studies using this system revealed distinct growth patterns and pharmacodynamics profiles of drugs against different leukemia subtypes as a function of matrix mechanics, highlighting relationships between genetic mutations and physical environments. Finally, the same hydrogel system was used in an in vivo xenograft model to validate the in vitro findings that matrix softening leads to resistance against standard chemotherapy.

Results

Matrix Mechanics Differentially Regulates Proliferation of Myeloid Leukemia Subtypes. When blood cells differentiate in the BM and traffic into the circulation, they transit from a solid-phase

Significance

Most chemotherapy drugs treat, but do not cure, cancer patients due to resistance. New high-throughput screening assays are emerging to better predict drug efficacy by recapitulating tumor microenvironments with three-dimensional hydrogels. Our platform exploits the mechanical tunability of alginate hydrogels to introduce biophysical cues into screening assays. The utility of this approach is demonstrated with the findings of unique modes of growth modulation by matrix stiffness and mechanosensitivity of drug actions in different myeloid leukemia subtypes. The same hydrogels were then adapted to confirm in vivo that matrix softening accelerates cancer growth kinetics and causes resistance to standard chemotherapy. We anticipate that this integrative workflow will be broadly useful to discover drugs that target cancer cells in different physical environments.

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microenvironment to a viscous phase (14) (Fig. 1*A*). A similar transition also occurs outside the BM ("extramedullary" sites) when peripheral blood cells undergo intravasation from tissues. To generalize this mechanical transition, alginate was used to form hydrogels, because ionic cross-linking controls hydrogel stiffness independent of pore size, ensuring constant diffusion of molecules up to hundreds of kilodaltons (15). Importantly, adhesion ligands can be conjugated at different densities and controlled independent of stiffness. The hydrogel was conjugated with different densities of the Arg-Gly-Asp (RGD) peptide, which binds preferentially to $\alpha_5\beta_1$ and $\alpha_v\beta_3/\beta_5$ integrins, mixed with leukemia cells and ionically cross-linked to provide varied stiffness, ranging from soft solid (Young's modulus, E = 0.075~3 kPa) to viscous uncross-linked (E = "0" kPa) matrix in 96-well plates (Fig. S1*A*). Because the BM is generally viscoelastic (16), ionic cross-linking is more appropriate than covalent cross-linking because of the stress relaxation behavior (17). The average E for in situ BM is ~0.3 kPa (8). The minimum E achieved with alginate hydrogels is ~0.075 Pa (5), whereas ~3 kPa is close to the E of a number of soft tissues (18) or stiffer parts of the marrow. Without cross-linking, the alginate fluid in this study recapitulates the known viscosity value of blood under low shear (~40 cP) (16). This platform thus allows individualized ex vivo testing of disease progression and drug sensitivity in a high-throughput format, which could inform personalized therapies to target cancer cells in different biophysical environments (Fig. 1*A*).

We characterized how different myeloid leukemia subtypes with distinct genetic mutations respond to varied stiffness and ligand density. A representative human cell line from each myeloid leukemia subtype was used: AML with *MLL-AF9* (MOLM-14), AML without *MLL-AF9* (U-937), and CML with *BCR-ABL* (K-562). These cells are known to express $\alpha_5\beta_1$, which binds to the RGD sequence in fibronectin (19). In general, leukemia cells grow as amorphous aggregates in the viscous matrix and as single large spheres in the solid matrices (Fig. 1*A*). In all cases, there is a net increase in cell number of at least ~10-fold at day-7 culture. Within this time frame, AML cells show biphasic proliferation responses across matrix mechanics whereas CML cells show a stiffness-dependent decrease in cell number (Fig. 1*B*). Increasing RGD density significantly increases the maximal cell number at 0.3 kPa for MOLM-14, whereas it shifts the curve to the right for U-937. In contrast, ligand density does not significantly affect proliferation of K-562. Therefore, this screen is potentially useful to resolve each myeloid leukemia subtype based on distinct proliferation profiles as a function of matrix mechanics.

