



Published in final edited form as:

J Biomech. 2021 May 24; 121: 110400. doi:10.1016/j.jbiomech.2021.110400.

Tumor cell nuclei soften during transendothelial migration

Anya B. Roberts¹, Jitao Zhang², Vijay Raj Singh^{3,4}, Miloš Nikoli⁵, Emad Moeendarbary⁶, Roger D. Kamm^{†,1,3}, Peter T. C. So^{‡,1,3,4}, Giuliano Scarcelli^{*,2,5}

¹Department of Biological Engineering, Massachusetts Institute of Technology, Cambridge, 02139, MA

²Fischell Department of Bioengineering, University of Maryland, College Park, 20742, MD

³Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, 02139, MA

⁴Laser Biomedical Research Center, Massachusetts Institute of Technology, Cambridge, 02139, MA

⁵Maryland Biophysics Program, University of Maryland, College Park, MD 20742, USA.

⁶Department of Mechanical Engineering, University College London, London WC1E 7JE, UK

Abstract

During cancer metastasis, tumor cells undergo significant deformation in order to traverse through endothelial cell junctions in the walls of blood vessels. As cells pass through narrow gaps, smaller than the nuclear diameter, the spatial configuration of chromatin must change along with the distribution of nuclear enzymes. Nuclear stiffness is an important determinant of the ability of cells to undergo transendothelial migration, yet no studies have been conducted to assess whether tumor cell cytoskeletal or nuclear stiffness changes during this critical process in order to facilitate passage. To address this question, we employed two non-contact methods, Brillouin confocal microscopy (BCM) and confocal reflectance quantitative phase microscopy (QPM), to track the changes in mechanical properties of live, transmigrating tumor cells in an *in vitro* collagen gel platform. Using these two imaging modalities to study transmigrating MDA-MB-231, A549, and A375 cells, we found that both the cells and their nuclei soften upon extravasation and that the nuclear membranes remain soft for at least 24 hours. These new data suggest that tumor cells adjust their mechanical properties in order to facilitate extravasation.

Keywords

Brillouin microscopy; Interference microscopy; Metastasis; Cell modulus

[†] rdkamm@mit.edu. [‡] ptso@mit.edu. ^{*} sarc@umd.edu.

Conflict of interest

RK is Co-founder of AIM Biotech with significant financial interests and has research agreements with Biogen, Amgen and Gore. GS has intellectual property related to Brillouin microscopy and has equity in Intelon Optics.

1. Introduction

The mechanical properties of a tumor cell and its nucleus play a critical role in cancer metastasis, especially since tumor cells transit through diverse microenvironments (Denais and Lammerding, 2014; Friedl et al., 2011). During metastatic transendothelial migration (TEM), tumor cells extend protrusions through what are likely to be spontaneously-formed endothelial gaps in the blood vessel wall (Escribano et al., 2019). As these leading protrusions penetrate the endothelium, $\beta 1$ integrin activation facilitates adhesion to the basement membrane laminin in the subendothelial extracellular matrix (ECM) (Chen et al., 2016). To complete the process of TEM, the cell utilizes actomyosin contraction to pull the rest of itself through the endothelial gap (Kale et al., 2015; Reymond et al., 2015). During TEM, tumor cells deform to sizes smaller than the initial nucleus, the stiffest and largest organelle in the cell. Since the nucleus is 3–10x stiffer than the cytoplasm (Caille et al., 2002; Guilak et al., 2000), these deformations are thought to be a limiting factor in TEM, as demonstrated *in vitro* (Chen et al., 2017) and previously modeled theoretically (Cao et al., 2016).

Previous *in vitro* work has revealed that cellular and nuclear stiffness are key factors in cancer metastasis. Tumor cells of greater metastatic potential are known to be softer (Cross et al., 2007; Guck et al., 2005; Han et al., 2020; Swaminathan et al., 2011). Additionally, nuclear softening by lamin A/C reduction facilitates cell migration through pores in ECM-like matrices and tight engineered constrictions comparable in size to gaps between endothelial cells during TEM (Davidson et al., 2014; Davidson et al., 2015; Harada et al., 2014; Ribeiro et al., 2014; Rowat et al., 2013; Wolf et al., 2013). Similarly, a softer nucleus may better facilitate migration through endothelial cell junctions. However, too soft of a nucleus could also leave a tumor cell vulnerable to nuclear membrane rupture and DNA damage (Denais et al., 2016; Harada et al., 2014), either during TEM or under the shear stresses of circulation preceding it. While previous studies have focused on observing nuclear deformation through fixed constrictions, no published studies have examined whether nuclear stiffness dynamically changes during transendothelial migration to facilitate this process and whether these changes persist.

Measurements of the Young's modulus of the nucleus vary widely from 0.1–10 kPa, depending on the technique and cell type (Caille et al., 2002; Dahl et al., 2005; Deguchi et al., 2005; Deguchi et al., 2007; Guilak et al., 2000; Liu et al., 2014; Tseng et al., 2004). In part, this variability stems from the difficulty of measuring nuclear stiffness in its intact state and environment, and that most measurements (such as micropipette aspiration, compression via parallel plates, optical tweezers, cantilever tensile test, and atomic force microscopy) require isolation of the nucleus from the cell in a potentially destructive process. Moreover, all these methods require direct physical perturbation of the nucleus which may alter the mechanical properties of the nucleus since the nucleus and surrounding cytoplasm are mechanically connected (Lombardi et al., 2011) and cells can react to external stimulus. Particle tracking microrheology can examine intracellular and plasma membrane forces (Herráez-Aguilar et al., 2020; Wirtz, 2009; Yamada et al., 2000); however, this approach involves invasive delivery of particles into the cells and isolation of the nucleus in some cases. In general, methods to assess intracellular mechanics are highly perturbative and

would not be possible while a cell is undergoing TEM. In order to make meaningful measurements of stiffness during and after TEM, it is therefore preferable to use a method that does not affect the transmigration process, and therefore should be a non-contact or minimally-invasive measurement.

In order to address the question of whether tumor cells alter their mechanical properties during the process of TEM, we apply two recently developed non-contact optical methods, Brillouin confocal microscopy (BCM) and confocal reflectance quantitative phase microscopy (QPM), to measure cell mechanical properties of the tumor cell and its nucleus in a 3D multi-cellular planar monolayer assay (Figure 1). BCM uses Brillouin light scattering to quantify intracellular longitudinal modulus without disturbing the cell (Nikoli and Scarcelli, 2019; Scarcelli et al., 2015) and recent work has shown this method can measure moduli of the nucleus inside cells with high spatial resolution (Wisniewski et al., 2020; Zhang et al., 2020). In contrast, confocal reflectance QPM, uses interferometry to measure the magnitude of thermal nuclear membrane fluctuations (Singh et al., 2019). While BCM and QPM measure different aspects of nuclear mechanics, their measurements provide new insight into the changes that occur in nuclear modulus during transendothelial migration.

2. Methods

2.1 Cell Culture

Human umbilical vein endothelial cells (Lonza) expressing mCherry LifeAct grew in culture in Vasculife basal media supplemented with VEGF LifeFactors (Lifeline) in 50 μ l/ml collagen I coated flasks. The metastatic tumor cells MDA-MB-231 (breast), A549 (lung), and A375 (melanoma, ATCC) grew in culture in DMEM supplemented with 10% FBS, 1% penicillin/streptomycin and 1% L-glutamate (Sigma). All cells were cultured in an incubator at 5% CO₂ at 37°C.

