Three-dimensional microfluidic model for tumor cell intravasation and endothelial barrier function


http://dx.doi.org/10.1073/pnas.1210182109

National Academy of Sciences (U.S.)

Final published version

Tue Feb 12 19:21:01 EST 2019

http://hdl.handle.net/1721.1/77583

Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.
Three-dimensional microfluidic model for tumor cell intravasation and endothelial barrier function

Ioannis K. Zervantonakis*, Shannon K. Hughes-AlfordK,b,c, Joseph L. Charestb, John S. Condeelisis,a, Frank B. Gertler¹, and Roger D. KammK,b,a

*Departments of Mechanical Engineering, bBiological Engineering, and cKoch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA 02139; bThe Charles Stark Draper Laboratory, Cambridge, MA 02139; and cDepartment of Anatomy and Structural Biology, Albert Einstein College of Medicine, Bronx, NY 10461

Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved July 10, 2012 (received for review June 18, 2012)

Entry of tumor cells into the blood stream is a critical step in cancer metastasis. Although significant progress has been made in visualizing tumor cell motility in vivo, the underlying mechanism of cancer cell intravasation remains largely unknown. We developed a microfluidic-based assay to recreate the tumor-vascular interface in three-dimensions, allowing for high resolution, real-time imaging, and precise quantification of endothelial barrier function. Studies are aimed at testing the hypothesis that carcinoma cell intravasation is regulated by biochemical factors from the interacting cells and cellular interactions with macrophages. We developed a method to measure spatially resolved endothelial permeability and show that signaling with macrophages via secretion of tumor necrosis factor alpha results in endothelial barrier impairment. Under these conditions intravasation rates were increased as validated with live imaging. To further investigate tumor-endothelial (TC-EC) signaling, we used highly invasive fibrosarcoma cells and quantified tumor cell migration dynamics and TC-EC interactions under control and perturbed (with tumor necrosis factor alpha) barrier conditions. We found that endothelial barrier impairment was associated with a higher number and faster dynamics of TC-EC interactions, in agreement with our carcinoma intravasation results. Taken together our results provide evidence that the endothelium poses a barrier to tumor cell intravasation that can be regulated by factors present in the tumor microenvironment.

We present an in vitro three-dimensional (3D) microfluidic model of the tumor-vascular interface designed to integrate live imaging, precise control of microenvironmental factors, and endothelial barrier measurement. In this study, we employ our model to explore the relationship between tumor cell intravasation and endothelial permeability in the context of cytokine-induced endothelial cell activation and paracrine signaling loops involving macrophages and tumor cells. Increases in endothelial permeability via signaling with macrophages or stimulation with tumor necrosis factor alpha (TNF-α) were associated with a higher intravasation rate. Blocking macrophage-secreted TNF-α reduced the intravasation rate and normalized endothelial barrier integrity. Furthermore, modulation of endothelial barrier function regulated the number and dynamics of tumor-endothelial cell interaction events. Interestingly, macrophage M1/M2 polarization status in the device during signaling with tumor and endothelial cells was similar to the macrophage monoculture conditions. These results demonstrate the utility of our microfluidic discovery.


The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

¹To whom correspondence should be addressed. E-mail: rdkamm@mit.edu.

This article contains supporting information online at www.pnas.orglookup/suppl/doi:10.1073/pnas.1210182109/-/DCSupplemental.
based approach for direct observation of different tumor cell phenotypes and heterotypic cell-cell interactions during intravasation, and provide evidence for the interplay between endothelial barrier function and tumor cell intravasation.

Results

Design of the 3D Tumor-Endothelial Intravasation Microfluidic-Based Assay. The microfluidic assay consists of two independently addressable microchannels (Fig. 1A), where tumor and endothelial cells are seeded. These two channels are interconnected via a 3D ECM hydrogel, which includes 37 regions (Fig. 1B) enabling multiple simultaneous observations. The tumor cells invade in 3D in response to externally applied growth-factor gradients [e.g., epidermal growth factor (EGF) (26, 27)] or paracrine signals by the endothelial cells or other stromal cell types [e.g., macrophages (28, 29)]. On the 3D ECM-endothelial channel interface, a continuous endothelial monolayer is formed, which enables the observation of intravasation across a hollow vascular lumen, and allows for access to the basal and apical endothelial surfaces through the microchannels. Another important advantage compared to two-dimensional and transwell assays, is the introduction of a 3D matrix, which allows for both paracrine and juxtacrine signaling between tumor and endothelial cells.