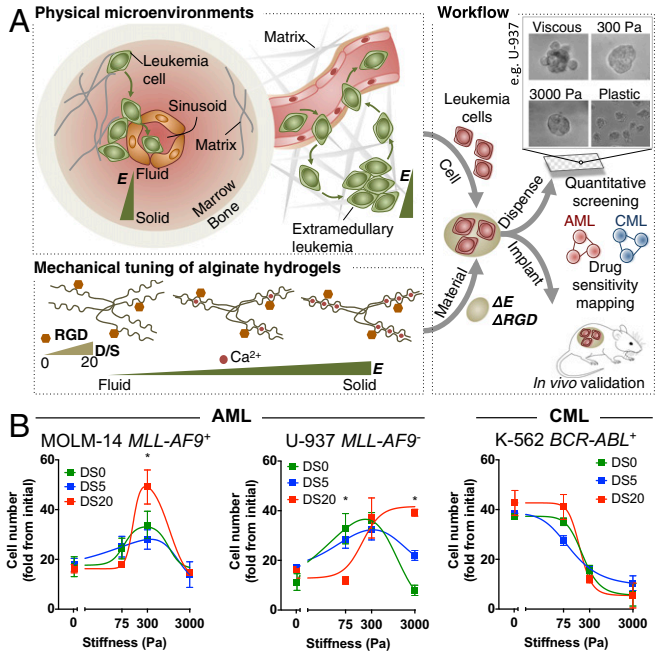

Fig. 1. Development of an integrative approach to systematically investigate the role of matrix mechanics in myeloid leukemias. (*A*) Schematic showing recapitulation of mechanical properties relevant to the hematopoietic system by ionic cross-linking of alginate hydrogels, followed by adaptation of the 3D hydrogels into quantitative screening and animal validation. (*B*) Different myeloid leukemia subtypes show distinct proliferative responses against matrix mechanics and ligand density. Ligand density is controlled by "degree of substitution" (DS), which indicates the number of RGD peptides conjugated per alginate molecule (0~20). The whole cell population was used for viability analysis. The data were fit to biphasic dose–response curves for AML cells and standard dose–response inhibition curves for CML cells. *$P < 0.05$ from one-way ANOVA with Tukey's honestly significant difference (HSD) test.

Autocrine Feedback Is Sufficient to Explain the Biphasic AML Growth with Matrix Stiffening. To explore mechanisms behind the biphasic response of AML cells, we asked whether matrix stiffening represents a component in biological circuits that can carry out two simultaneously opposing effects on cell growth and death. Because leukemia cells secrete a number of cytokines that can serve as autocrine signals (20), we hypothesized that matrix stiffening increases AML proliferation, but also leads to secretion of soluble factors that affect cell death. We first addressed this hypothesis by developing a computational model with a set of ordinary differential equations. In this model, the cell proliferation rate and the factor secretion rate depend on matrix stiffness in a sigmoidal function (Michaelis–Menten kinetics), whereas the cell death rate depends on the concentration of soluble factors in a linear function (Fig. 2 *A*, *i*). This model is sufficient to show a biphasic growth pattern with matrix stiffening (*SI Methods*) and simulate the experimental results with AML cells. Two parameters are important: (*i*) potency of factor secretion in response to matrix stiffening [E at half maximal $\delta(E)$: "δE_{50}" in pascals] and (*ii*) potency of cell proliferation in response to matrix stiffening [E at half maximal $\beta(E)$: "βE_{50}" in pascals]. Higher values of these two parameters mean lower sensitivities. Interestingly, increasing δE_{50} alone increases the amplitude of the biphasic curve (Fig. 2 *A*, *ii*), whereas increasing both δE_{50} and βE_{50} shifts the curve to the right (Fig. 2 *A*, *iii*). The curves generated from an analytically derived equation also recapitulate this trend (*SI Methods*). These two results simulate the growth profiles of MOLM-14 and that of U-937, respectively. The results also predict that increasing the RGD ligand density should decrease the sensitivity of factor secretion upon matrix stiffening in MOLM-14 cells, whereas it should decrease both the sensitivity of factor secretion and that of cell proliferation upon matrix stiffening in U-937 cells. Consistent with this model, the conditioned media derived from cells in the matrix at 3 kPa suppress proliferation of AML cells cultured on plastic (Fig. 2*B*), as contrasted to conditioned media from cells cultured in softer gels or on plastic. The cell number at the time of collecting the conditioned media (week 1) remains the same across different conditions (Fig. 1*B*). The results can also be potentially explained by decreased secretion of proliferation promoting factors. Some cytokines are secreted in an autocrine manner to simultaneously regulate both cell growth and death, and this paradoxical regulation can be required to maintain stable steady-state cell concentrations (21). However, mathematically, no biphasic relationship between cell number and matrix stiffness exists in a model when secreted factors directly regulate both cell growth and death rates (*SI Methods*). Although more complex scenarios are possible, the goal here is to identify a parsimonious model to explain the experimental data using a minimal number of variables and functions. The results thus indicate that an autocrine feedback mechanism could regulate the biphasic AML growth induced by matrix stiffening.