2.2 Transendothelial Migration (TEM) Assay

After preparing a 2.5 mg/ml pH 7.4 rat-tail collagen I solution (Corning) on ice, we injected the gel into the 14mm diameter glass bottom well of a MatTek (P35G-0-14-C, MatTek) dish or on the mirror glass bottom inside 9mm diameter silicone rings (666505, Grace BioLabs) for QPM measurements, generating a thin (~100 μ m) layer. After the collagen polymerized at 37°C in the incubator for 30 minutes, we seeded 100,000 HUVECs/ml onto the collagen gel surfaces. We provided the assays with fresh supplemented Vasculife medium after initial cell attachment and daily thereafter.

To begin a TEM experiment (Figure 1A), we harvested tumor cells, stained the nuclei with 1:2000 Hoechst (33342, ThermoFisher) in PBS and seeded onto the confluent HUVEC monolayer at a 3×10^5 cell/ml concentration. The time is noted as the initial time for the extravasation events. For Brillouin experiments, epifluorescence enabled identification of cell state (pre-extravasation, in-process, or extravasated) by morphological change previously confirmed with confocal fluorescence imaging (Figure 1B). Before extravasation, tumor cells appear as spheres on top of the endothelial cells. During TEM, the round cell

body remains above the monolayer, while part of the cell spreads out below the endothelial cells (as in Figure S1). After TEM, tumor cells are entirely flattened (no more roundness) below the HUVEC monolayer.

To measure cell mechanical properties independently of the TEM process we seeded MDA-MB-231 cells inside (3D), and on top of the collagen matrix (2D) in absence of endothelial cells. In the 2D condition cells were seeded directly on top of a polymerized 2.5mg/ml collagen type I. In the 3D condition, cells were mixed with the ice-cold liquid collagen at 7.4 pH, and immediately placed in the incubator at 37°C for 30 min to allow the collagen to polymerize. Cell experiments were then performed within 1.5 hours.

2.3 Brillouin confocal microscopy (BCM)

The Brillouin confocal microscope (Figure 1C) consists of a commercial inverted microscope (IX81, Olympus) and a two-stage VIPA (virtually imaged phased array) based Brillouin spectrometer, which has been reported before (Scarcelli et al., 2015; Zhang et al., 2020). Briefly, 10 mW power from a 660nm continuous-wave laser (Torus, Laser Quantum, Inc) was focused into the cell through an objective lens (40x/0.6 NA, LUCPLFLN40X, Olympus), which provides a lateral resolution of $\sim 0.7\mu\text{m}$ and axial resolution of $\sim 2.5\mu\text{m}$. The backscattered Brillouin light was collected by the same objective lens and sent into the Brillouin spectrometer via a single mode optical fiber. An EMCCD camera (iXon 897, Andor) was used to record the Brillouin spectrum with a dwell time of 50ms, and the Brillouin shift was derived by fitting the spectrum with a Lorentzian function. Two-dimensional Brillouin image was acquired by scanning the cell with a motorized translational stage in horizontal and/or vertical planes. The step size was $0.5\mu\text{m}$. The Brillouin microscope was also integrated with a brightfield and fluorescent imaging modality such that the Brillouin image can be co-registered with the brightfield and fluorescent images for the same cell (see Figure S1 for more clarification). This enabled confirmation of the tumor cell state (before, during, or after TEM) in the multicellular system.

To separate the Brillouin shift measurements of nucleus from the rest of the cell in cases where co-registration with fluorescence images is not available (e.g. in vertical plane images), we analyzed the distribution of shifts inside the cell. Typically, the distribution of Brillouin shifts inside a cell has two main components corresponding to nucleus and cytoplasm (Zhang et al., 2017). We identified these two components by fitting the histogram from the Brillouin shift data of the cell with a sum of two normal distribution functions and used the average of the higher distribution as the indicator of the average nuclear modulus (Figure S2). We confirmed the accuracy of this method by cross validating it against the average of nuclear Brillouin shift in images that were co-registered with the nuclear fluorescence, showing the deviation between the fluorescence and histogram method is on the order of the instrumental precision of Brillouin shift in each pixel (8.4 MHz) (Figure S3).

The longitudinal modulus $M' = \Omega_B^2 \cdot \lambda^2 \cdot \rho / 4n^2$, where Ω_B is the measured Brillouin shift, λ is the wavelength of the laser, and n and ρ are the refractive index and mass density of the sample, respectively. While both the refractive index and the density may vary with conditions, their ratio ρ / n^2 was found to be constant within cells (Kim and Guck, 2020).

Therefore, we here use the Brillouin shift to interpret the relative modulus change of cells under transendothelial migration. The high-frequency (GHz) longitudinal modulus detected by Brillouin technique is different from the quasi-static Young's modulus measured by traditional methods, such as atomic force microscopy. However, strong correlation between two moduli has been observed in many biological samples, indicating both moduli change in the same direction in these physiological and pathologic processes (Scarcelli et al., 2015). Therefore, with prior calibration, Brillouin-derived modulus can be interpreted in terms of Young's modulus in some cases. For live cells, a log-log linear relationship between Brillouin-derived longitudinal modulus M' and Young's modulus E' measured by atomic force microscopy has been empirically determined as $\log(M') = a \log(E') + b$. Thus, the relative change of the Young's modulus and the Brillouin shift are related by $\delta E' / E' = (2/a) \cdot \delta \Omega_B / \Omega_B$, and the value of the coefficient a was previously calibrated as 0.0671 with NIH 3T3 cells. Here, we will also use this empirical relationship to estimate the relative change of Young's modulus based on measured Brillouin shifts.

2.4 Confocal reflectance quantitative phase microscopy (QPM)

Confocal reflectance QPM measures nanometer-scale thermally-driven nucleic and plasma membrane fluctuations with high sensitivity. Light from a 532nm laser light source (opus 532 from Laser Quantum) passes through a DMD (DLP discovery 4100 from Texas Instruments), creating a diffraction-limited size pinhole array and incident on the sample. The backscattered light from the sample passes back through the DMD, for confocal detection, followed by interferometric detection. In this multi-point scanning confocal reflectance interferometric microscope, foci size at the sample plane is 1.02 μm and system provides 1.5 μm axial resolution. The DMD scanning speed is 22 kHz, which provide the full field measurement speed at 14 ms.

The specular reflection from the mirror, located at an off-focal plane, underneath the sample, generates the highly phase-stabilized reference field. The common-path interferometry at the detection arm (shown in Figure 1D) provides the detection of optical phase information of the back scattered signal from nucleic membranes with height measurement accuracy better than 200 pm. For common path interferometer design, a transmission grating (with 80 line pairs per mm), placed at the image plane, diffracts the signal beam into 0 and +1 orders and generate the two copies of field incident on it. A DMD, located at the Fourier plane, allows the 0th order light to pass and create the object field. To generate the reference field, a COMB pattern spatial frequency filter (the Fourier transform of the pinhole array at the first image plane) is used for the +1 order, which provides the average phase of the object field. A CMOS sensor (Basler avA series) measures the interference pattern of the object and reference beams. A time series of wide-field interferograms at the nuclear membrane was acquired and converted into height maps of temporal fluctuations.

