Vimentin impacts centrosome function and microtubule acetylation

Renita Saldanha [1,2], Minh Tri Ho Thanh[1,2], Nikhila Krishnan[2,3], Heidi Hehnly[2,3], Alison Patteson[1,2]

1 – Physics Department, Syracuse University
2 – BioInspired Institute, Syracuse University
3 – Department of Biology, Syracuse University

Abstract
Cell polarity is important for controlling cell shape, motility, and cell division processes. Vimentin intermediate filaments are necessary for proper polarization of migrating fibroblasts and assembly of vimentin and microtubule networks is dynamically coordinated, but the precise details of how vimentin mediates cell polarity remain unclear. Here, we characterize the effects of vimentin on the structure and microtubule-nucleating activity of the cell centrosome and the dynamics of the microtubule network in wild-type and vimentin-null mouse embryonic fibroblasts (mEF's). We find that vimentin mediates the structure of the pericentrosomal material, promotes centrosomemediated microtubule regrowth, and increases the level of stable acetylated microtubules in the cell. Our results suggest that vimentin modulates centrosome structure and function as well as microtubule network stability, which has important implications for how cells establish proper cell polarization and persistent migration.

Introduction
Animal cells must be dynamic to move and change shape while also stable and rigid to generate sustained polarized motion. Central to these features is the cell's cytoskeleton. The animal cell's cytoskeleton is comprised of three interconnected filamentous networks: F-actin, microtubules, and intermediate filaments (1). These networks coordinate different functional aspects of the cell. Filamentous actin is the cell's main force-generating machinery, producing protrusive forces at the cell membrane and working with myosin motors to generate cellular contractile forces (2,3). Microtubules are rigid polarized polymers that span the length of cell and direct cargo transport and organization within the cell (4-6), and intermediate filaments form a passive filamentous network that supports and stabilizes the cell (7-10). Many cellular functions rely on coordinated crosstalk amongst these cytoskeletal networks, though there is much more known about how they work individually than together (11,12).
A number of emerging studies is pointing to a mutually reinforcing connection between vimentin intermediate filaments (IF) and the microtubule network (9,13-15). Vimentin is an IF protein expressed in mesenchymal cells and highly invasive cancer cells (16-18). Disruption of microtubules collapse the vimentin network (13) and likewise disrupting vimentin alters the microtubule network (15). Vimentin has been shown to enhance the persistence of the microtubule network by serving as a stable long-standing template for new microtubule growth (9), and recent work has shown in reconstituted *in vitro* systems that vimentin destabilizes microtubules against depolymerization through direct interaction (14). Together, these works highlight a subtle interplay between microtubules and vimentin that is important for polarized cell migration.
The cell's centrosome acts as the microtubule-organizing center of the cell and serves as the main microtubule-nucleating organelle (19). The centrosome is essential for whole-cell polarization and is typically positioned near the cell nucleus between the nucleus and the leading edge of the cell (20). Vimentin IFs are also localized around the cell nucleus, forming a dense physical mesh in the perinuclear region of the cell (7,10,16,17). Experiments with cells on patterned adhesive substrates show loss of vimentin increases variability in centrosome positioning (21). Cells lacking vimentin also have impaired polarization (22-26), which suggest that vimentin might interact with

both microtubules and their organizing center, the centrosome. Based on these studies, we hypothesized a functional link between vimentin and the cell's centrosome in establishing cell polarization and directed migration. Here we report novel experimental data that addresses the role of vimentin intermediate filaments in centrosome structure and microtubule-nucleating function. Our results suggest new mechanisms by which vimentin mediates cell polarization and cross-talks with the cell's microtubule architecture.