To demonstrate the formation of confluent, 3D endothelial barriers (Fig. 1C), we visualized the endothelial cell-cell junctions using a vascular endothelial-cadherin (VE-cadherin) antibody. The endothelial cells formed continuous cell-cell junctions spanning the full area of the microchannel surfaces and the 3D ECM-endothelial channel interface (Fig. 1C). These confluent endothelial monolayers formed in the presence of invading tumor cells in 3D (Fig. 1D). High-resolution imaging allowed us to monitor endothelial cell-cell cadherin junctions as the tumor cells invaded toward the endothelial monolayer (Fig. 1E) and contacted the endothelial cells (Fig. 1F).

Characterization of Endothelial Monolayer Barrier Function. Using fluorescence conjugated dextran we established a diffusion-based solute flux across the endothelial monolayer (Fig. 2A) that was used to measure the diffusive endothelial permeability ($P_D$). Detailed computational modeling (Fig. 2B) based on device geometry and measured permeability coefficients predicted the experimental concentration distribution, thus confirming the validity of our quantification framework. By monitoring the intensity profiles (Fig. 2C) in time, we could also measure the temporal response of the endothelium to biochemical factors (Fig. S1). $P_D$ was measured in the presence of tumor cells for 10 and 70 kDa dextrans, yielding values of $4.08 \pm 1.11 \times 10^{-5}$ cm/s and $0.75 \pm 0.093 \times 10^{-5}$ cm/s, respectively. The ratio of 10 to 70 kDa $P_D$ values was 5.5 (Fig. 2D), indicating that the endothelial monolayer within our devices forms a size-selective barrier for transendothelial transport.

Macrophages Regulate Tumor Cell Intravasation Across the Endothelium. To model a physiologically relevant intravasation phenotype, we seeded human breast carcinoma cells in the 3D matrix and

![Fig. 1. Microfluidic tumor-vascular interface model.](image)

![Fig. 2. Characterization of endothelial permeability.](image)
investigated whether the presence of macrophages in contact with the endothelium regulates intravasation. Intravasation is indicated by the migration of tumor cells from within the 3D matrix across the basal endothelial surface and subsequent appearance on the apical endothelial surface inside the vascular lumen. Fig. 3A, demonstrates a characteristic example of an intravasation event, where the breast tumor cell has adhered to the apical surface of the endothelium, as shown by the top and side views. In the absence of macrophages, tumor cells were observed predominantly on the basal side of the endothelial monolayer (Fig. 3B). This finding was also confirmed by quantifying the tumor cell numbers in contact with the endothelium (Fig. S2A and B) and was further validated by live cell imaging, (Fig. 3C and Movie S1). Intravasation was a rare and inefficient event and occurred for a small fraction of the tumor cells in contact with the endothelial monolayer. In the presence of macrophages a significantly (P = 0.048) higher percentage of tumor cells (4.08 ± 0.87%; 13 out of 289 cells) intravasated, compared to control conditions (0.45 ± 0.28%; 2 out of 304 cells), i.e., a ninefold increase (Fig. 3D). Furthermore, we showed that macrophages enabled tumor cell intravasation for endothelial cells of different origin, and that the percentage of tumor cells that had intravasated (Fig. S2B) was similar for human microvascular endothelial (MVEC) and human umbilical vein endothelial (HUVEC) cells. To examine the effects of macrophages on the endothelial monolayer, we monitored changes in endothelial barrier function and measured a statistically significant (P = 0.03) 2.83-fold increase in endothelial diffusive permeability to 70 kDa dextran (Fig. 3E). Macrophages were present in both the subluminal and luminal endothelial spaces (Fig. S2C) at similar numbers (6.42 ± 1.88 vs. 5.29 ± 1.00 cells/region, P = 0.61).