The nuclear membrane regions of cells with sufficient signal-to-noise ratio were analyzed by employing the previously published fluctuations measurement algorithm (Singh et al., 2019). The number of cells measured was limited due to increased noise in the system from the endothelial cells fluctuations and 3D collagen matrix.

2.5 Statistical analysis

Data were analyzed using MATLAB (Mathworks) or R. All two-group comparisons were conducted with two-sample t-tests. Larger multi-group comparisons were achieved with one-way ANOVA tests followed by post-hoc Tukey's tests.

3. Results

3.1 Brillouin microscopy shows softening of tumor cells and their nuclei during and after TEM

We acquired 2D Brillouin images of tumor cells before, during, and after TEM. The three metastatic human tumor cell lines measured are derived from different kinds of cancer, all of which involve metastasis into the extracellular matrix from the blood stream. As A549 and A375 originated from the primary tumor site, the transendothelial migration observed in this work is the first extravasation event for these cells. The MDA-MB-231 tumor cell line differs in that it came from a secondary metastatic site in the lung and is mesenchymal. The A549 (lung) is the most invasive, followed by MDA-MB-231 (breast), and A375 (skin) (Vilalta et al., 2014; Xu et al., 2016).

These measurements exhibited a decrease in the Brillouin shift as TEM progressed, especially in the nuclear region. Figure 2A shows the colormaps of Brillouin frequency shift for MDA-MB-231 tumor cells before, during, and after TEM in the *z*-direction. As tumor cells crossed the endothelial monolayer, both the cells and most notably the nuclei softened. TEM typically occurred during a period of 2–8 hours. All three cell line types (A549, A375, MDA-MB-231) showed a significant difference in the Brillouin shift in the cell region between the before and after TEM populations (Figure 2B). We did not observe the alteration of the mechanical properties of the endothelial layer during TEM process (Figure S5). Based on the relationship between Young's modulus and the longitudinal modulus (Scarcelli et al., 2015), the Brillouin frequency shift changes (– 64 MHz, – 42 MHz, –41 MHz) correspond to a 30% (A549 nuclei), 20% (A375 nuclei), and 20% (MDA-MB-231 nuclei) reduction in Young's modulus from before to after TEM, respectively. Some of the cell softening occurred while the cell was in the process of crossing the endothelial monolayer. In-process A549 and A375 cells were significantly softer than cells before TEM (26 and 25 MHz Brillouin shift reduction correspond to approximately 12% reduction in Young's Modulus for each), suggesting tumor cells start softening during transendothelial migration. A549 and MDA-MB-231 in-process cells were also significantly stiffer than extravasated cells (40 MHz and 29 MHz Brillouin shift reduction, correspond to 18% and 14% reduction in Young's Modulus), respectively, supporting the claim that softening continued while tumor cells were crossing the endothelial monolayer.

Analysis of the nuclear regions of these tumor cells furthermore revealed significant softening of the nucleus during extravasation (Figure 2C). A549, A375, and MDA-MB-231 tumor cell nuclei after TEM presented significantly lower Brillouin shift. The Brillouin frequency shift changes –68 MHz (A549), –44 MHz (A375), and –53 MHz (MDA-MB-231) correspond to a 32% (A549 nuclei), 21% (A375 nuclei), and 25% (MDA-MB-231 nuclei) reduction in Young's modulus, respectively, from before to after TEM.

In summary, these Brillouin confocal microscopy experiments revealed that these three tumor cell lines (MDA-MB-231, A549, and A375) experienced a reduction in Brillouin shift in the cell, especially in the nucleus, during the process of transendothelial migration, indicating that tumor cells soften during the process of extravasation.

To investigate if the observed change in cell mechanics was due to the cell response to change in the external geometry experienced before and after TEM, we measured the Brillouin shift of MDA-MB-231 cells on top of a collagen surface (2D) and embedded inside a collagen gel (3D) (Figure 3A). We compared these 2D and 3D measurements with the prior experimental dataset of MDA-MB-231 cells before, during and after TEM (Figure 3B,C, and S4). The cells and nuclei before extravasation were notably softer than the 2D case. This may be due to differences in stiffness between the collagen substrate and the endothelial monolayer, which would influence the mechanical properties of the tumor cells, with cells on stiff substrates becoming less compliant (Wullkopf et al., 2018). By contrast, in another study (Abidine et al., 2018), it was found that tumor cells are stiffer on an endothelial cell monolayer than on an 8 kPa gel surface. There are several possible explanations for this discrepancy, however, including the lower stiffness of our collagen gel compared to the polyacrylamide gels used in the Abidine study, as well as the challenges associated with using AFM to measure cell and nuclear stiffness in a non-perturbative way.

While we had previously observed that Brillouin shift decreases as cells enter the 3D collagen gel during TEM, here we found that MDA-MB-231 cells seeded inside 3D collagen gel (without endothelial cells and the TEM process) have consistently higher Brillouin shifts than cells in 2D on top of the collagen surface (2D) (Figure 3). This finding aligns with previous studies of metastatic cancer cell mechanics in relation to 2D versus 3D collagen environment (Mak et al., 2014; Staunton et al., 2016). These results show that the MDA-MB-231 cell softening is a consequence of the mechanical and/or biochemical interaction with the endothelium during TEM, and not due to the 3D collagen gel environment.

3.2 QPM measurements show nuclear membranes soften after TEM

To further study whether tumor cells modulate their mechanical properties during TEM and if these changes persist, we used confocal reflectance quantitative phase microscopy (QPM). This complementary approach enabled quantification of the nuclear membrane fluctuations of tumor cells within the first hour of contact with the endothelial monolayer (pre-extravasation, Figure 4A, left) and tumor cells in the same sample 24 hours later after extravasation into the collagen gel (Figure 4A, right). The later time point ensured that all tumor cells measured not only had extravasated, but also were farther into the collagen away from the fluctuations of the endothelial cell membranes.

Figure 4B shows representative root mean square (rms) fluctuation maps of A549 tumor cells before and after extravasation. The A549 lung carcinoma cells 24 hours after extravasation showed dramatically higher nuclear fluctuations (approximately a 2.4-fold increase) than the same cells before extravasation. (Figure 4C). Hence, the membranes and/or the nuclear chromatin and cytoskeleton of tumor cells were more compliant after they extravasated into the collagen gel. For A375 melanoma cells, however, the change in nuclear fluctuations between the pre-extravasation was not significant ($p = 0.053$).

4. Discussion

This study presents the first known experimental observations of a modulation in mechanical properties of tumor cells and their nuclei during transendothelial migration. We have observed this alteration to occur during transendothelial migration and to persist at least 24 hours. Two non-perturbative confocal methods, Brillouin confocal microscopy and confocal reflectance quantitative phase microscopy, enabled these intracellular measurements in a 3D TEM assay that maintained cell-cell and cell-collagen interactions. Although neither of these optical methods permits direct conversion to Young's modulus, they do non-invasively yield relative measurements of stiffness inside cells in 3D ECM-like microenvironments. BCM quantifies the Brillouin frequency shift, which is directly proportional to the longitudinal modulus and has been shown to correlate with Young's modulus for biological materials including cells (Scarcelli et al., 2011; Scarcelli et al., 2015). In the case of QPM, no model has been developed yet to directly link nuclear fluctuations to a modulus value. As a result, both BCM and QPM are best used for comparison of changes in mechanical properties rather than absolute values.