Materials and Methods

Cell Culture. Wild-type (vim+/+), vimentin-null (vim-/-) mouse embryonic fibroblasts (mEFs) were kindly provided by J. Ericsson (Abo Akademi University, Turku, Finland). Cells were maintained in Dulbecco's Modified Eagle's Medium (DMEM) including HEPES and sodium pyruvate supplemented with 10% fetal bovine serum (FBS), 1% penicillin streptomycin, and non-essential amino acids. Cell cultures were maintained at 37°C with 5% CO_2.

Immunofluorescence. Cells were fixed for immunofluorescence using methanol for 10 minutes at -20°C. Cell membranes were permeabilized with 0.05% Triton-X in PBS for 15 minutes at room temperature and blocked with 1% bovine serum albumin (BSA) for 1 hour at room temperature. For vimentin visualization, cells were incubated with primary rabbit anti-vimentin antibody (Abcam) diluted 1:200 in 1% BSA in PBS for 1.5 hour at room temperature; the secondary antibody anti-rabbit Alexa Fluor 555 (Invitrogen) was used at a dilution of 1:1000 in 1% BSA in PBS for 1 hour at room temperature. For visualizing microtubules, we used primary alpha-tubulin rat antibody (Bio-rad) diluted 1:200 in 1% BSA in PBS for 1.5 hours at room temperature and secondary antibody antirat Alexa Fluor 647 (Invitrogen) at a dilution of 1:1000 in 1% BSA in PBS for 1 hour at room temperature. For visualizing acetylated microtubules, cells were incubated with primary acetylated tubulin mouse antibody (Sigma Aldrich) diluted 1:200 in 1% BSA in PBS and incubated for 1.5 hour at room temperature; secondary antibody anti-mouse Alexa Fluor 568 (Invitrogen) was used at a dilution of 1:1000 in 1% BSA in PBS for 1 hour at room temperature. Cells were stained using Hoechst 33342 (Molecular Probes) for 1 hour at room temperature. For visualizing centrosome, cells were incubated with primary Cdk5rap2 rabbit antibody (Bethyl Laboratories), gamma-tubulin rabbit antibody (Sigma Aldrich), Pericentrin rabbit anibody (Abcam), Cenexin rabbit antibody (Protein tech) and centrin mouse antibody (EMD Millipore) diluted 1:200 in 1% BSA in PBS for 1.5 hours at room temperature; secondary antibody anti-rabbit Alexa Fluor 568 (Invitrogen) was used at a dilution of 1:1000 in 1% BSA in PBS for 1 hour at room temperature. Cells were mounted using Prolong diamond antifade mountant (Life Technologies) for Epi-fluorescence and Confocal Imaging.

Western Blot. Cell lysates were obtained by suspending the cells in lysis buffer (HSEG buffer pH 7.4, 40 mM NaCl (Fischer Scientific), 5mM EDTA (Fischer Scientific), 4% Glycerol (Fischer Scientific), 20mM NaF (Fischer Scientific), 1% TritonX-100 (Fischer Scientific), 1X protease inhibitor; 0.1mM PMSF. Bio-Rad Protein Assay Kit II (Bio-Rad laboratories) was used to measure the acetylated tubulin concentration from the post-nuclear supernatant collected from the lysates. Standard Western blot procedures were performed. The nitrocellulose membranes were probed with primary acetylated tubulin mouse antibody (Sigma-Aldrich) horseradish peroxidase diluted in TBS-Tween20 (ThermoFischer) and incubated overnight at 4^0C. The membranes were probed using mouse secondary antibody (Invitrogen) for an hour at room temperature. The protein levels were visualized using Clarity ™ western ECL (Bio-rad Laboratories) substrate and imaged using Bio-Rad ChemiDoc ™ imager.