Modulation of the Mechanosensitive AML Growth by Inhibition of AKT. AKT becomes more phosphorylated with matrix stiffening (5) and is required for autocrine secretion in some solid tumor cells (22).

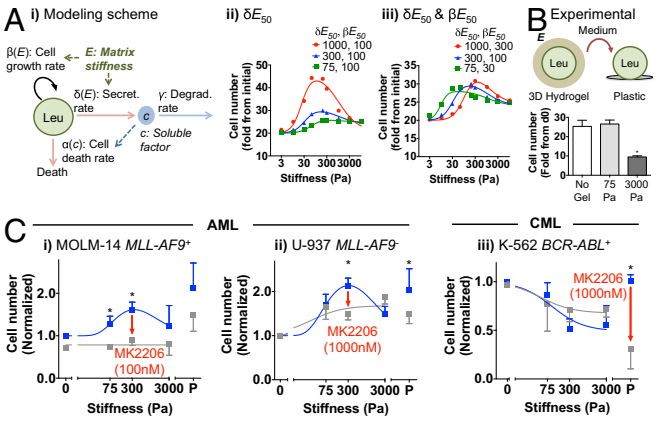

Fig. 2. Matrix stiffness regulates AML cell proliferation through autocrine signaling. (*A*) Simulations by a set of ordinary differentiation equations (*SI Methods*) mimic the biphasic cell proliferation of AML cells. (*i*) A modeling scheme showing an autocrine feedback circuit. $\alpha(c)$, rate of cell death as a function of soluble factor concentration; $\beta(E)$, rate of cell proliferation as a function of *E;* $\delta(E)$, rate of soluble factor secretion as a function of *E;* γ, natural decay rate of soluble factors; *c*, soluble factor concentration; Leu, leukemia cells. The simulation results from (*ii*) increasing δE_{50} alone and (*iii*) increasing both δE_{50} and βE_{50}. The data were fit to biphasic dose–response curves. (*B*) MOLM-14 cells secrete factors that inhibit cell proliferation when cultured in 3D stiff gels. (*Top*) An experimental scheme. (*Bottom*) Total viable cell number after 7 d in the conditioned media from cells in different matrix stiffness. No Gel, 2D culture on plastic. $n = 3$ experiments, $^*P < 0.05$ from one-way ANOVA with Tukey's HSD test, 25 vs. 1,000 Pa. (*C*) Total leukemia cell numbers in 3D hydrogels with or without the presence of the AKT inhibitor MK-2206. The cell numbers from different conditions were normalized against that in the viscous matrix without drug treatment. The whole cell population was used for viability analysis. The data were collected from cells in alginate hydrogels with DS20 RGD. P on the *x* axis, 2D culture on plastic. $n = 4$ experiments, $^*P < 0.05$ from one-way ANOVA with Tukey's HSD test, control vs. MK-2206.

We thus explored whether inhibition of AKT reverses the biphasic AML growth with matrix stiffening. MK-2206 (MK) is an inhibitor against AKT that is in a clinical trial for treatment of solid tumors (23). Interestingly, MK equalizes the number of MOLM-14 across different stiffness at a dose close to IC_{50} (100 nM) (Fig. 2 *C*, *i*). The effect is moderate but significant for U-937 at a higher dose (1,000 nM) (Fig. 2 *C*, *ii*). Consistent with these results, the IC_{50} for suppressing cell proliferation by MK is generally similar regardless of culture environments for AML cells (Fig. S1*B*). Regardless of the basal level of phosphorylated AKT (pAKT) in different AML cells across different matrix stiffness (Fig. S1*C*), MK decreases pAKT in both AML cells with IC_{50} ~50 nM at 300 Pa (Fig. S1*D*). The results thus suggest that AKT inhibition can reverse the matrix stiffness-induced biphasic AML growth because the sensitivity of the AML cells to MK is independent of matrix stiffness.

Matrix Stiffness Modulates Chemosensitivity: Systematic Characterization by Biophysical Screening. In contrast to AML MOLM-14 and U-937 cells, CML K-562 cells become resistant to MK in 3D matrices, whereas they respond to MK on plastic (Fig. 2 *C*, *iii*). Indeed, K-562 cells show 10~20-fold higher IC_{50} values of MK in 3D matrices than on plastic (Fig. S1*B*). Therefore, the same target can exhibit differential chemosensitivity with matrix mechanics in a leukemia cell-type-dependent manner. This motivated broader investigations into how different molecular targets show chemosensitivity as a function of matrix mechanics. To achieve this goal, we first performed dose–response characterization of select drugs against K-562 cells in our screen system. To facilitate this investigation in a high-throughput format, K-562 cells were virally transduced with mCherry and firefly luciferase (Fig. S2*A*). The clone 3 shows similar proliferation kinetics as the whole cell population (Fig. S2*B*) and was used in subsequent studies. Fluorescence signals are linearly proportional to the number of viable cells in hydrogels (Fig. S2*C*).