BCM and QPM are particularly complementary in noninvasively providing information about internal mechanical properties of cells during TEM and what parts may be contributing to the overall alteration in stiffness. The results show that the Brillouin shift of A549, A375 and MDA-MB-231 tumor cells and their nuclei decrease as they migrate across the endothelial monolayer. This observed modulation of stiffness of MDA-MB-231 cells is not due to the transition from a suspended state to a state embedded in 3D collagen (Figure 3), but rather due to the process of TEM, which incorporates tumor cell – endothelial cell interactions. Changes in the chromatin structure rather than changes in the nuclear membrane properties are mostly likely to contribute to this alteration in stiffness inside the tumor cell nuclei, since the changes appear throughout the nuclear volume. Chromatin decompaction is known to soften cells (Stephens et al., 2017; Stephens et al., 2018) and likely drives our observed modulation in Brillouin shift in the nuclear region as demonstrated by Zhang (Zhang et al., 2020).

Measurements of nuclear membrane fluctuations from QPM show a marked increase in A549 tumor cells, demonstrating either a reduction in modulus of the external cytoskeleton, internal chromatin or the nuclear membrane or a combination. In addition, they show that the changes in A549 tumor cells persist even 24 hours after endothelial contact. This further supports the Brillouin data that shows a softening of the extravasated A549 nuclei and suggests that the softening effect is longer term. While nuclear rupture could explain an increase in nuclear membrane fluctuations, this event is rare and would likely cause a more significant effect than observed here. This measurement is not only dependent on the inherent stiffness of the membrane, but also the modulus on either side of the nuclear membrane. As BCM reveals the intranuclear softening, we hypothesize that the nuclear membrane fluctuations are increasing due to softening inside the nucleus and result from changes in chromatin structure during TEM. Our findings align with recent AFM work showing that tumor cells soften when migrating into confined spaces (Rianna et al., 2020). Observations from that study also suggest that nuclear exclusion of YAP may contribute to nuclear softening. Additionally, cell cycle phase may play a role in the observed softening.

During the S/G2 cell cycle phase, chromatin decondense and tumor cell nuclei soften (Krause et al., 2019). During and/or after transendothelial migration, tumor cells may be softening due to transition into the S/G2 phase.

Future work will be required to understand the mechanisms by which tumor cells soften during TEM. Partial wave spectroscopy may be a valuable tool in assessing chromatin condensation for this application, although the method is currently best applied to samples in 2D on glass (Stephens et al., 2018). While, the implications of changes in the chromatin structure may be vast, more work is required to prove that chromatin alterations cause the change in stiffness we observe during TEM.

While many models of extravasation exist, none account for a change in nuclear stiffness during this event. New models incorporating this finding may present new understanding in how tumor cells metastasize. The softening of tumor cell nuclei may enable the process of TEM, as well as affect processes in later steps of metastasis. As softer tumor cells are known to be more metastatic (Guck et al., 2005), the lasting softening effect observed in A549 lung carcinoma cells may enable further migration into the extracellular matrix and suggest a continued proliferative phenotype. Furthermore, a recent study showed that softer melanoma cells metastasized to the lungs and formed significantly more tumors *in vivo* than stiffer cells (Lv et al., 2021). Also, potential increase in euchromatin likely correlate with further transcriptional alterations (Rochman et al., 2009), which may promote metastasis or influence the subsequent fate of a tumor cell at the metastatic site. The softening of the nucleus likely plays an important role in facilitating the metastasis of tumor cells, but more experimental and theoretical work will be needed to shed light on the underlying mechanisms.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This research was supported by the National Cancer Institute (U01 CA202177, R33CA204582) and the National Science Foundation (CMMI 1929412).

References

- Abidine Y, Constantinescu A, Laurent VM, Rajan VS, Michel R, Laplaud V, Duperray A, Verdier C, 2018. Mechanosensitivity of cancer cells in contact with soft substrates using AFM. *Biophysical Journal* 114(5), pp. 1165–1175. [PubMed: 29539402]
- Caille N, Thoumine O, Tardy Y, Meister J-J, 2002. Contribution of the nucleus to the mechanical properties of endothelial cells. *Journal of Biomechanics* 35(2), pp. 177–187. [PubMed: 11784536]
- Cao X, Moeendarbary E, Isermann P, Davidson PM, Wang X, Chen MB, Burkart AK, Lammerding J, Kamm RD, Shenoy VB, 2016. A chemomechanical model for nuclear morphology and stresses during cell transendothelial migration. *Biophysical Journal* 111(7), pp. 1541–1552. [PubMed: 27705776]
- Chen MB, Lamar JM, Li R, Hynes RO, Kamm RD, 2016. Elucidation of the roles of tumor integrin $\beta 1$ in the extravasation stage of the metastasis cascade. *Cancer Research* 76(9), pp. 2513–2524. [PubMed: 26988988]