Microtubule re-nucleation experiments and microtubule analysis. Cells were first treated with 1µM nocodazole (Sigma Aldrich M1404) for 30 minutes at room temperature to disrupt microtubule filaments. To allow for microtubule regrowth, nocodazole was washed out and cells

were placed back in cell media. Cells were fixed at 0, 1, 2, and 5 minute intervals after washout and stained for microtubules and vimentin. The microtubule re-growth was analyzed by tracing the radial region of microtubules stemming from the cell centrosome. Tracing was done manually in FIJI-ImageJ software. A minimum of 75 cells were analyzed over 3+ independent experiments per condition. For analyzing microtubules after nocodazole treatment, we used the Source Steger's algorithm in curve trace (27) in FIJI-ImageJ and computed the total microtubule contour length per cell; a minimum of 90 cells were analyzed over 3+ independent experiments per condition.

Imaging

Epi-fluorescence imaging. Epi-fluorescence imaging was performed using a Nikon Eclipse Ti (Nikon Instruments) inverted microscope equipped with an Andor Technologies iXon em+ EMCCD camera (Andor Technologies). Cells were imaged using a Plan Fluor (NA of 1.49) 100X oil immersion objective. A minimum of 100 cells were analyzed over 3+ independent experiments per condition. NIS Elements software was used to acquire images.

Confocal Imaging. Confocal imaging was performed using a Nikon microscope with spinning disk equipped with CMOS/CCD camera. Cells were imaged using a 63X (NA of 1.2) water objective. A minimum of 100 cells were analyzed over 3+ independent experiments. NISElements software was used to acquire images. All the images obtained were analyzed with FIJI – ImageJ.

Airy-Scan Confocal Imaging. Confocal images of microtubules and vimentin filaments were obtained using Zeiss Airy-Scan LSM 980 confocal microscope equipped with Plan Apochromat 63X Oil immersion objective with 1.4 NA, 8Y multiplex mode and GaAsP detector. Images obtained were processed using Airy-scan processing technique from Zeiss Zen 3.2 software. FIJIImageJ was used to visualize colocalization of microtubules and vimentin in vim+/+ cells.

Statistics. Data are presented as a mean value ± standard error of mean (SEM). Each experiment was performed at least three times. The unpaired Student's t-test with 95% confidence level was used to determine statistical differences between distributions. Denotations: *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$; ****, $p \leq 0.0001$; n.s., $p > 0.05$. n represents number of independent experiments. N represents the sample size. All the graphs and statistical analysis was done using GraphPad PRISM version 9 (GraphPad Software, Inc.).

Results

Loss of vimentin perturbs the pericentriolar matrix

We used confocal light sheet and fluorescence microscopy to examine the centrosome in vim+/+ and vim-/- mEFs (Fig. 1). To label the centrosome, cells were fixed and stained for the centrosomal protein CEP215 (cdk5rap2), a major pericentriolar material (PCM) protein associated with the organization of microtubules from the centrosome (28,29). Figure 1b shows immunofluorescence images of microtubules, CEP215, and vimentin taken by a confocal lightsheet microscope. In wild-type cells, as expected, there is a strong accumulation of tubulin at the centrosome with long microtubule filaments extending out radially. In vim -/- cells, there appears to be less tubulin around the centrosome. Interestingly, the centrosome itself (marked by CEP215) is noticeably more condensed and smaller in the vim -/- mEFs compared to vim +/+

mEFs. In addition, we observe an accumulation of vimentin that colocalizes with the centrosome in wildtype cells.

Based on these observations, we next sought to quantify centrosome structure in vim+/+ and vim/- mEFs (Fig. 1). The centrosome is composed of two perpendicular centrioles (a mother and daughter centriole) embedded in a dense matrix of PCM proteins (Fig. 1c, schematic). To examine the PCM and centriole structure, we fixed and labeled cells for multiple centrosomal proteins localized in either the PCM (CEP215, gamma-tubulin, pericentrin) or centriole protein complexes (cenexin and centrin). We found that the loss of vimentin significantly decreased the mean projected area of the centrosome by 40% as marked by CEP215 (Fig. 1d, $p \leq 0.001$) and by 40% as marked by gamma-tubulin (Fig. 1e, $p \leq 0.001$), which indicates that loss of vimentin perturbs the peri-centriolar matrix. There was no significant difference in centrosomal area observed by staining for pericentrin (Fig. 1f), but the intensity for cells lacking vimentin is lower compared to wild-type cells ($p<0.001$, SI Fig. 1c), suggesting cells lacking vimentin have less pericentrin protein. There was no significant difference observed for the mean area and intensity of centrosome marked by non PCM-proteins, cenexin (Fig 1g) and centrin (Fig. 1h). From these observations, we conclude that loss of vimentin disrupts multiple PCM proteins but does not affect the non-PCM proteins, cenexin and centrin.

