Reprogramming Directional Cell Motility by Tuning Micropattern Features and Cellular Signals

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Mammalian cells exhibit directed cell movement on micropatterned surfaces.[1–3] A key challenge is to better understand the parameters and mechanisms that orient cell movement on micropatterns and to apply these insights to rationally modulate cellular traffic on synthetic materials. Here, using quantitative insights gleaned from the analysis of cell movement on teardrop-shaped micropatterns, we redesign the geometrical features of micropatterns to enhance the directional bias and to modulate the flux of cell movement. Furthermore, we demonstrate that perturbing an intracellular signal involved in lamellipodial extensions (Rac1) flips the preferred direction of cell movement. Our findings reveal a key role for lamellipodial extensions in determining the directional bias of cell movement on micropatterns and offer design strategies to modulate and reprogram this bias by manipulating pattern features and cellular signals. These insights begin to lay a foundation for constructing materials to channel cellular traffic in applications such as tissue engineering.

Micropatterned surfaces have been effectively used to control cell shape, survival, proliferation, and differentiation.[4–6] More recently, it has been shown that cells can exhibit persistent, directional movement on micropatterned surfaces.[2,3] When cells were released from confinement within a teardrop-shaped micropattern, their initial trajectory favored the blunt end over the tip end.[1] This short-lived bias is consistent with the stereotypical teardrop-like shape ascribed to a migrating cell with a broad leading edge and a narrow trailing tail.[7,8] A more persistent bias in cell movement was observed on a micropattern composed of four disjointed teardrop-shaped islands that were arranged to form a square.[2] On this pattern, the asymmetry of the teardrop defined a major axis for the cell body, but the direction of movement did not favor the blunt or tip end. The direction was dictated by the availability of an adjacent island along the cell body axis.

In this work, we seek to better understand the micropattern features and cellular signals that orient cell movement on micropatterns and to apply these insights to rationally modulate and reprogram the directional bias of cell movement. To begin our study, we used the teardrop-shaped micropatterns described previously[2] and quantified the movement tendencies of MCF-10A mammary epithelial cells. The percentage of complete jumps that were made in either direction of the pattern was measured (**Figure 1**, labeled arrows). Teardrop islands in Pattern A (Figure 1a and Movie 1, Supporting Information) induced a strong directional bias in which 81% of the jumps were observed to be sideways (*s*) from the tip (*T*) of a teardrop to the blunt (*B*) end of an adjacent teardrop ($sT \rightarrow B$ jump), while the remaining 19% of the jumps were head-on (*h*) from the blunt end of a teardrop to tip of an adjacent teardrop ($hB \rightarrow T$ jump). Even slight alteration of island placement to Pattern B (Figure 1b and Movie 2, Supporting Information) eliminated this bias. On Pattern B, 60% of the jumps were observed to be sideways from the blunt end of a teardrop to the tip of an adjacent teardrop ($sB \rightarrow T$ jump), while the remaining 40% of the jumps were head-on from the tip of a teardrop to the blunt end of an adjacent teardrop ($hT \rightarrow B$ jump). Patterns lacking asymmetric islands (Figure 1c), gap size (Figure 1d,e), or both (Figure 1f) also exhibited no bias. Thus, only Pattern A exhibited strong directional bias, demonstrating that gap size, teardrop asymmetry, and the relative positioning of the teardrops are all essential features.

We have observed the same directional bias in normal human epidermal keratinocytes (NHEK) migrating on similar patterns (Figure S1, Supporting Information). It is noteworthy that the directional bias observed here differs from that reported in the previous study involving 3T3 fibroblast and human microvascular endothelial cell (HMVEC) movement on teardrop micropatterns.[2] This difference may be attributed to disparate cell migration properties of mesenchymal versus epithelial cell types (Figure S2, Supporting Information) and the significantly different environmental signals, including growth factors and extracellular matrix (ECM) proteins, to which cells were exposed. That different cell types exhibit distinct movement tendencies is expected and has been documented, for example, in tumor cells with different requirements for extracellular proteolysis.[9] The key question of interest here is whether and how the movement bias can be rationally reprogrammed by modulating micropattern features and key cellular signals.

