Original Paper

Chorein Sensitivity of Actin Polymerization, Cell Shape and Mechanical Stiffness of Vascular Endothelial Cells

Ioana Alesutan^{a,e} Jan Seifert^{b,e} Tatsiana Pakladok^a Johannes Rheinlaender^b
Aleksandra Lebedeva^{a,c} Syeda T. Towhid^a Christos Stournaras^{a,d} Jakob Voelkl^a
Tilman E. Schäffer^{b,f} Florian Lang^{a,f}

Department of Physiology^a and Physics^b, University of Tübingen, Tübingen, Germany; ^cDepartment of Immunology, Institute of Experimental Medicine, St. Petersburg, Russia; ^dDepartment of Biochemistry, University of Crete Medical School, Crete, Greece; ^econtributed equally and thus share first authorship; ^fcontributed equally and thus share last authorship

Key Words

Chorein • HUVECs • Cytoskeleton • Stiffness • Focal adhesion kinase • Caspase 3 • Apoptosis • Necrosis • VPS13A

Abstract

Background/Aims: Endothelial cell stiffness plays a key role in endothelium-dependent control of vascular tone and arterial blood pressure. Actin polymerization and distribution of microfilaments is essential for mechanical cell stiffness. Chorein, a protein encoded by the VPS13A gene, defective in chorea-acanthocytosis (ChAc), is involved in neuronal cell survival as well as cortical actin polymerization of erythrocytes and blood platelets. Chorein is expressed in a wide variety of further cells, yet nothing is known about the impact of chorein on cells other than neurons, erythrocytes and platelets. The present study explored whether chorein is expressed in human umbilical vein endothelial cells (HUVECs) and addressed the putative role of chorein in the regulation of cytoskeletal architecture, stiffness and survival of those cells.

Methods: In HUVECs with or without silencing of the VPS13A gene, VPS13A mRNA expression was determined utilizing quantitative RT-PCR, cytoskeletal organization visualized by confocal microscopy, G/F actin ratio and phosphorylation status of focal adhesion kinase quantified by western blotting, cell death determined by flow cytometry, mechanical properties studied by atomic force microscopy (AFM) and cell morphology analysed by scanning ion conductance microscopy (SICM). **Results:** VPS13A mRNA expression was detectable in HUVECs. Silencing of the VPS13A gene attenuated the filamentous actin network, decreased the ratio of soluble G-actin over filamentous F-actin, reduced cell stiffness and changed cell morphology as compared to HUVECs silenced with negative control siRNA. These effects were paralleled by a significant decrease in FAK phosphorylation following VPS13A silencing. Moreover, silencing of the VPS13A gene increased caspase 3 activity and induced necrosis in HUVECs. **Conclusions:** Chorein is a novel regulator of cytoskeletal architecture, cell shape, mechanical stiffness and survival of vascular endothelial cells.

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Introduction

Chorein, a protein encoded by the VPS13A (vacuolar protein sorting 13 homolog A) gene [1], is expressed in a wide variety of cells [2-5]. Loss of function mutations [5] of the VPS13A gene [6-9] leads to chorea-acanthocytosis (ChAc), an autosomal recessive genetic disease characterized by progressive hyperkinetic movement disorder with muscle dystrophy, cognitive dysfunction, behavioural abnormalities, chronic hyperkalemia and variable acanthocytosis of red blood cells [5, 10]. Clinically overt disease develops at an age between 30 and 70 years and progresses to disability and premature death [10]. The lack of chorein action in ChAc leads to disappearance of cortical actin filaments in erythrocytes and thus to the spectacular erythrocyte shape change of acanthocytosis [3, 11]. Chorein is further expressed and modifies actin polymerization in blood platelets [12]. Loss of chorein renders cells more vulnerable to apoptosis [3], possibly contributing to increased susceptibility of neurons to cell death and neurodegeneration.

Chorein interacts with phosphoinositide-3-kinase (PI3K) [13, 14] leading to stimulation of PI3K signaling with subsequent activation of p21 protein-activated kinase (PAK1) [3]. PI3K signaling further involves focal adhesion kinase (FAK) [15-17]. FAK may transmit extracellular signals by activating downstream molecules such as: PI3K [18-20], paxillin [21] α -actinin [22], PAK1 [23-25], Nhe1 [26, 27], or rho kinase [28-34] and by stimulating polymerization of actin [35-37]. FAK plays a critical role in the formation and maintenance of focal adhesion complexes, thereby preventing anoikis in vascular endothelial cells [38-41].