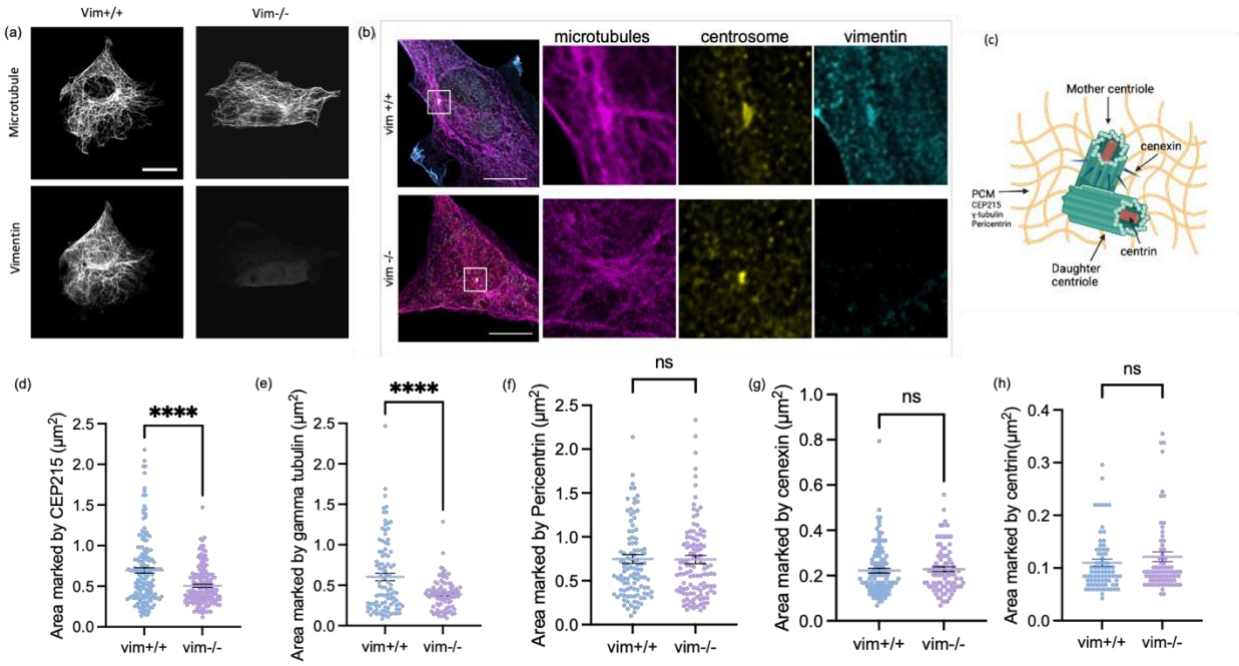

Figure 1: (**a**) Confocal images of microtubules and vimentin in vim+/+ and vim-/- mEF's. (**b**) Confocal Light-sheet microscopy images of microtubules, centrosomes and vimentin in vim+/+ and vim-/- mEF's**. (d-h)** Loss of vimentin decreases the projected area of the centrosome marked by CEP215 and gamma tubulin and shows no significant difference for pericentrin, cenexin and centrin. Denotation: ***, $p \leq 0.001$; **, $p \leq 0.01$) n=3, N>90 cells analyzed per condition. Scale bar is 10 µm.