Based on our quantitative measurements of cell movement on teardrop squares, we sought to design a new pattern that enhances the directional bias. The preference for $sT \rightarrow B$ jumps on Pattern A (Figure 1a) was only 80% with the other 20% involving $hB \rightarrow T$ jumps. We reasoned that the bias for $sT \rightarrow B$ jump may be further enhanced if this jump option were juxtaposed against an even more unfavorable type of jump. One possibility for a highly unfavorable jump came from the observations of cell movement on Pattern B (Figure 1b). Cell movement on Pattern B was not only unbiased, but the frequency of jumps was also significantly lower than on Pattern A (Table S1, Supporting Information). These observations suggested that the $hB \rightarrow T$ and $sT \rightarrow B$ jumps are highly unfavorable and could be ideal candidates to juxtapose against the highly favored $sT \rightarrow B$ jump from Pattern A.

Thus, we designed a new yin-yang pattern that juxtaposed the $sB \rightarrow T$ jump against the $sT \rightarrow B$ jump and where only sideway

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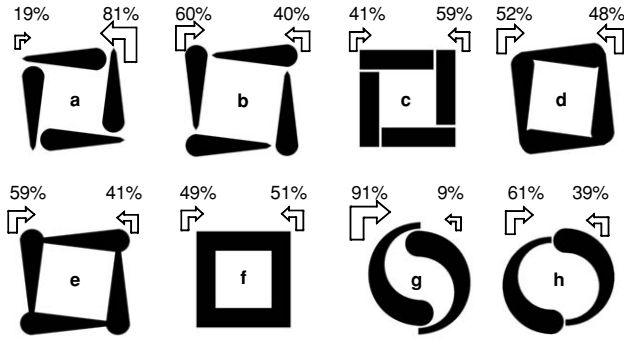

Figure 1. Directional bias of MCF-10A epithelial cells on teardrop-based micropatterns. Standard di Simple geometrical constraints of micropatterned substrates mensions for the adhesive islands were 20 μm in width and 80 μm in length with 3 μm nonadhesive gaps between islands. The width of the teardrop was 3 μm at the tip and 20 μm at the blunt end. The patterns are: a) disjointed teardrops with the blunt end running into a tip, b) disjointed teardrops with tip running into the blunt end, c) disjointed adhesive islands lacking asymmetry, d) Pattern A without gaps, e) Pattern B without gaps, f) pattern with both gaps and island asymmetry eliminated, g) sideways yin-yang pattern, and (h) head-on yin-yang pattern. Percentages of complete jumps in each direction are shown (greater than 100 jumps quantified for each pattern).

jumps were possible ($sB \rightarrow T$ or $sT \rightarrow B$ jumps; Figure 1g). As a control, we designed another yin-yang pattern where only head-on jumps were possible (Figure 1h) at both ends of the curved teardrop. Consistent with our hypothesis, the sideway yin-yang pattern resulted in an enhanced $T \rightarrow B$ directional bias (91%; Movie 3, Supporting Information) compared to the original Pattern A in which the $T \rightarrow B$ directional bias was 80%. In contrast, the control head-on yin-yang pattern yielded little bias in cell movement.

In addition to using quantitative analysis of movement tendencies to engineer patterns with enhanced directional bias, we sought to better understand the preference that epithelial cells exhibit for the $sT \rightarrow B$ jump as opposed to the $sB \rightarrow T$ jump or the head-on alternatives. We examined more closely the $sT \rightarrow B$ jump at 63× magnification. On Pattern A, we noticed that as the lamellipodium of a moving cell becomes constrained at the tip end of a teardrop and the cell extends a new side lamellipodium that is stabilized by latching onto a lateral island (**Figure 2a** and Movie 4, Supporting Information). In sharp contrast, Pattern B does not provide a lateral island to stabilize a new side lamellipodia; thus, in order to jump onto an adjacent island, cells encountering a tip on Pattern B must use their pre-existing spatially constrained lamellipodia to reach out in a head-long direction (Movie 5, Supporting Information). Thus, high directional bias seems to be the consequence of side lamellipodial protrusions at the tip ends, which are stabilized by adhesions to a lateral adjacent island.