- Chen MB, Whisler JA, Fröse J, Yu C, Shin Y, Kamm RD, 2017. On-chip human microvasculature assay for visualization and quantification of tumor cell extravasation dynamics. *Nature Protocols* 12(5), pp. 865–880. [PubMed: 28358393]
- Cross SE, Jin Y-S, Rao J, Gimzewski JK, 2007. Nanomechanical analysis of cells from cancer patients. *Nature nanotechnology* 2(12), pp. 780–783.
- Dahl KN, Engler AJ, Pajerowski JD, Discher DE, 2005. Power-law rheology of isolated nuclei with deformation mapping of nuclear substructures. *Biophysical Journal* 89(4), pp. 2855–2864. [PubMed: 16055543]
- Davidson PM, Denais C, Bakshi MC, Lammerding J, 2014. Nuclear deformability constitutes a rate-limiting step during cell migration in 3-D environments. *Cellular and Molecular Bioengineering* 7(3), pp. 293–306. [PubMed: 25436017]
- Davidson PM, Sliz J, Isermann P, Denais C, Lammerding J, 2015. Design of a microfluidic device to quantify dynamic intra-nuclear deformation during cell migration through confining environments. *Integrative Biology* 7(12), pp. 1534–1546. [PubMed: 26549481]
- Deguchi S, Maeda K, Ohashi T, Sato M, 2005. Flow-induced hardening of endothelial nucleus as an intracellular stress-bearing organelle. *Journal of Biomechanics* 38(9), pp. 1751–1759. [PubMed: 16005465]
- Deguchi S, Yano M, Hashimoto K, Fukamachi H, Washio S, Tsujioka K, 2007. Assessment of the mechanical properties of the nucleus inside a spherical endothelial cell based on microtensile testing. *Journal of Mechanics of Materials and Structures* 2(6), pp. 1087–1102.
- Denais C, Lammerding J, 2014. Nuclear mechanics in cancer, in: Schirmer Eric C., J.I.d.I.H. (Ed.), *Cancer Biology and the Nuclear Envelope*. Springer, New York, NY, pp. 435–470.
- Denais CM, Gilbert RM, Isermann P, McGregor AL, Te Lindert M, Weigelin B, Davidson PM, Friedl P, Wolf K, Lammerding J, 2016. Nuclear envelope rupture and repair during cancer cell migration. *Science* 352(6283), pp. 353–358. [PubMed: 27013428]
- Escribano J, Chen MB, Moeendarbary E, Cao X, Shenoy V, Garcia-Aznar JM, Kamm RD, Spill F, 2019. Balance of mechanical forces drives endothelial gap formation and may facilitate cancer and immune-cell extravasation. *PLoS Computational Biology* 15(5), p. e1006395. [PubMed: 31048903]
- Friedl P, Wolf K, Lammerding J, 2011. Nuclear mechanics during cell migration. *Current Opinion in Cell Biology* 23(1), pp. 55–64. [PubMed: 21109415]
- Guck J, Schinkinger S, Lincoln B, Wottawah F, Ebert S, Romeyke M, Lenz D, Erickson HM, Ananthakrishnan R, Mitchell D, 2005. Optical deformability as an inherent cell marker for testing malignant transformation and metastatic competence. *Biophysical Journal* 88(5), pp. 3689–3698. [PubMed: 15722433]
- Guilak F, Tedrow JR, Burgkart R, 2000. Viscoelastic properties of the cell nucleus. *Biochemical and Biophysical Research Communications* 269(3), pp. 781–786. [PubMed: 10720492]
- Han YL, Pegoraro AF, Li H, Li K, Yuan Y, Xu G, Gu Z, Sun J, Hao Y, Gupta SK, 2020. Cell swelling, softening and invasion in a three-dimensional breast cancer model. *Nature physics* 16(1), pp. 101–108. [PubMed: 32905405]
- Harada T, Swift J, Irianto J, Shin J-W, Spinler KR, Athirasala A, Diegmiller R, Dingal PDP, Ivanovska IL, Discher DE, 2014. Nuclear lamin stiffness is a barrier to 3D migration, but softness can limit survival. *Journal of Cell Biology* 204(5), pp. 669–682.
- Herráez-Aguilar D, Madrazo E, López-Menéndez H, Ramírez M, Monroy F, Redondo-Muñoz J, 2020. Multiple particle tracking analysis in isolated nuclei reveals the mechanical phenotype of leukemia cells. *Scientific Reports* 10(1), pp. 1–12. [PubMed: 31913322]
- Kale VP, Hengst JA, Desai DH, Amin SG, Yun JK, 2015. The regulatory roles of ROCK and MRCK kinases in the plasticity of cancer cell migration. *Cancer Letters* 361(2), pp. 185–196. [PubMed: 25796438]
- Kim K, Guck J, 2020. The relative densities of cytoplasm and nuclear compartments are robust against strong perturbation. *Biophysical Journal* 119(10), pp. 1946–1957. [PubMed: 33091376]
- Krause M, Yang FW, Te Lindert M, Isermann P, Schepens J, Maas RJ, Venkataraman C, Lammerding J, Madzvamuse A, Hendriks W, 2019. Cell migration through three-dimensional confining pores:

speed accelerations by deformation and recoil of the nucleus. *Philosophical Transactions of the Royal Society B* 374(1779), p. 20180225.

- Liu H, Wen J, Xiao Y, Liu J, Hopyan S, Radisic M, Simmons CA, Sun Y, 2014. In situ mechanical characterization of the cell nucleus by atomic force microscopy. *ACS nano* 8(4), pp. 3821–3828. [PubMed: 24673613]
- Lombardi ML, Jaalouk DE, Shanahan CM, Burke B, Roux KJ, Lammerding J, 2011. The interaction between nesprins and sun proteins at the nuclear envelope is critical for force transmission between the nucleus and cytoskeleton. *Journal of Biological Chemistry* 286(30), pp. 26743–26753.
- Lv J, Liu Y, Cheng F, Li J, Zhou Y, Zhang T, Zhou N, Li C, Wang Z, Ma L, 2021. Cell softness regulates tumorigenicity and stemness of cancer cells. *The EMBO journal* 40(2), p. e106123. [PubMed: 33274785]
- Mak M, Kamm RD, Zaman MH, 2014. Impact of dimensionality and network disruption on microrheology of cancer cells in 3D environments. *PLoS Computational Biology* 10(11), p. e1003959. [PubMed: 25412385]
- Nikoli M, Scarcelli G, 2019. Long-term Brillouin imaging of live cells with reduced absorption-mediated damage at 660nm wavelength. *Biomedical optics express* 10(4), pp. 1567–1580. [PubMed: 31086695]
- Reymond N, Im JH, Garg R, Cox S, Soyer M, Riou P, Colomba A, Muschel RJ, Ridley AJ, 2015. RhoC and ROCKs regulate cancer cell interactions with endothelial cells. *Molecular Oncology* 9(6), pp. 1043–1055. [PubMed: 25677806]
- Rianna C, Radmacher M, Kumar S, 2020. Direct evidence that tumor cells soften when navigating confined spaces. *Molecular Biology of the Cell* 31(16), pp. 1726–1734. [PubMed: 31995446]
- Ribeiro AJ, Khanna P, Sukumar A, Dong C, Dahl KN, 2014. Nuclear stiffening inhibits migration of invasive melanoma cells. *Cellular and Molecular Bioengineering* 7(4), pp. 544–551. [PubMed: 25544862]
- Rochman M, Postnikov Y, Correll S, Malicet C, Wincovitch S, Karpova TS, McNally JG, Wu X, Bubunenko NA, Grigoryev S, 2009. The interaction of NSBP1/HMGN5 with nucleosomes in euchromatin counteracts linker histone-mediated chromatin compaction and modulates transcription. *Molecular Cell* 35(5), pp. 642–656. [PubMed: 19748358]
- Rowat AC, Jaalouk DE, Zwerger M, Ung WL, Eydelnant IA, Olins DE, Olins AL, Herrmann H, Weitz DA, Lammerding J, 2013. Nuclear envelope composition determines the ability of neutrophil-type cells to passage through micron-scale constrictions. *Journal of Biological Chemistry* 288(12), pp. 8610–8618.
- Scarcelli G, Kim P, Yun SH, 2011. In vivo measurement of age-related stiffening in the crystalline lens by Brillouin optical microscopy. *Biophysical Journal* 101(6), pp. 1539–1545. [PubMed: 21943436]
- Scarcelli G, Polacheck WJ, Nia HT, Patel K, Grodzinsky AJ, Kamm RD, Yun SH, 2015. Noncontact three-dimensional mapping of intracellular hydromechanical properties by Brillouin microscopy. *Nature methods* 12(12), pp. 1132–1134. [PubMed: 26436482]
- Singh VR, Yang YA, Yu H, Kamm RD, Yaqoob Z, So PT, 2019. Studying nucleic envelope and plasma membrane mechanics of eukaryotic cells using confocal reflectance interferometric microscopy. *Nature communications* 10(1), pp. 1–8.
- Staunton JR, Doss BL, Lindsay S, Ros R, 2016. Correlating confocal microscopy and atomic force indentation reveals metastatic cancer cells stiffen during invasion into collagen I matrices. *Scientific Reports* 6(1), pp. 1–15. [PubMed: 28442746]
- Stephens AD, Banigan EJ, Adam SA, Goldman RD, Marko JF, 2017. Chromatin and lamin A determine two different mechanical response regimes of the cell nucleus. *Molecular Biology of the Cell* 28(14), pp. 1984–1996. [PubMed: 28057760]
- Stephens AD, Liu PZ, Banigan EJ, Almossalha LM, Backman V, Adam SA, Goldman RD, Marko JF, 2018. Chromatin histone modifications and rigidity affect nuclear morphology independent of lamins. *Molecular Biology of the Cell* 29(2), pp. 220–233. [PubMed: 29142071]
- Swaminathan V, Myhre K, O'Brien ET, Berchuck A, Blobel GC, Superfine R, 2011. Mechanical stiffness grades metastatic potential in patient tumor cells and in cancer cell lines. *Cancer Research* 71(15), pp. 5075–5080. [PubMed: 21642375]