Loss of vimentin disrupts centrosome-mediated microtubule re-nucleation

CEP215, gamma-tubulin and pericentrin are PCM proteins associated with the organization and nucleation of microtubules from the centrosome (28-31). Thus, based on our results from Fig. 1, we hypothesized that loss of vimentin may disrupted the microtubule nucleation function of the cell centrosome. To quantitatively analyze centrosome-mediated microtubule-nucleating activity, we performed nocodazole-washout microtubule re-nucleation assays in vim+/+ and vim-/- mEFs (Methods, Fig. 2a). Microtubules were first disassembled by treating cells with 1 µM nocodazole for 30 minutes, and then microtubule nucleation from the centrosome was examined at different times after nocodazole washout (1, 2 and 5 minutes).

The rate of microtubule re-nucleation was quantified by tracing the area around the centrosome showing microtubules re-nucleation (Fig. 2b). At time = 0 minutes (post nocodazole washout), the amount of tubulin at the centrosome is slightly lower in vimentin-null cells compared to wild-type cells (12% difference, p=0.04). At 1 min of regrowth, the centrosome in vim +/+ showed 28% more microtubule re-nucleation than in null-cells (p<0.001), and by 2 min, regrowth was 33% greater in wild-type than null-cells (p<0.001). At 5 min, re-nucleated microtubules span nearly the whole length of cell for both vim+/+ and vim-/- mEFs (Fig 2a). By computing the change in centrosomenucleated microtubule area over 0-2 minutes, we find that the area of centrosome-nucleated microtubules grows at a rate 40% higher in vim+/+ mEFs (0.64 µm^2/min) than vim-/- mEFs (0.39 µm^2/min) (Fig. 2c). Taken together, the results in Fig. 2 indicate vimentin impacts centrosome function, in particular enhancing the microtubule-nucleation activity of centrosomes.

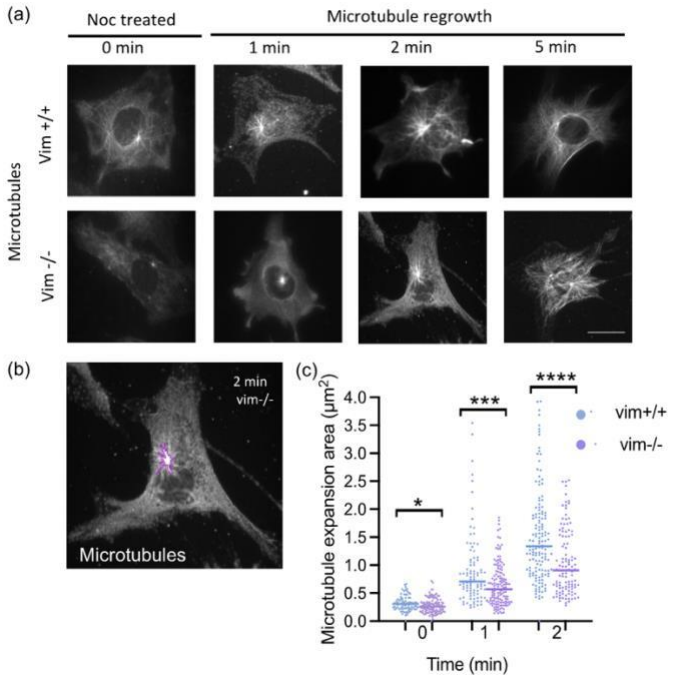

Figure 2: (a) Epi-fluorescence microscopy images of microtubules in vim+/+ and vim-/- mEFs after nocodazole treatment (0 min) and regrowth at 1, 2, and 5 minutes after nocodazole washout. **(b)** The area marked to study microtubule re-nucleation. **(c)** The quantification of microtubule expansion area in vim+/+ and vim-/- mEFs for 0,1 and 2 mins respectively. (Denotation: *, $p \leq 0.05$; ***, $p \leq 0.001$; n.s., $p > 0.05$). N ≥ 75 cells analyzed per condition, n=3. The scale bar is 20 µm.