The tested drugs are either approved by the Food and Drug Administration for treatment of cancers or used to perturb targets involved in mechanotransduction (Table S1). K-562 cells do not respond to two of the tested drugs, including fasudil (Rho-kinase inhibitor) and ruxolitinib (JAK inhibitor). Interestingly, hierarchical clustering analysis of IC_{50} values across different stiffness classifies the remainder of the tested drugs into three categories for K-562 cells (Fig. 3*A*). First, cells become resistant to ~28% of the tested drugs, including doxorubicin and MK, in the RGD ligand-conjugated hydrogel, regardless of matrix stiffness ("class I"). Second, cells are sensitive to ~44% of the drugs, including imatinib, a clinically used inhibitor against CML, and cytosine arabinoside (Ara-C), in a matrix stiffness-dependent manner ("class II"). Third, cells respond to drugs that target the RAF/MAPK pathway (Sorafenib, PD-98059) and the JNK pathway (SP-600125) with similar IC_{50} values across different matrix stiffness ("class III"). Indeed, IC_{50} values are significantly decreased upon matrix stiffening for class II but not for class I and III drugs (Fig. S3*A*). The negative correlation observed with class II drugs is still significant when drugs from all of the classes are combined (Fig. S3*B*). The same trend is also observed with the area under curve (AUC) parameter considering all of the drug classes (Fig. S3*C*), as expected because IC_{50} and AUC generally correlate with each other (24). No significant trend was observed with the Hill slope (m) parameter (Fig. S3*D*), suggesting that potency is a unique parameter that can be used to classify drugs as a function of matrix mechanics.

Dose–response of the same select drugs was also characterized against MOLM-14 cells for systematic comparison with K-562 cells. Hierarchical clustering again classifies these drugs into class I–III for MOLM-14 cells (Fig. 3*B*). Some of the tested drugs belong to different classes with MOLM-14 cells, compared with K-562 cells. Interestingly, MK is a class III drug, whereas drugs against RAF/MAPK and JNK belong to class II with MOLM-14 cells (Fig. 3*B*). The resistance of both K-562 and MOLM-14 cells against their class I and class II drugs was found to depend on the presence of RGD, because the absence of RGD in the hydrogel abolishes differences in IC_{50} between the hydrogel and plastic or across matrix stiffness (Fig. S4*A*). The results thus suggest that *BCR-ABL*$^+$ K-562 cells are sensitive to inhibition of the RAF/MAPK pathway but not the AKT

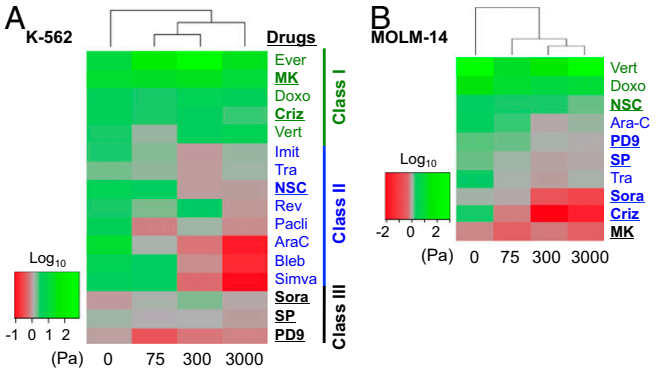

Fig. 3. Matrix stiffness regulates drug sensitivity against distinct targets in myeloid leukemia subtypes. IC_{50} values from (*A*) K-562 cells (clone 3, Fig. S2*B*) and (*B*) MOLM-14 cells (the whole cell population) treated with select drugs (for full name and target pathway of each drug, see Table S1) in 3D hydrogels conjugated with the RGD peptide (DS = 5) were normalized by respective IC_{50} values from plastic, and then log-transformed before hierarchical clustering analysis. Drugs are classified into three classes: class I (ligand sensitive), class II (ligand and matrix stiffness sensitive), and class III (mechanics independent). The data were derived from $n \geq 15$ experiments for *A* and $n \geq 4$ experiments for *B*. Bold, underlined drugs belong to different classes in K-562 and MOLM-14 cells.

pathway, whereas the opposite trend is observed with *MLL-AF9*$^{+}$ MOLM-14 cells.