TNF-α Stimulation of Endothelial Monolayer Modulates Tumor Cell Intravasation, Tumor-Endothelial Cell Interactions, and Endothelial Barrier Function. To test the hypothesis that the macrophage-induced permeability increase results in higher intravasation rates, we perturbed the endothelial barrier using biochemical factors and measured intravasation rates. We modulated endothelial permeability by stimulation of the endothelial monolayer with 2 ng/mL TNF-α in the presence of breast carcinoma cells alone, while simultaneously establishing a 20 ng/mL per mm EGF gradient to guide carcinoma cells toward the endothelial channel. We observed a significantly (P = 0.034) higher number (9 out of 124 cells) of intravasated tumor cells compared to control (2 out of 304 cells), suggesting that TNF-α stimulation increased endothelial permeability (Fig. S1C) and enhanced intravasation rate (Fig. S3A). Moreover, to characterize the TNF-α-induced endothelial barrier disruption in detail we measured permeability at different doses of TNF-α (0, 0.2, 2 and 20 ng/mL) and observed a graded response in endothelial permeability (Fig. S1A).

We further investigated the role of endothelial permeability in tumor-endothelial interactions during tumor cell invasion. Here, we used a highly invasive human fibrosarcoma (HT1080) cell line, in the absence of macrophages. To facilitate analysis, we developed a quantification framework that enabled the automatic detection (SI Materials and Methods) of tumor-endothelial interaction events, defined as a tumor cell in direct physical contact with the endothelial monolayer. This event can occur in the endothelial channel, or on the ECM-endothelial channel interface after migration of the tumor cell from the 3D matrix toward the endothelial barrier. Fig. 4A and B show two confocal image 3D volume renderings at t = 0 and t = 10 h of the HT1080 fibrosarcoma cells inside the 3D matrix as they invade toward the endothelial monolayer. The number of tumor cells that had migrated beyond the ECM-endothelial channel interface (Fig. 4C and D) increased with time, as the tumor cells were migrating in response to the EGF gradient toward the endothelium. Stimulation of the endothelium with 2 ng/mL TNF-α resulted in a 1.7-fold (P = 0.006) increase in percentage of tumor cells that interacted with the endothelium compared to the control (Fig. 4E). We confirmed that at t = 0 h, prior to tumor cell migration toward the endothelial, the number of tumor cells located within 250 μm from the ECM-endothelial channel interface was similar between the two conditions (Fig. S3B).

In addition to changes in the number of tumor-endothelial interaction events, the TNF-α-stimulated endothelium showed a fivefold increase (P = 0.002) in endothelial permeability compared to the control (Fig. 4F). Real-time measurements of Pd also confirmed the endothelial barrier impairment for 10 and 70 kDa dextrans (Fig. S1A). The TNF-α concentration (2 ng/mL) used was determined by titration experiments on endothelial monolayers seeded on collagen hydrogels to ensure a confluent endothelial monolayer was present after 24 h of stimulation (SI Materials and Methods and Fig. S3C).

Characterization of Macrophage Polarization and Role of Macrophage-Secreted TNF-α in Regulating Tumor Cell Intravasation and Endothelial Barrier Function. To characterize whether macrophages were polarized in the microfluidic device, we performed immunostaining for M1 and M2 markers (SI Materials and Methods and

---

**Fig. 3.** Macrophages enable tumor cell intravasation. (A) Top (Upper Left) and side (Upper Right) views showing the device schematic with the endothelial monolayer, the tumor cells, and the location of the 3D ECM. (Lower) Confocal images, demonstrating intravasation of a single breast carcinoma cell (green) across the endothelium (MVEC, stained red for VE-cadherin). (Scale bar: 30 μm.) (B) Top (Upper Left) and side (Upper Right) views with the same orientation as in A, showing tumor cells on the basal side of the endothelium. (C) Time sequence of a single confocal slice showing a breast carcinoma cell (white arrow) in the process of intravasation across a HUVEC monolayer (magenta) in the presence of macrophages (RAW264.7). The dashed line illustrates the endothelial-ECM interface. (Scale bar: 30 μm.) (D) Percentage of carcinoma cells that intravasated across a HUVEC monolayer was increased in the presence of macrophages (Mϕ, P = 6 x 10^-4). Blocking TNF-α resulted in a significant reduction in intravasation compared to the IgG antibody control (P = 0.035). Average values (n = 3 devices) for each condition. (E) Quantification of endothelial permeability to 70 kDa dextrans. Presence of macrophage led to significant permeability increase (P = 0.002). TNF-α blocking also resulted in a significant reduction (P = 0.036) compared to the IgG antibody control. Average values (n = 12 regions); error-bars represent SEM.
Dynamics of Tumor-Endothelial Cell Interactions. Our ability to visualize the endothelium en face allows a qualitative characterization of the process of tumor cell migration at a 3D endothelial monolayer with a well-defined lumen (Fig. 1C). Such dynamic observation of tumor-endothelial cell interactions can offer valuable insights into the timescales, spatial organization, and mechanism of tumor cell intravasation, complementary to detailed immunofluorescent staining (Fig. S4A and Fig. S5). Fig. S4A shows a time series of images demonstrating one example of a fibrosarcoma cell migrating from the 3D matrix to the endothelial monolayer. Analysis of the time-lapse movies led to a number of interesting observations: (i) Invasive protrusions form dynamically and appear to probe the surrounding 3D environment. (ii) Tumor cells exhibit significant cell shape changes as they migrate from the 3D matrix, adhere to the endothelium, and migrate through it to the endothelial channel. (iii) Tumor cells were observed to migrate toward remodeled regions (Fig. S5) of the endothelium or next to a macrophage (Fig. S2C).