- Tseng Y, Lee JS, Kole TP, Jiang I, Wirtz D, 2004. Micro-organization and visco-elasticity of the interphase nucleus revealed by particle nanotracking. *Journal of Cell Science* 117(10), pp. 2159–2167. [PubMed: 15090601]
- Vilalta M, Rafat M, Giaccia AJ, Graves EE, 2014. Recruitment of circulating breast cancer cells is stimulated by radiotherapy. *Cell Reports* 8(2), pp. 402–409. [PubMed: 25017065]
- Wirtz D, 2009. Particle-tracking microrheology of living cells: principles and applications. *Annual review of biophysics* 38), pp. 301–326.
- Wisniewski EO, Mistriotis P, Bera K, Law RA, Zhang J, Nikolic M, Weiger M, Parlani M, Tuntithavornwat S, Afthinos A, 2020. Dorsoventral polarity directs cell responses to migration track geometries. *Science advances* 6(31), p. eaba6505. [PubMed: 32789173]
- Wolf K, Te Lindert M, Krause M, Alexander S, Te Riet J, Willis AL, Hoffman RM, Figdor CG, Weiss SJ, Friedl P, 2013. Physical limits of cell migration: control by ECM space and nuclear deformation and tuning by proteolysis and traction force. *Journal of Cell Biology* 201(7), pp. 1069–1084.
- Wullkopf L, West A-KV, Leijnse N, Cox TR, Madsen CD, Oddershede LB, Ertler JT, 2018. Cancer cells' ability to mechanically adjust to extracellular matrix stiffness correlates with their invasive potential. *Molecular Biology of the Cell* 29(20), pp. 2378–2385. [PubMed: 30091653]
- Xu H, Li Z, Yu Y, Sizdahkhani S, Ho WS, Yin F, Wang L, Zhu G, Zhang M, Jiang L, 2016. A dynamic in vivo-like organotypic blood-brain barrier model to probe metastatic brain tumors. *Scientific Reports* 6(1), pp. 1–12. [PubMed: 28442746]
- Yamada S, Wirtz D, Kuo SC, 2000. Mechanics of living cells measured by laser tracking microrheology. *Biophysical Journal* 78(4), pp. 1736–1747. [PubMed: 10733956]
- Zhang J, Alisafaei F, Nikoli M, Nou XA, Kim H, Shenoy VB, Scarcelli G, 2020. Nuclear mechanics within intact cells is regulated by cytoskeletal network and internal nanostructures. *Small* 16(18), p. 1907688.
- Zhang J, Nou XA, Kim H, Scarcelli G, 2017. Brillouin flow cytometry for label-free mechanical phenotyping of the nucleus. *Lab on a Chip* 17(4), pp. 663–670. [PubMed: 28102402]

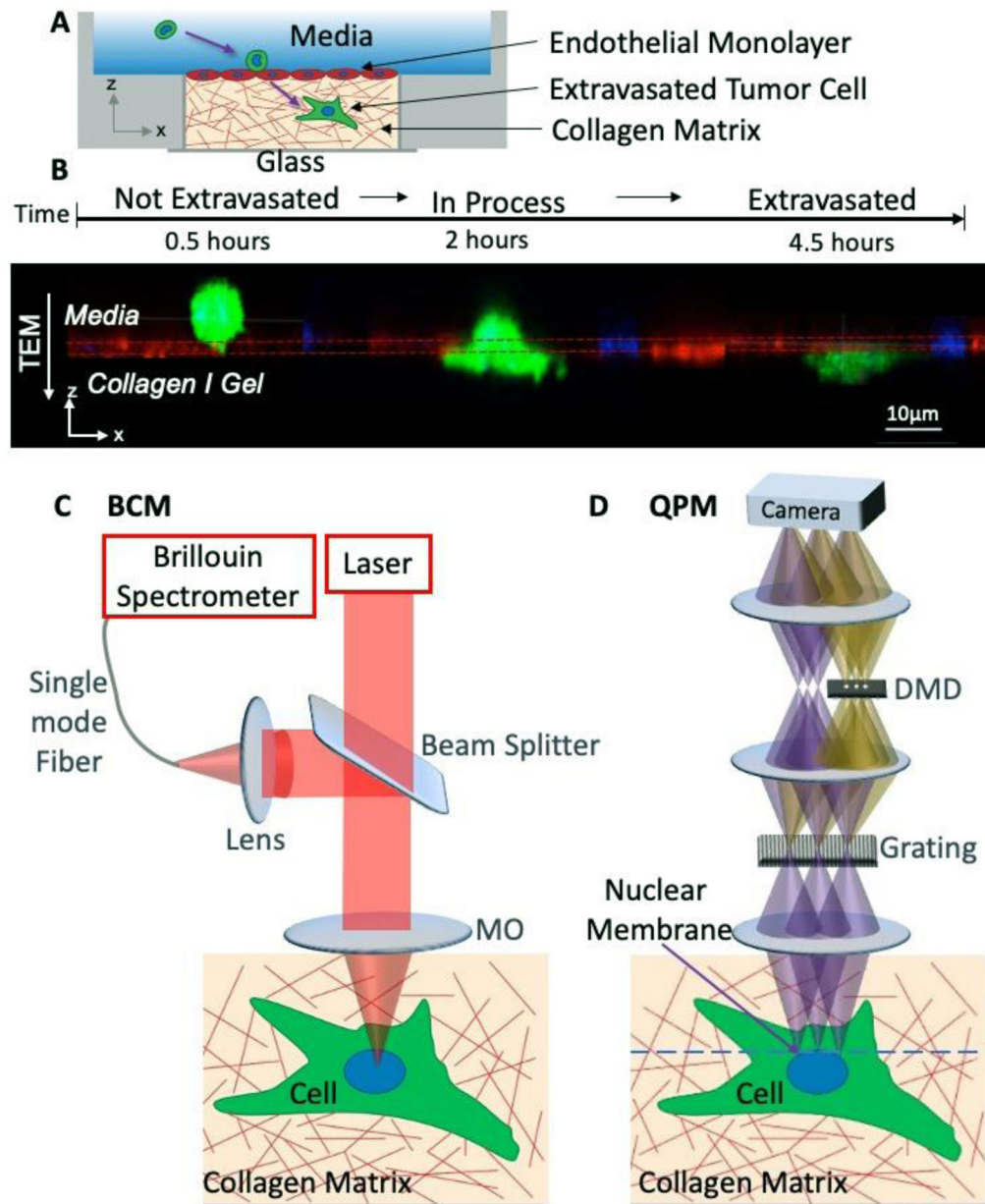


Figure 1: Methods to study stiffness during transendothelial migration.