We thus sought to better understand how gene products that define leukemia subtypes affect the regulation of chemosensitivity by matrix mechanics. A physical interaction network was computationally constructed from a list of experimentally verified protein–protein interactions from curated databases (*SI Methods*). The network shows that BCR and ABL1 proteins interact more directly with the RAF/MAPK pathway components but less with the AKT pathway components (Fig. S4*B*). The opposite trend is observed with AF9 (*MLLT3*) protein. Based on the results in Fig. 3, the network analysis suggests a possibility that *BCR-ABL* and *MLL-AF9* confer sensitivity to RAF/MAPK and AKT inhibitors, respectively, regardless of matrix stiffness. To test this idea, retroviral transduction was used to introduce *BCR-ABL* and *MLL-AF9* to MOLM-14 and K-562 cells, respectively, followed by drug studies. Cells transduced with empty vectors were used as control (Fig. S5*A*). The protein expression level of MLL-AF9 introduced in K-562 cells is comparable to the endogenous level in MOLM-14 cells, whereas the expression level of BCR-ABL in MOLM-14 cells is comparable to the endogenous level in K-562 cells (Fig. S5*B*). *MLL-AF9* significantly increases the sensitivity of K-562 cells against MK across different matrix stiffness (Fig. 4 *A*, *i*), switching the class from I to III (Fig. 3*A*), whereas it does not cause resistance against sorafenib (Fig. 4 *A*, *ii*). However, *BCR-ABL* increases the sensitivity of MOLM-14 cells against sorafenib, switching the class from II to III (Fig. 3*B*), whereas it does not cause resistance against MK (Fig. 4*B*). Therefore, some oncogenes can decouple the dependence of chemosensitivity against specific pathways on matrix ligand or stiffness.

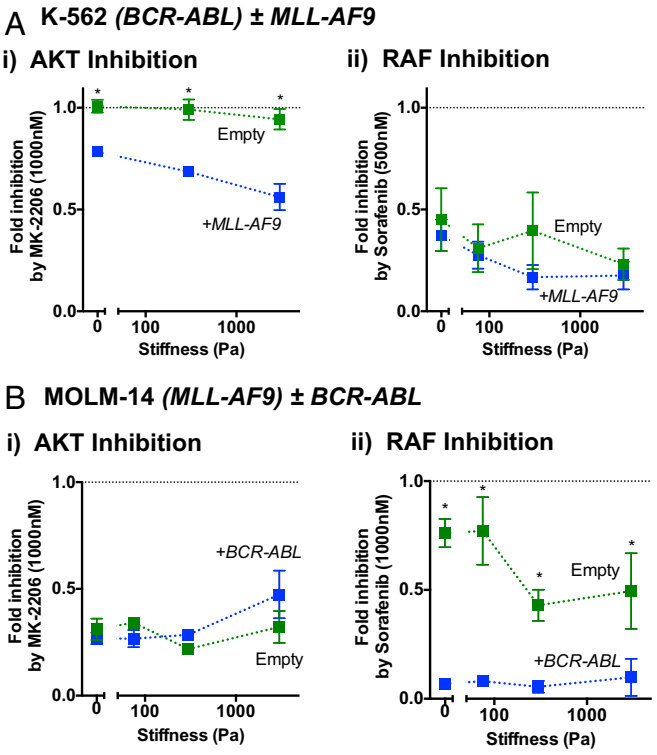

Fig. 4. Leukemic oncogenes decouple the dependence of chemosensitivity on integrin ligands and matrix stiffness. (*A*) Overexpression of *MLL-AF9* into K-562 cells increases their sensitivity against MK-2206 (AKT inhibitor) (*i*) but does not affect the sensitivity against sorafenib (RAF inhibitor) (*ii*) across different matrix stiffnesses. (*B*) Overexpression of *BCR-ABL* into MOLM-14 cells does not alter their sensitivity against MK-2206 (*i*) but increases the sensitivity against sorafenib (*ii*). The whole cell population was used for viability analysis. *$P < 0.05$, paired t test between empty oncogene vectors. $n = 3$ experiments. Error bars indicate ± SEM.