We studied the dynamic interactions of tumor-endothelial cells under control and TNF-α conditions by tracking tumor cell trajectories (Fig. 5B) and quantifying the time (Fig. 5C) required for tumor cells to migrate a specific distance (60 μm) across the ECM-endothelial channel interface. Tumor cells migrated faster from the 3D matrix into the endothelial channel in the TNF-α stimulated (1.35 ± 0.25 h) compared to the control monolayer (2.42 ± 0.38 h) (P = 0.024). To confirm that TNF-α did not modulate tumor cell invasion in the 3D matrix, we quantified tumor cell migration speeds (Fig. 5D) and found similar values (29.59 ± 2.57 vs. 29.53 ± 4.16 μm/h, P = 0.99) under the two conditions. These findings suggest that impaired endothelial barrier function facilitates faster tumor cell invasion across the

Fig. S4A). Although we found that macrophages within the device could be driven toward an M1 or M2 phenotype through stimulation with lipopolysaccharide (LPS) or interleukin-4 (IL4) (Fig. S4C), respectively, when in the presence of tumor cells and endothelial cells the macrophages were variable in their expression for M1 or M2-specific markers (Fig. S4 D and E). Furthermore, coculture of macrophages with tumor cells within the device did not significantly change their phenotype vs. culture of macrophages alone (Fig. S4 D and E). We also characterized macrophage-secreted factors under control conditions and M1/M2 polarization and confirmed that the macrophages secreted TNF-α (Fig. S4 A and B).

To investigate whether the effects of macrophages on intravasation and endothelial permeability are regulated via paracrine signals, we performed antibody blocking experiments to neutralize soluble TNF-α and measured significant changes in permeability (Fig. 3E, 1.67-fold decrease, P = 0.04) and intravasation (Fig. 3D, 2.45-fold decrease, P = 0.03) compared to control IgG antibody. We also performed permeability measurements to investigate the effects of other cell types (tumor and epithelial cells) on endothelial barrier function compared to macrophages. Interestingly, the presence of all cell types resulted in increased endothelial permeability (Fig. S2D) compared to the control condition. However, the presence of macrophages resulted in a significant increase in PD compared to tumor cells (5.6 × 10⁻⁵ cm/s vs. 3.9 × 10⁻⁵ cm/s, P = 0.049), whereas there was no significant difference compared to the epithelial cell (5.6 × 10⁻⁵ cm/s vs. 4.5 × 10⁻⁵ cm/s, P = 0.36) condition.
EC-matrix barrier and are in agreement with our observations of increased endothelial permeability and higher number of tumor cells interacting with the TNF-α stimulated endothelium.

Discussion
Despite progress in identifying critical regulators (16, 30–32) of tumor-endothelial interactions, it is not clear whether tumor cell entry into the blood stream requires an impaired endothelial barrier (30, 33). In this work, we present a unique approach using a microfluidic-based in vitro assay that enables real-time visualization and quantification of the interactions between tumor cells and an endothelial monolayer in the context of tumor cell invasion and intravasation. Because tumor blood vessels are structurally (18) and functionally (19) abnormal, we hypothesized that endothelial barrier function impairment contributes to tumor cell intravasation. We found that modulation of endothelial barrier permeability by added soluble biochemical factors, such as TNF-α, and via macrophages can facilitate intravasation, and regulate the number and dynamics of tumor-endothelial cell interactions. Our findings are consistent with in vivo observations of high tumor cell counts in the portal venous blood in metastatic tumors with higher blood vessel density (34) and with a study that demonstrated that vascular endothelial growth factor (VEGF) overexpression by tumor cells induced endothelial barrier disruption and facilitated transendothelial migration (32).