Vimentin increases the amount of acetylated microtubules

On analyzing the nocodazole-treated cells (Fig. 2), we observed the presence of stable microtubule filaments that remained in vim+/+ mEFs but not vim -/- mEFs after sustained nocodazole treatment. As shown in Fig. 3a., after nocodazole treatment (t=0 min), a number of long microtubule filaments persist in wild-type mEF that are not observed in the null cells. To quantify the amount of remaining microtubules, microtubules were identified using a line/curve detection algorithm (Source Steger's algorithm, Methods) and the total microtubule contour length was computed per cell. As shown in Fig. 3b, wild-type cells had a greater amount of nocodazoleresistant microtubule filaments than vimentin-null cells.

The presence of long-lived nocodazole-resistant microtubules in wild-type mEF indicates a change in microtubule dynamics and stability. Microtubules dynamically assemble and disassemble with a turnover rate of 3-5 minutes (32). Nocodazole disrupts microtubule networks by inhibiting microtubule polymerization; for nocodazole-treatment times greater than the microtubule turnover time, microtubules will depolymerize unless they have been stabilized, for instance by post-translational modifications. Acetylation is a post translational modification in which an acetyl group is attached to the lysine group (K40) of α-tubulin (33). Acetylation increases the flexibility of microtubules, making them more resistant against mechanical forces and breakage (33). In living cells, microtubules are frequently damaged and subsequently depolymerized; thus, acetylation protects against breaking and increases the stability of microtubules (34).

To investigate changes in microtubule acetylation levels, we next performed immunofluorescence and immunoblotting studies of acetylated tubulin, as shown in Fig. 4. Figure 4a shows immunofluorescence images of acetylated tubulin in vim +/+ and vim -/- mEF. In wild-type cells, we observe significant amounts of acetylated tubulin that forms long filaments and a network-like structure in the cell. In contrast, in vimentin-null cells, the acetylated tubulin is much sparser and forms mostly small filamentous squiggles. As shown in Fig. 4b, the mean immunofluorescence intensity of acetylated tubulin is approximately 20% higher in vim+/+ cells compared to vim-/- cells ($p \leq 0.001$;). The immunoblotting studies further confirmed that acetylated tubulin is higher in vim+/+ cells compared to vim-/- cells (Fig 4c). Taken together, the results in Fig. 3 and 4 suggest vimentin positively influences the levels of microtubule acetylation, which enhances microtubule stability.

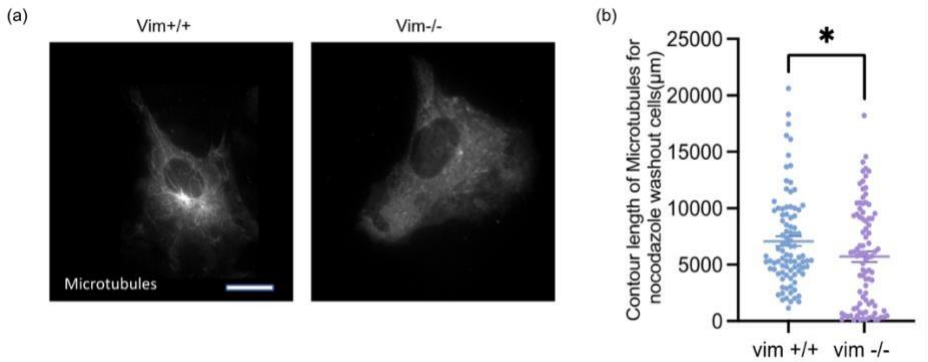

Figure 3: (a) Immunofluorescence images of microtubules in nocodazole treated vim +/+ and vim -/- mEFs. Vim+/+ mEF's show the presence of microtubules even after nocodazole treatment**. (b)** Quantification of the contour length of the microtubules using the curve fit algorithm from FIJIImageJ (Denotation: *, $p \leq 0.05$). N>90 cells analyzed per condition for n=3. The scale bar is 20 µm.