Matrix Stiffness Controls the Growth Kinetics and Resistance to Chemotherapy in Vivo. To evaluate the in vivo relevance of the in vitro results, we used a xenograft model of human extramedullary myeloid leukemias [leukemia cutis (25)] (Fig. 1*A*) by s.c. implanting K-562 cells (clone 3 from Fig. 3*A*) in hydrogel discs with different stiffness into NOD/SCID/IL-2$\gamma^{-/-}$ (NSG) mice (Fig. 5 *A*, *i*). No difference in total viable cell number across different matrix stiffness was observed after cell encapsulation (Fig. S6*A*). Because tumor was not visible by eye for the first 3 wk, bioluminescence live imaging for firefly luciferase in K-562 cells was used to track in vivo growth during this time frame (Fig. 5 *A*, *i*). The in vivo growth follows the first-order kinetics at the natural log scale as described by the classical Gompertz model of tumor growth (26) (Fig. 5 *A*, *ii* and *SI Methods*). Specifically, matrix stiffening decreases both the initial growth rate and the deceleration rate by ∼1.5-fold (Fig. 5 *A*, *iii* and *iv*), and hence maintains a constant maximal tumor signal (i.e., plateau = growth/deceleration). The results are consistent with the in vitro growth kinetics measured for 2 wk (Fig. S6*B*). The in vivo cell number in soft matrix is up to ∼100-fold higher than that in stiff matrix at 2 wk (*SI Methods*), and the difference gradually diminishes afterward (Fig. S6*C*). Therefore, initial matrix stiffening leads to both delayed and sustained cancer growth in vivo.

We then tested whether soft matrix confers resistance to standard chemotherapy in vivo as observed the in vitro drug screen studies. After 1-wk implantation, a myelosuppresive dose of Ara-C [62.5mg/kg (27)] was intraperitoneally administered daily into each mouse for 3 wk (Fig. 5 *B*, *i*). Interestingly, fitting the bioluminescence data for the first 3 wk shows that Ara-C suppresses the cell growth in the stiff matrix predominantly by increasing deceleration rate (∼2.5-fold) rather than decreasing initial growth rate (Fig. 5 *B*, *ii*). In fact, initial growth rate in stiff matrix is increased slightly by ∼1.4-fold after Ara-C (Fig. S6 *D*, *i*). It is thus estimated that Ara-C decreases the plateau of the tumor signal in the stiff matrix by ∼1.6-fold (Fig. S6 *D*, *i*). In contrast, cells are resistant to Ara-C in the soft matrix (Fig. S6 *D*, *ii*). To confirm these results, we investigated whether the treatment affects tumor growth at later time points after the withdrawal for 2 wk. An overall tumor volume rather than bioluminescence was measured at week 6 (*SI Methods*), because bioluminescence signals become saturated at week 4 (Fig. S6*E*). The tumor volume remains higher in soft than in stiff matrix at week 6, with the difference less than an order of magnitude (Fig. 5 *B*, *iii*). Consistent with the prediction from the earlier time points (Fig. S6 *D*, *i*), Ara-C decreases the volume of tumors originating from stiff but not soft matrix (Fig. 5 *B*, *iii*), in a dose-dependent manner (Fig. S6*F*).

Considering that the diameter of leukemia cells is ∼10 μm, the initial 1 million implanted K-562 cells per 20 μL gel disk occupies ∼2.5% of the total gel volume. This means that after 1 wk, when the tumor luminescence is increased by >40 fold (Fig. 5*A*), the cell number reaches the limit of the initial scaffold volume. Indeed, histological analyses after 2 wk from the implantation show that both blood and stromal-like cells are present with gel fragments, suggesting both donor cell overgrowth and host cell infiltration (Fig. S7*A*). This could be explained by stress relaxation of hydrogels followed by the loss of structural integrity, which is typical of ionically cross-linked hydrogels as cells proliferate (28). Histological observations suggest a qualitative trend where fewer stromal-like cells may be present with Ara-C compared with vehicle control, but more dead hematopoietic cells are visible in stiff matrices compared with soft (Fig. S7*B*). This is likely due to increased apoptosis, as indicated by increased cleaved caspase-3 staining (Fig. S8*A*). To characterize mechanobiological features further, we performed immunofluorescence studies on implanted K-562 cells. Whereas nonhuman stromal-like cells generally express higher yes-associated protein (YAP), a mechanosensitive transcription factor (29), than human K-562 cells, YAP^{+} human cells are more visible in the stiff matrix compared with the soft matrix (Fig. S8*B*). No difference was observed in F-actin distribution. Ara-C