Previous studies of cancer cell intravasation have largely taken a cancer cell-centric approach identifying signaling pathways that increase tumor cell dissemination (9–11). For example, a recent in vitro study identified changes in endothelial myosin light chain kinase upon tumor-endothelial cell contact (16), however this method did not allow for measurement of endothelial permeability or the accurate control of the microenvironmental stimuli. Compared to other in vitro models (16, 21) and microfluidic models of tumor-endothelial interactions (25, 35), our assay provides a number of unique features, such as high-resolution live cell imaging, the formation of an endothelial monolayer on a 3D ECM enabling us to model intravasation, and for precise quantification and control of critical tumor microenvironmental factors. The readily accessible apical side of the endothelium allows for the introduction of cell types in the tumor microenvironment, such as macrophages, the precise establishment of growth-factor gradients, fluid flow, and real-time spatially resolved endothelial barrier function measurements. All three cell types (tumor, endothelial, macrophages) can interact in a 3D environment with an ECM which can be remodeled by cells, enabling autocrine, paracrine, and juxtacrine cell-cell interactions mimicking the angiogenic tumor microenvironment (17) more faithfully than studies on two-dimensional substrates (36).

Endothelial barrier function quantitation in the presence of invading cells showed size-selective transendothelial transport and the $P_D$ values in our microfluidic model agree well with measurements in transwell systems (37) and in engineered blood vessels in 3D matrices (38). Although our measurements are significantly higher than in vivo values of healthy vasculature (39), they are of the same order of magnitude (Fig. 2C), $P_D \sim 10^{-6}$ cm/s as those measured in murine tumors with 70 KDa dextran (40). Contrary to the traditional transwell method that provides only a single $P_D$ value across the entire monolayer, our approach allows for (i) detailed regional investigation of endothelial permeability changes in response to tumor-stromal cell interactions and (ii) the accurate measurement of the endothelial permeability dynamics (in cm/s) for direct comparison between different studies.

The ability to image the tumor-endothelial cell dynamics in high-resolution allowed us to visualize the diverse array of tumor cell phenotypes: 3D invasion in response to growth factor gradients, direct physical contact with, and migration on an endothelial monolayer. Detailed single tumor cell tracking was performed to quantify the timescales of tumor-endothelial cell interactions in the context of intravasation. We found that these timescales and the number of tumor cells interacting with the endothelium were dependent on endothelial barrier function. Under conditions of unperturbed endothelial barrier function, carcinoma cells were observed predominantly on the basal endothelial side, whereas increased permeability facilitated intravasation and enhanced the number of tumor-endothelial interactions. Our results agree with in vivo studies in a zebrafish model (10) that found increased intravasation by tumor cells that overexpressed angiogenic growth factors, with studies in murine models (9, 12), and in clinical specimens (41) that demonstrated macrophage-assisted intravasation. Interestingly, our measured timescales of tumor cell migration across the EC-matrix interface (Fig. 5C) in the device are comparable to in vivo measurements (12). The measured increase in intravasation rate associated with the presence of macrophages (Fig. 3E) may also be facilitated by the EGF/Colony stimulating factor 1 (CSF-1) paracrine loop between tumor cells and macrophages, leading to enhanced tumor cell invasiveness (42). In the absence of macrophages the TNF-α-induced intravasation rate enhancement (Fig. S3A) may also involve proinvasive effects of TNF-α on the tumor cells (43). Moreover, blocking antibody experiments demonstrated an important role for macrophage-secreted TNF-α (Fig. 3E), increasing endothelial permeability in the presence of macrophages. Interestingly, blocking TNF-α did not reduce intravasation to baseline levels, suggesting that there may be additional macrophage-secreted factors or juxtacrine interactions that facilitate intravasation. Permeability experiments with tumor and epithelial cells in place of macrophages (Fig. S2D) showed that although all cell types resulted in increased permeability values macrophages are the most potent. The measured permeability increases for the tumor and epithelial cells may be facilitated via secretion of angiogenic factors such as VEGF (44). Our observations of enhanced tumor cell intravasation rate and tumor-endothelial interactions may also be linked to physical remodeling of the endothelial barrier. Through immunofluorescence imaging we observed that at locations of tumor-endothelial cell contact the VE-cadherin junctions appear remodeled (Fig. S5) in agreement with other studies (31). Finally, although we could polarize macrophages in an M1 or M2 state in the device through LPS or IL4 stimulation (Fig. S4C), the macrophages were variable in their expression of M1 and M2 marker during coculture conditions, forming a mixed and heterogeneous population similar to in vivo (45).