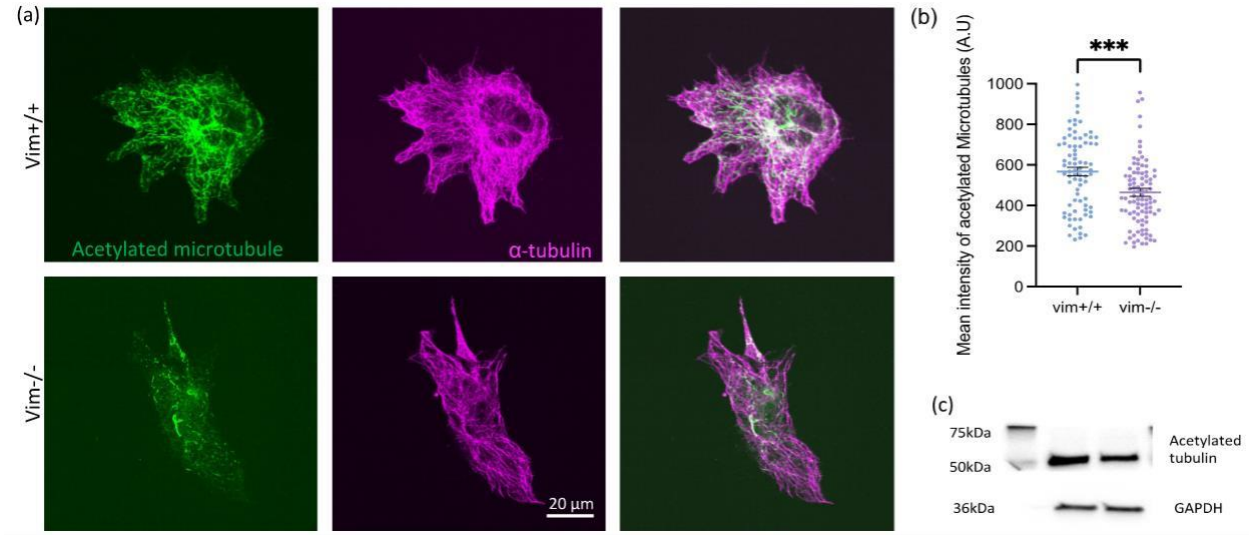

Figure 4: (a) Immunofluorescence images of acetylated microtubules for vim+/+ and vim-/- mEFs. **(b)** quantification of mean intensity of acetylated microtubules for vim+/+ and vim-/- mEFs (Denotation: ***, $p \leq 0.001$). $N \geq 90$ cells analyzed per condition, n=3. **(c)** Western blot analysis for acetylated tubulin in vim+/+ and vim-/- mEFs with GAPDH as control. The scale bar is 20 µm.

Discussion

Coordinated polarized cell migration requires an organized effort of three cytoskeletal networks- F-actin, microtubules, and vimentin - but the details of how these distinct networks interact to enable cell motility remain largely unclear. Our results here suggest that vimentin networks are important for centrosome function and stabilizes microtubule dynamics. In the presence of vimentin, we found that the size of centrosome is amplified, and centrosome-mediated microtubule nucleation is enhanced. Further, the presence of vimentin increases levels of microtubule acetylation, boosting microtubule stability in the cell. From these observations, we propose that vimentin can modulate centrosome structure and function as well as microtubule network stability.