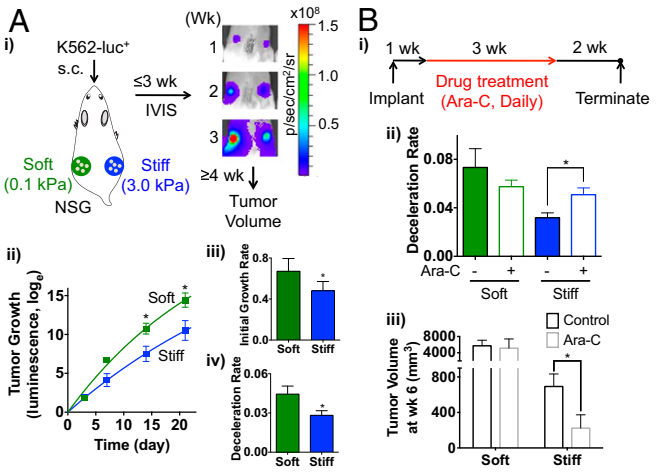

Fig. 5. Resistance of leukemia cells against conventional chemotherapy in soft matrix in vivo. (*A*) Matrix stiffness affects K-562 (clone 3) cell growth in vivo. (*i*) Experimental scheme and representative images showing tumor growth from soft and stiff matrix in the human xenograft extramedullary leukemia model. (*ii*) Tumor growth for the first 3 wk after implantation described by first-order kinetics based on luminescence signals (normalized to Y0; see *SI Methods*). (*iii*) Mean initial growth rate. (*iv*) Mean deceleration rate. $n = 15$ mice, three experiments, $^*P < 0.01$, paired t test. (*B*) CML cells are resistant to Ara-C in soft matrix. (*i*) Experimental scheme. (ii) Ara-C increases deceleration rate in stiff but not in soft matrix. (iii) Ara-C decreases tumor volume at week 6 in stiff but not in soft matrix. $n = 6$ mice, two experiments, $^*P < 0.01$ from one-way ANOVA with Tukey's HSD test, stiff control vs. treated.

does not seem to alter these trends. Together, the results show that initial matrix softening increases resistance against standard chemotherapy.

Discussion

A variety of molecular signals emanating from stromal cells in the BM microenvironment are known to play important roles in modulating tumor survival and drug sensitivity. The use of tumor–stroma coculture systems to identify new small-molecule inhibitors against tumor cells highlights the importance of recapitulating different components of the microenvironment to discover next-generation cancer therapies. Prior efforts have primarily focused on incorporating molecular and cellular components into in vitro drug screens on culture plastic. We demonstrate that engineering biophysical factors of the microenvironment, especially 3D matrix stiffness, into a quantitative, high-throughput screen format (Fig. 1*A*) reveals systematic variations in proliferation and drug responses of myeloid leukemias.

Matrix stiffening initially enhances the proliferation of MOLM-14 and U-937 cells but suppresses that of K-562 cells (Fig. 1*B*). This result mirrors the previous observation that TGF-β1 secreted from parathyroid hormone receptor-stimulated osteoblasts in vivo enhances *MLL-AF9*$^+$ AML proliferation but attenuates *BCR-ABL*$^+$ CML (3). Because TGF-β1 also regulates leukemia cells in an autocrine manner (30), it is possible that physical cues differentially regulate the proliferation of myeloid leukemia subtypes through the autocrine secretion of TGF-β. In addition, cell-generated mechanical tension resulting from matrix stiffening may increase release of matrix-bound active TGF-β (31). In contrast to K-562, the effect of stiffness on growth of MOLM-14 and U-937 is biphasic, suggesting the presence of other autocrine factors secreted specifically in stiffer matrices that suppress proliferation (Fig. 2 *A* and *B*). Delineating the interplay between specific growth factors and physical cues will thus be important to understand how matrix stiffness in the tumor microenvironment differentially regulates myeloid leukemias with distinct mutations.

Although a number of molecular targets are known to be involved in matrix stiffness sensing, most previous studies were performed with compounds at a single concentration. However, this approach does not reveal whether drug sensitivity against each target is influenced by matrix mechanics. This is an important consideration, because for drug targets whose inhibition depends on matrix stiffness a very high dose needs to be used to achieve similar efficacies in different physical environments, and this could increase the risk of off-target effects and toxicity. For instance, blebbistatin, an inhibitor against the myosin-II motor, at a high dose is known to eliminate differences in cellular functions and phenotypes caused by changes in matrix stiffness (5). However, higher concentrations of blebbistatin show off-target effects in some myosin-II mutant cells (32). Indeed, our results suggest that matrix stiffness modulates the sensitivity of cells against blebbistatin (Fig. 3*A*). Our 3D screen approach thus helps delineate how drug actions against different targets depend on mechanical cues for individual cancer subtypes, which could then further allow the identification of compounds that can potently target cells regardless of their physical environments.