This observation of side lamellipodium formation suggested that the bias of the cells on these micropatterns may be sensitive to intracellular signals that control lamellipodial extensions, such as Rac1, a small GTPase signaling protein. Specifically, moderate Rac1 knockdown has been shown to reduce the formation of new lamellipodia and increase the directional persistence of cells on nonpatterned tissue culture substrates.[10] Thus, we reasoned that moderate Rac1 suppression may enhance the stability of a pre-existing lamellipodium and thereby improve the ability to make head-on jumps instead of switching direction via a sideway jump.

To test this hypothesis, we suppressed the expression level of Rac1 by ≈60% using RNA interference (Figure S3, Supporting Information). MCF-10A cells with reduced Rac1 expression exhibited a different motility bias compared to cells transfected with control small interfering RNA (siRNA, Figure 2b). Rac1 suppression significantly reduced the bias for $sT \rightarrow B$ jumps in Pattern A (from 90% to 61%; Figure 2b and Movie 6, Supporting Information) and increased the bias for $hT \rightarrow B$ jumps in Pattern B (from 53% to 80%; Figure 2b and Movie 7, Supporting Information). By discouraging sideways jumps and promoting head-on jumps, we dampened the biased movement on Pattern A and created a new bias on the previously ineffective Pattern B. Conferring this new bias in movement comes with an expected cost in the speed of cell movement: due to dampened lamellipodial activity in cells transfected with Rac1 RNAi, the speed of migration and frequency of jumps were reduced. These results demonstrate that the directional bias of cell motility on micropatterned surfaces may be reprogrammed by tuning an intracellular signal that regulates lamellipodial extensions.

It is noteworthy that attenuating Rac1 expression enhances the tendency of cells to hop in a direction parallel to the major axis of the teardrop. On Pattern B, the preference for hops

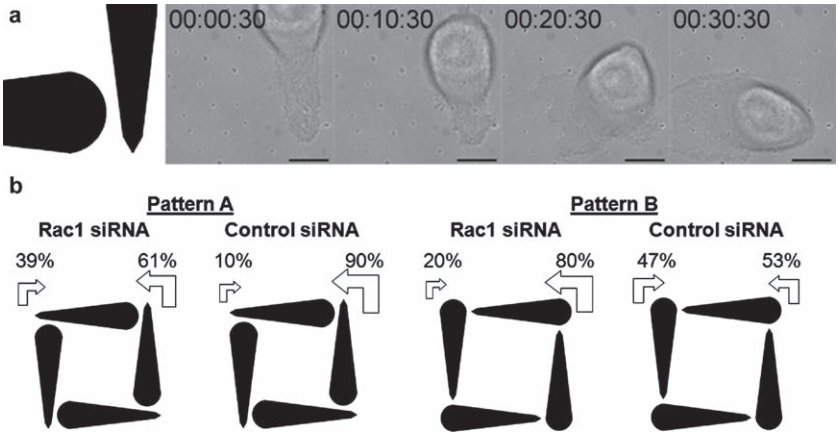

Figure 2. The role of lamellipodial extensions in determining the directional bias of cell movement on micropatterns. a) Timelapse images show the formation of a new, side lamellipodium as a cell jumps sideway from the tip to a blunt end on Pattern A. The corner of Pattern A at which the cell is jumping is shown in the first panel. The time stamps correspond to Movie 4 (Supporting Information) and are displayed as h:min:s. b) The effect of Rac1 knockdown on the directional bias of MCF-10A cells on micropatterned surfaces. Directional bias of Rac1 siRNA-treated and control siRNA-treated cells on Patterns A and B are shown. Percentages of complete jumps in each direction are shown (greater than 100 jumps were quantified for each pattern).