Recent work is revealing intricate, complex pathways at the signaling crossroads among vimentin, microtubules, and F-actin in coordinating cell dynamics. Prior work by Jiu et al indicated that vimentin is antagonistic to actin stress fiber assembly through the microtubule-associated guanine nucleotide exchange factor GEF-H1 that activates RhoA (35). FRAP studies showed loss of vimentin increased GEF-H1 dynamics and increased GEF-H1 phosphorylation on Ser886, which was attributed to increased GEF-H1 activity in the absence of vimentin by using a phosphomimetic mutant protein (35). Our results here suggest a possible parallel pathway for increased GEF-H1 activity in vimentin-deficient cells through altered microtubule acetylation (Fig 5): we speculate that the increased levels of actin stress fiber assembly and cellular traction stresses in vimentin-deficient cells, which have been observed before, arises from the loss of stable acetylated microtubules, which releases GEF-H1 and increases the soluble pool of GEFH1 that activates RhoA. On the other hand, recent work on microtubule acetylation by Seetharaman *et al* would predict the reverse effect. Seetharaman *et al* found that microtubule acetylation can promote the release of GEF-H1 from microtubules to activate RhoA and actomyosin contractility (36). This

indicates a mechanism by which GEF-H1 activity increases with the level of acetylated microtubules, which here is greater in wild-type than vimentin-null mEF and would thus predict an increase in actin stress fiber assembly and contractility in wild-type cells, which we note has been observed in some contexts, such as cells plated on soft substrates or in soft gels compared to on rigid substrates (37-39). These two different expected effects of increased microtubule acetylation in vimentin-expressing cells on RhoA activity through GEF-H1. suggest at least two distinct biochemical signals that engage vimentin in regulating GEFH1 activity and actin stress fiber formation.

Our results showing vimentin intermediate filaments impact centrosome size and function might be surprising, given that the primary function of the cell centrosome in organizing microtubules. Given the interdependent organization of vimentin and microtubules, early work in the intermediate filament field did examine a possible link between vimentin and the centrosome (40,41). Results have been mixed. One of the first studies using electron microscopy in 1985 found no direct interaction between centrioles and vimentin in HeLa cells (40), whereas later in 1995 an association of vimentin and pericentriolar material was found in SW-13 cells stably transfected with low levels of vimentin (41). Our results indicate a possible functional role of vimentin in the microtubule-nucleating capacities of the centrosome. Our results suggest that vimentin impacts the size of the pericentral material of the cell centrosome, though it is not yet clear whether the change in size is due to altered spatial distribution of centrosomal protein or a change in the amount of PCM protein per centrosome, which are both possible structural changes for the centrosome (42). While there are relatively few studies on the association of vimentin and the centrosome, we note that vimentin was identified in a 2003 proteomic characterization of the human centrosome by protein correlation profiling (43). Taken together, these works highlight a need to re-examine the link between vimentin, centrosome, and its implications for whole cell organization and polarity.

Our results here suggest new mechanisms by which vimentin coordinates polarized cell migration by regulating centrosome function and microtubule stability. Our recent work has shown loss of vimentin leads to abnormally persistent cell migration through confining microfluidic channels and that the presence of vimentin is needed for the ability of cells to stop and turn around (23,24). In confining three-dimensional spaces, such as tissue, tight spaces add extra constraints and restriction to motion of the cytoskeleton. In many (though not all) 3D settings, the centrosome trails the cell nucleus, defining the tailing direction of the cell, and for the cell to change direction, the centrosome must reposition around the nucleus to a new trailing side of the cell (44). We propose that by promoting centrosome activity vimentin boosts the ability of the centrosome to dynamically organize and re-organizing microtubules and thus the capacity of the cell to coordinate polarized, directional motion. The microtubule network stabilizing effect of vimentin of the microtubule network may further allow the cell to build an internal compass that competes against externally imposed constraints.

Conclusions

Taken together, our results demonstrate a new role for VIFs in maintaining centrosome size and microtubule network stability. Our data provides evidence that VIFs are involved in regulating the microtubule-nucleating function of the cell centrosome and the expression levels of acetylated tubulin. Our results provide new insight into the coordinated crosstalk between vimentin and the microtubule networks in cell polarization.

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