A. In the assay, an endothelial monolayer (red) grows on top of a 2.5 μg/ml collagen I matrix over 100 μm in height. Tumor cells (green) are seeding into the media, attach to the endothelial cells, and transmigrate into the collagen matrix. **B.** Time-lapse confocal slices showing the tumor cell (A549-GFP, green) before extravasation, in process, and after transmigration across the endothelial monolayer (HUVEC-RFP, red). Nuclei (blue) are Hoechst-stained. **C.** The Brillouin Confocal Microscopy (BCM) measures Brillouin shift via raster scan throughout the cell in 3D. MO is the mirror and objective. **D.** Quantitative Phase Microscopy (QPM) measures the fluctuations of the nuclear membrane. In the backscattering detection arm, a common-path interferometer, comprised of the grating, DMD-2 and spatial frequency filter, enables depth-resolved optical phase measurements of

the nuclear membrane fluctuations. The camera collects the interferogram of the reference and object beams.

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

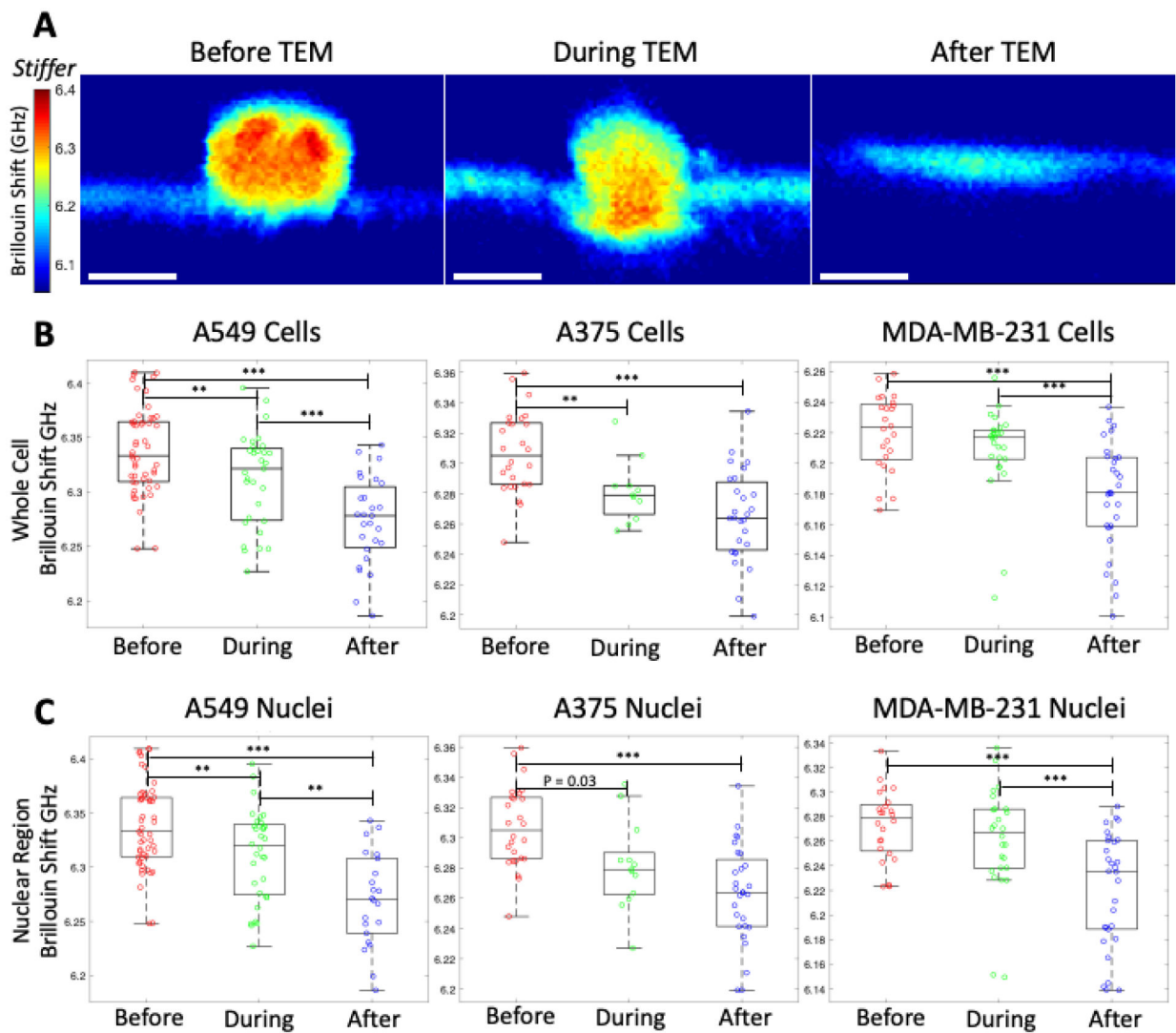
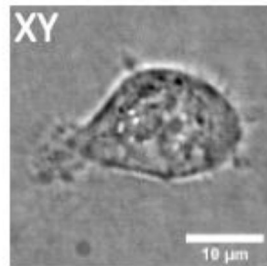
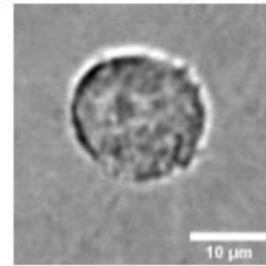
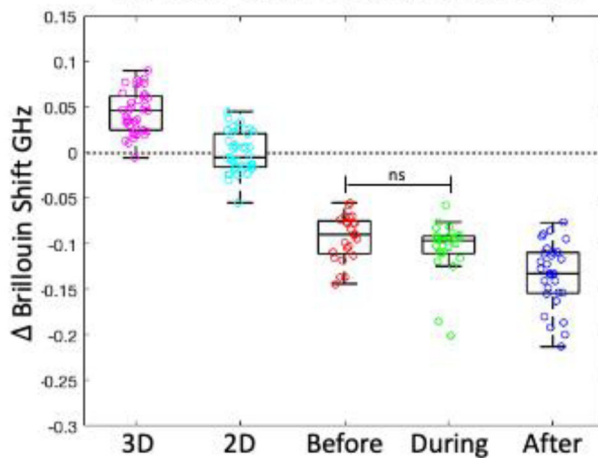
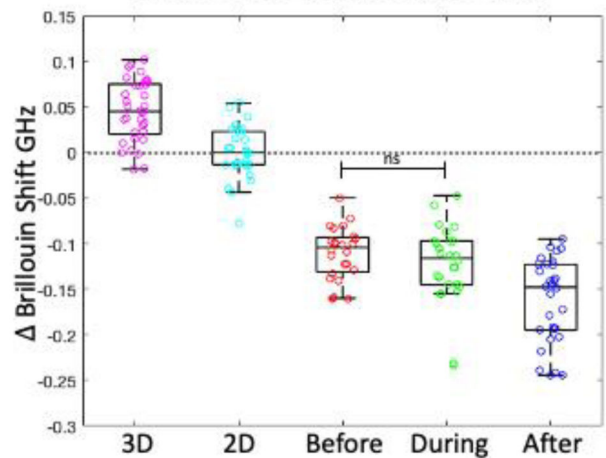


Figure 2: Tumor cells soften after transendothelial migration (TEM) according to Brillouin confocal microscopy.