It has been suggested that the tumor microenvironment induces the dormancy of leukemia cells, and hence they become more resistant to anticancer drugs due to slow proliferation (33). However, increasing evidence suggests that the cytotoxic effects of chemotherapeutic agents are not likely dependent on proliferation in human tumors (34). Indeed, adhesion of AML cells to matrix or stromal cells is known to decrease chemosensitivity, regardless of alterations in proliferation rates (35). Consistent with this notion, no clear correlation was observed between cell proliferation and drug sensitivity in our screen. In addition, although K-562 growth is independent of RGD (Fig. 1*B*) it mediates chemosensitivity regulated by matrix mechanics (Fig. S4*A*). Therefore, chemosensitivity may not always be a function of cell proliferation in pathophysiological contexts, providing evidence against the antiproliferative hypothesis.

We demonstrate the utility of implanting the same hydrogels used in an in vitro screen into xenograft models to bridge the gap between in vitro and in vivo preclinical studies. Although it is presently difficult to control matrix stiffness orthotopically in BM for systemic leukemia models, s.c. implantation models the extramedullary manifestation of leukemias, which often predicts rapid disease progression and poor prognosis in advanced-stage patients (36). Even though in vivo tumor growth is a complex process that involves angiogenesis and matrix remodeling after implantation, the impact of stiffness on growth kinetics parameters of K-562 cells in vitro (Fig. S6*B*) are consistent with those in vivo (Fig. 5*A*). This suggests that matrix stiffness is a dominant parameter that regulates tumor growth.

The s.c. xenograft model can also be used to study drug resistance against human leukemias, because chemotherapy adequate to induce marrow remission does not always control the extramedullary sites due to a high probability of relapse (25). Indeed, the dose of Ara-C used in previous studies to control systemic leukemias (6.25 mg/kg) (37) is not sufficient to induce regression in s.c. sites (Fig. S6*F*). Upon dose escalation, leukemia cells become more sensitive to standard chemotherapy in the stiff matrix (Fig. 5*B*) where cells grow slowly but steadily (Fig. 5*A*), again providing evidence against the antiproliferative hypothesis. In contrast to previous studies with 2D plastic culture, Ara-C acts on leukemias originating from the stiff matrix by increasing the deceleration rate rather than decreasing the growth rate, suggesting involvement of additional mechanisms in its tumor effect in vivo. One possible explanation is that Ara-C increases apoptosis (Fig. S8*A*), giving rise to augmented compensatory proliferation of surviving cells (Fig. S6 *D*, *i*), as previously observed in chemical hepatocarcinogenesis (38).

YAP is relatively low in hematopoietic cells compared with other cell types (Fig. S8*B*) (18), and this could explain why leukemia cells are generally resistant to a YAP inhibitor alone (Fig. 3). Although a functional significance of YAP up-regulation in in vivo implanted K-562 cells upon matrix stiffening (Fig. S8*B*) remains to be determined, it was previously shown that YAP overexpression

increases cisplatin-induced apoptosis of breast cancer cells in the presence of p73, which is activated by DNA damage (39). The results thus suggest a possibility that up-regulation or increased nuclear localization of YAP upon matrix stiffening (29) may sensitize some leukemia cells against chemotherapeutic drugs that target DNA.

Overall, we present a combined biophysical screening and in vivo validation workflow that could be applied to a range of cancers to reveal their growth kinetics and pharmacodynamics profiles as a function of physical environments. The resistance of leukemia cells against standard chemotherapy with matrix softening underscores the utility of this quantitative approach for investigating physically induced cellular drug resistance and discovering molecular targets that can be potentially modulated across different mechanical environments.

Methods

Cell culture, mechanical characterization of hydrogels, in vivo tumor growth studies, mathematical modeling, and other standard techniques are described in *SI Methods*. All animal work was performed in compliance with NIH and the ethical committee from Harvard University.

For chemical screen in hydrogels, cells in culture were washed two times, followed by resuspension in the serum-free Fluorobrite DMEM media. Cells were then mixed with the alginate solution to make the final gel concentration of 1%. Eighty microliters of the cell–alginate mixture was then deposited into each well of a 96-well plate (U-Bottom; Corning) that contained different concentrations of 5× calcium sulfate (20 μL). Immediately after deposition, the content was rapidly mixed by swirling with pipette tips and pipetting up and down ∼10 times. The plate was then incubated at 37 °C for 2 h to allow gels to form, and 100 μL of phenol red-free RPMI with 10% FBS was added on top of each gel; 1,000–10,000 cells were plated per well. Dose–response curves at day 7 were obtained for 20 drugs titrated at five or more doses (1/3∼1/10 serial dilutions) (Table S1). The proliferation of unlabeled cells was measured by alamarBlue (Invitrogen), and that of $mCherry^+$ cells was measured by reading fluorescence signals (emission 587 nm and excitation 620 nm).

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