parallel to the teardrop axis ($hT \rightarrow B$ jump) increases from 53% (control siRNA) to 80% (Rac1 siRNA). The result is a movement bias that closely resembles that reported previously for fibroblasts and HMVECs on similar patterns.[2] On Pattern A, Rac1 suppression has a similar effect although the conversion is not complete: the preference to hop parallel to the major axis of the teardrop ($hB \rightarrow T$ jump) increases from 10% (control siRNA) to 39% (Rac1 siRNA). These results are consistent with our hypothesis that partial suppression of Rac1 stabilizes pre-existing lamellipodia, thereby enhancing the ability to make headlong jumps. It also suggests that Rac1 level may be a molecular determinant of the observed differences in the movement preference of fibroblasts/HMVEC versus epithelial cells and may serve as a quantitative index to predict the movement of other cell lines on micropatterns.

In addition to reprogramming the directional bias, it is desirable to tune the flux of cell movement on synthetic materials. To explore this possibility, we adapted the aforementioned teardrop micropatterns into a "splitter" design (**Figure 3a**). Cells originating in the source island (S) would jump to one of the available lateral target islands (T1 and T2). We reasoned that by varying the position of T2, the relative flux of cells moving to T1 versus T2 may be modulated. Thus, we designed micropatterns with the relative position of S and T1 fixed while varying the gap distance or the position offset of T2.

These splitter features have qualitatively distinct effects. Cell movement is highly sensitive to gap distance, displaying a switch-like transition as the gap distance is shifted from 3 to 5 μm (Figure 3b). On the other hand, position offset provided a graded transition as the offset is increased from 0 to 15 μm (Figure 3c). Cells had a higher likelihood of jumping to T1 with no offset, and this bias can be gradually increased to near 100% by increasing the offset of T2. These results suggest that varying the offset can be useful in modulating the relative flux of cells along two micropatterned lanes emanating from a splitter design.

An emerging property of micropatterned surfaces is their ability to orient cell movement.[1–3] Our signal perturbation experiments along with quantitative analysis of cell movement tendencies reveal a key role for lamellipodial extensions and stabilization in determining the directional bias of epithelial cells on micropatterned surfaces. Manipulating pattern features and cellular signals to exploit and modulate lamellipodial extensions enables both quantitative tuning and qualitative reprogramming of the directional bias of cell movement. These findings provide a foundation for modulating the direction and flux of epithelial cell movement on micropatterned surfaces as a powerful complement to gradient-based approaches.[11–13] Together with similar studies focused on other cell types, we envision developing a complete toolbox for programming cellular traffic on micropatterned surfaces for applications such as tissue engineering.

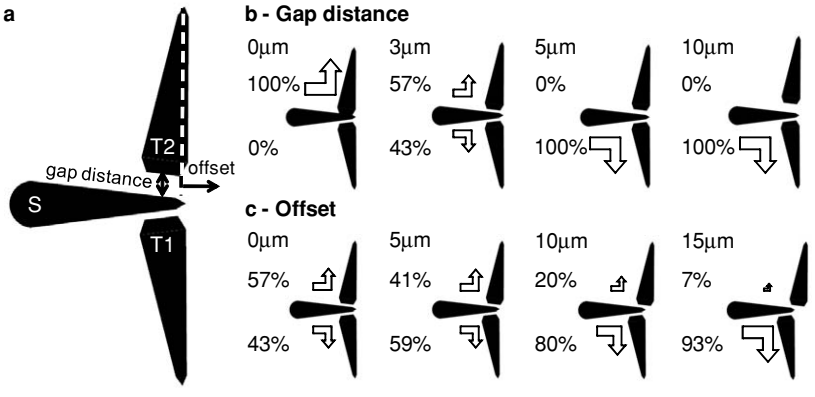

Figure 3. The effect of splitter design features on the directional bias. a) Cells jumping from S to the adjacent T1 or T2 were counted. While the positions of S and T1 were held fixed, b) the gap distance and c) the position offset of T2 were varied. Percentages of complete jumps in each direction are shown (greater than 100 jumps were quantified for each pattern).