In summary, we present a microfluidic-based approach to investigate tumor cell intravasation through the integration of high-resolution live imaging with endothelial barrier function measurement in the presence of macrophages. Also, by virtue of the small amounts of reagents and cells needed, and the capability to embed clinical tissue in the 3D ECM, our microfluidic model may find applications in personalized medicine, enabling economical drug screening and discovery integrating two or more cell types. Here, we characterize the previously unexplored timescales of tumor-endothelial cell interactions during intravasation and demonstrate the interplay of endothelial permeability and tumor-endothelial signaling. The ability to model the interactions of invading cells with an endothelium in a 3D microenvironment also offers the possibility to study the interplay of endothelial barrier function and transendothelial migration in other physiological and pathological processes, such as immune cell trafficking and cancer cell extravasation.

Materials and Methods

Cell Culture, Staining, and Reagents. The human fibrosarcoma HT1080 [American Type Culture Collection (ATCC)] and breast carcinoma MDA231 overexpressing GFP-tagged MenaAV (Gertler Lab) cell lines were cultured in DMEM supplemented with antibiotics and 10% FBS (Invitrogen) and grown until 70% confluence. Primary MVEC (Lona) and macrovascular endothelial cells (HUVEC; Chan Lab, National University of Singapore, Singapore) were grown in Endothelial cell medium (EGM2-MV) (Lonza) to confluence. For

Zervantonakis et al. PNAS vol. 109 no. 34 13519

PNAS | August 21, 2012
the invasation studies, we used the murine macrophage cell line Raw264.7 (ATCC) cultured in DMEM supplemented with 10% heat inactivated FBS.

Microfluidic Device Design. The microfluidic device design is based on previous work from our lab on forming endothelial sprouts under growth-factor gradients and the fabrication protocols are described in detail elsewhere (46). Compared with previous microfluidic systems from our group, two unique characteristics of the present design are (i) the incorporation of a y-junction for precise control of concentration gradients, required for accurate measures of endothelial permeability and (ii) the high number (n = 37) of hydrogel ECM regions (Fig. 1B).

Endothelial Barrier Function Characterization. We developed a quantitative framework to measure the local diffusive permeability (P₀) of the endothelial monolayer using fluorescent dextran and an analytical model based image analysis (see SI Materials and Methods for details and data analysis).

Tumor-Endothelial Cell Interactions Assay. HT1080 cells were seeded in the tumor channel and were allowed to invade for 3 d into the 3D ECM, when, a confluent endothelial monolayer was formed on the 3D ECM-endothelial channel. Prior live cell imaging was performed an EGFR gradient and TNF-α stimulation were applied. Images were analyzed using Imaris (Bitplane) to identify the ECM-endothelial channel interface and track tumor cell centroids (see SI Materials and Methods for detailed methods and data analysis).

Tumor Cell Invasation Assay. Breast carcinoma cells were seeded in the presence or absence of macrophages inside the 3D ECM and after 24 h an endothelial monolayer was formed. EGFR gradients were established in all experimental conditions, and cells were allowed to interact for 48 h, after which fixation, staining, and imaging were performed (see SI Materials and Methods for detailed methods and data analysis).

ACKNOWLEDGMENTS. We acknowledge Dr. Joan Brugge and Dr. Jean-Paul Thiery for helpful discussions, Dr. Seok Chung for establishing earlier microfluidic coculture assays in the Kami Lab and Dr. Ron Weiss for kindly allowing us access to the confocal microscope facilities of his lab. Funding from National Cancer Institute R21CA140096 (to J.L.C., R.D.K.), CA100324 (to J.S.C.), National Institutes of Health Grant GMS8801 (to F.B.G.), CDMRP Department of Defense Breast Cancer Research Program Grant W81XWH-10-1-0040 (to S.K.H.-A.), and wafer fabrication facilities at Microsystems Technology Laboratory (Cambridge, MA) are greatly appreciated.