A. Brillouin shift image of an MDA-MB-231 tumor cell on top of the endothelial cell monolayer before TEM, between endothelial cells during TEM, and after TEM under the monolayer. Higher GHz shift (red) corresponds to stiffer material. Scale bars are 20 μ m long.

B. Whole cell Brillouin shift (GHz) of A549, A375, and MDA-MB-231 cells before TEM (red), in-process of transendothelial migration (green), and after TEM (blue). Average Brillouin shifts for tumor cells before, during, and after TEM are: 6.34, 6.31, and 6.27 GHz (A549), 6.31, 6.28, and 6.27 GHz (A375), and 6.22, 6.21, and 6.18 GHz (MDA-MB-231).

C. Brillouin Shift in the nuclear region of A549, A375, and MDA-MB-231 cells before TEM (red), in-process of transendothelial migration (green), and after TEM (blue). Average nuclear Brillouin shifts for tumor cells before, during, and after TEM are: 6.34, 6.31, and 6.27 GHz (A549), 6.31, 6.28, and 6.26 GHz (A375), and 6.27, 6.26, and 6.22 GHz (MDA-MB-231). Higher GHz shift corresponds to stiffer material. Post-hoc Tukey's test p-values of 0.01 and 0.001 are signified by ** and ***, respectively.

A 2D (on top of collagen I gel)**3D (inside collagen I gel)****B** Whole Cell Δ Brillouin Shift**C** Nuclear Δ Brillouin Shift**Figure 3: Tumor cells in 3D collagen I have higher Brillouin shift than in 2D on collagen.**

A. In the 2D case, MDA-MB-231 tumor cells were placed in media on top of a collagen matrix. For 3D measurements, tumor cells were embedded in 2.5mg/ml rat tail collagen I. Brightfield images of 2D (left) and 3D (right) cells. Error bar is 10 μ m long. **B** and **C** Whole cell and nuclear (respectively) Brillouin shift measurements of MDA-MB-231 cells in 3D. (magenta), in 2D (cyan), and before (red), during (green), and after (blue) transendothelial migration. All data are normalized for comparison by subtracting the mean of the 2D measurements. Each circle represents a different cell. All post-hoc Tukey's tests were significant at $p < 0.001$, except as indicated. "ns" is not significant.

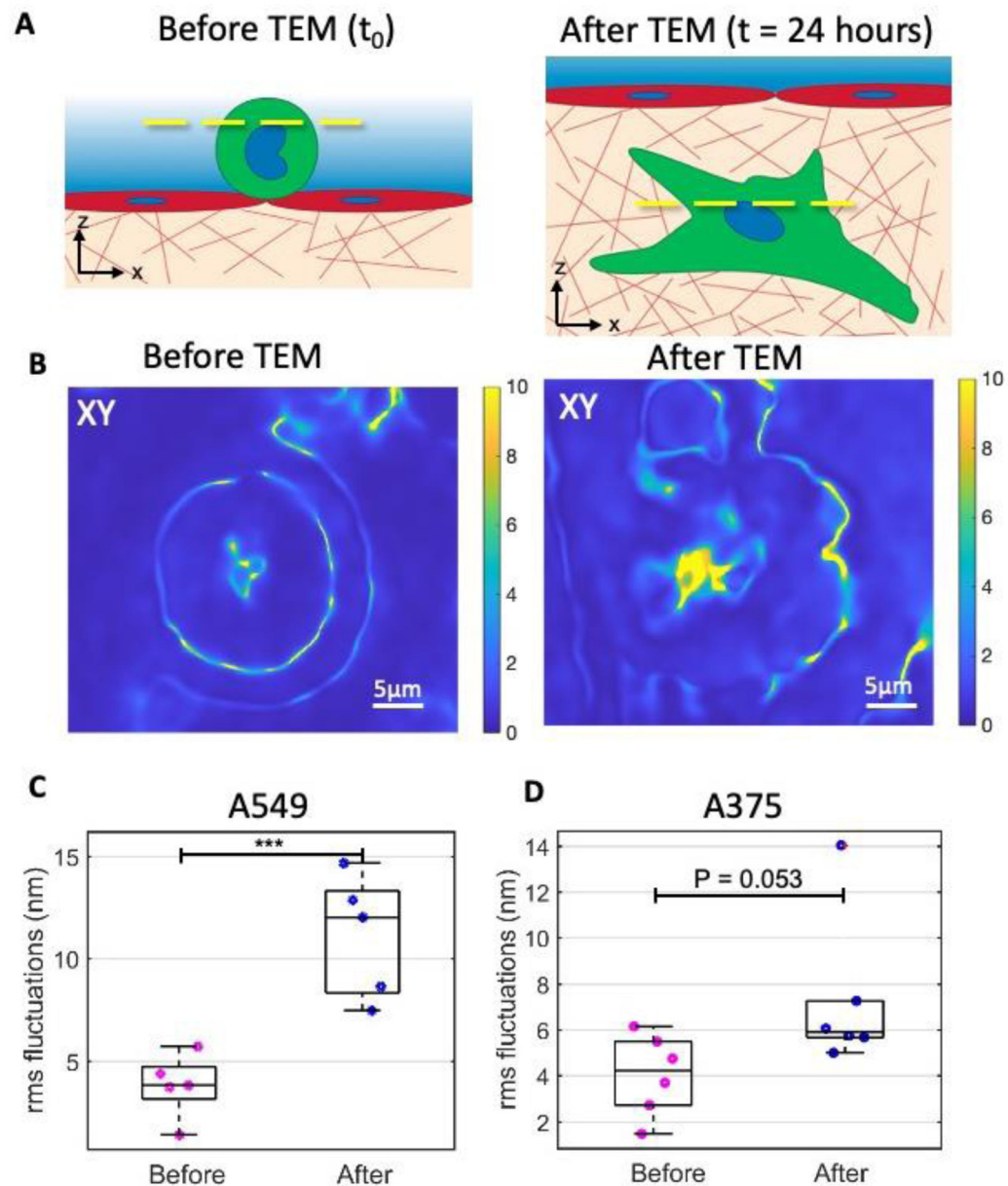


Figure 4: The nuclear membranes of tumor cells soften after transendothelial migration
A. Nuclear fluctuations were measured at the tumor cell nuclear membrane interface (yellow dotted line) before transendothelial migration (TEM), right after the tumor cells attach to the endothelial wall (left), and 24 hours later after the TEM event has occurred (right). **B.** QPM maps of root mean square fluctuation heights (nm) of A549 cells before and after TEM. These fluctuations are recorded in the plane of the nuclear membrane. **C.** QPM nuclear fluctuations (nm) of A375 cells before extravasation and after extravasation (24 hours post endothelial contact). $***$ signifies $p < 0.001$ (2-sample t-test). **D.** QPM nuclear fluctuations (nm) of A375 cells before extravasation and after extravasation (24 hours post endothelial contact). $P = 0.053$ (2-sample t-test).