Experimental Section

Fabrication of micropatterned substrates: Microcontact printing with a polydimethylsiloxane (PDMS; Momentive, Albany, NY, USA) stamp was used to pattern the adhesion ligand, fibronectin, onto a gold-coated coverslide. Briefly, the PDMS stamp was microfabricated using the standard photolithographic techniques[14]; UV light was passed through a chrome mask containing the pattern (Nanoelectronics Research Facility at UCLA, Los Angeles, CA, USA) onto a layer of SU-8 photoresist to make a mold, onto which PDMS was cast to make the stamp. The stamp was then "inked" with 16-mercaptohexadecanoic acid (Sigma Aldrich, St. Louis, MO, USA) dissolved in 99% ethanol and used to print the pattern onto a gold-coated chambered coverslide (Thermo Fisher Scientific-NUNC, Rochester, NY, USA). The unprinted area was passivated using the compound HSC11-EG6 (polyethylene glycol(6)-thiol; Prochimia, Sopot, Poland) dissolved in 99% ethanol to prevent nonspecific binding of cells. After washing with phosphate buffered saline (PBS) twice, 1-ethyl-3-[3-dimethylaminopropyl] carbodiimide hydrochloride (EDC; Thermo Fisher Scientific-Pierce, Rockford, IL, USA) and *N*-hydroxysulfosuccinimide (sulfo-NHS; Thermo Fisher Scientific-Pierce) dissolved in PBS was added to the coverslide to activate the acid to crosslink covalently with the amine group of the subsequently added fibronectin (Sigma Aldrich) dissolved in PBS (10 μg mL^{-1}). Finally, BSA conjugated with Alexa Fluor 594 (Invitrogen, Carlsbad, CA, USA) was doped into the fibronectin solution for the purpose of pattern visualization (Figure S4, Supporting Information).

Cell culture: MCF-10A human epithelial cells were cultured in growth medium composed of Dulbecco's modified Eagle's medium/Ham's nutrient mixture F-12 (DMEM/F12; Invitrogen) containing 2-(4-(2-hydroxyethyl)piperazin-1-yl)ethanesulfonic acid (HEPES) and L-glutamine, and supplemented with 5% horse serum (Invitrogen), 1% penicillin/streptomycin, 10 μg mL^{-1} insulin (Sigma Aldrich), 0.5 μg mL^{-1} hydrocortizone (Sigma Aldrich), 20 ng mL^{-1} epidermal growth factor (EGF; Peprotech, Rocky Hill, NJ, USA), and 0.1 μg mL^{-1} cholera toxin (Sigma Aldrich) and maintained under humidified conditions at 37 °C and 5% CO_2. Cells were passaged regularly by dissociating confluent monolayers with 0.05% trypsin-ethylenediaminetetraacetic acid (EDTA; Invitrogen) and suspending cells in DMEM/F12 supplemented with 20% horse serum and 1% penicillin or streptomycin. After two washes, cells were diluted 1:4 and plated in growth medium.

Timelapse microscopy: Cells were seeded in growth medium for 1 h onto the micropatterned substrate. After washing to remove nonadherent cells, the culture was incubated with fresh growth medium for 1 h and imaged at 10× magnification every 5 min for 12 h or at 63× magnification every 30 s for 2 h. For siRNA-treated cells, the seeding time was increased by 2 h. Cells were maintained at 37 °C and 5% CO_2

in a heated chamber with temperature and CO_2 controller (Pecon, Erbach, Germany) during timelapse imaging. Images and movies were acquired using Axiovert 200M microscope (Carl Zeiss MicroImaging, Thornwood, NY, USA) and Axio Vision LE Rel. 4.7 (Carl Zeiss MicroImaging) was used for image analysis.

siRNA knockdown: siRNA targeting human Rac1 mRNAs (siGENOME SMARTpool, M-003560-06-0005) and nontargeting siRNA (siGENOME Non-Targeting siRNA pool #2, D-001206-14-05) were obtained from Thermo Fisher Scientific. Cells were transfected with 20 nM siRNA using lipofectamine RNAiMAX 2000 (Invitrogen).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author

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