At least in theory, the effect of chorein on cortical actin polymerization could impact on cell stiffness, which may affect endothelial cell function [42]. Aldosterone and salt-sensitive insertion of ENaC into the cell membrane of endothelial cells is known to trigger early swelling and later stiffening of those cells [43-46]. Endothelial cell stiffness compromises endothelial nitric oxide (NO) formation and thus the ability of endothelial cells to trigger vasodilation [43]. Accordingly, endothelial cell stiffening is thought to increase blood pressure [42]. ENaC insertion into the cell membrane and thus cell stiffness is further enhanced by C-reactive protein [47], an effect, which may well contribute to C-reactive protein-induced vascular lesions [48] including atherosclerosis [49]. Stiff endothelial cell syndrome (SECS) [42] may thus bear considerable pathophysiological relevance.

The present study explored whether chorein influences FAK signaling, actin polymerization, cell morphology, mechanical stiffness and cell survival of human umbilical vein endothelial cells.

Materials and Methods

Cell culture and silencing of HUVECs

Human umbilical vein endothelial cells (HUVECs) [50, 51] from Promocell (Heidelberg, Germany) were routinely cultured in VasculLife basal medium (Lifeline Cell Systems, Kirkland, USA) supplemented with 2% fetal bovine serum (FBS), 10 mM L-Glutamine, 5 ng/ml rh VEGF, 5 ng/ml rh EGF, 5 ng/ml rh FGF basic, 15 ng/ml rh IGF-1, 50 μ g/ml ascorbic acid, 1 μ g/ml hydrocortisone hemisuccinate and 0.75 units/ml heparin sulfate (Lifeline Cell Systems, Kirkland, USA). For silencing, HUVECs were cultured on six-well plates. After 24 hours, the cells were subsequently transfected with 5 nM validated VPS13A siRNA (ID no. S23342, Ambion, Life Technologies GmbH, Germany) or with 5 nM negative control siRNA (ID no. 4390843, Ambion, Life Technologies GmbH, Germany) using siPORT amine transfection agent (Ambion, Life Technologies GmbH, Germany) according to the manufacturer's protocol. The cells were used 48 hours after transfection.

Quantitative RT-PCR

To determine VPS13A mRNA levels and verify the silencing efficiency of the VPS13A gene in HUVECs, quantitative real-time PCR was performed [52-55]. Total RNA was isolated from HUVECs using Trifast

Reagent (Pqrlab, Erlangen, Germany) according to the manufacturer's instructions. Reverse transcription of 2 µg RNA was performed using oligo(dT)₁₂₋₁₈ primers (Invitrogen, Life Technologies GmbH, Germany) and SuperScriptIII Reverse Transcriptase (Invitrogen, Life Technologies GmbH, Germany). cDNA samples were treated with RNaseH (Invitrogen, Life Technologies GmbH, Germany). Quantitative real-time PCR was performed with the iCycler iQ™ Real-Time PCR Detection System (Bio-Rad Laboratories, Hercules, CA) using Universal TaqMan Master Mix (Applied Biosystems, Foster City, CA, USA) as recommended by the manufacturer. TaqMan primers and probes for *VPS13A* (ID no. Hs00362901_m1; Unigene ID: Hs.459790) and *HPRT1* (ID no. Hs02800695_m1; Unigene ID: Hs.412707) were purchased from Applied Biosystems (Applied Biosystems, Foster City, CA, USA). All PCRs were performed in duplicate, and mRNA fold changes were calculated by the $2^{-\Delta\Delta C_t}$ method using *HPRT1* as internal reference.

Measurement of the G/F actin ratio by Triton X-100 fractionation

To quantify actin polymerization in HUVECs [3, 56], cells were incubated in 500 µl of Triton X-extraction buffer containing 0.3% Triton X-100, 5 mM Tris, pH 7.4, 2 mM EGTA, 300 mM sucrose, 2 µM phalloidin, 1 mM PMSF, 10 µg/ml leupeptin, 20 µg/ml aprotinin, 1 mM sodium orthovanadate, and 50 mM NaF for 5 min on ice. The supernatant containing the soluble proteins was removed by aspiration. The Triton X-insoluble pellet was scraped from the plate directly into 500 µl of RIPA buffer (Cell Signaling, Danvers, MA). Any remaining insoluble material was removed by centrifugation. Equal volumes of each fraction were boiled in Roti Load 1 protein loading buffer (Carl Roth, Karlsruhe, Germany) at 100°C for 10 min. Proteins were separated on SDS-polyacrylamide gels and transferred to PVDF membranes. The membranes were incubated overnight at 4°C with monoclonal rabbit anti-β-Actin (13E5)-HRP conjugated antibody (1:1000, Cell Signaling, Danvers, MA). Antibody binding was detected with the ECL Western Blotting Substrate (Pierce, Rockford, IL) and bands were quantified using Quantity One Software (Bio-Rad, München, Germany).

Western Blotting

HUVECs were lysed with ice-cold RIPA lysis buffer (Cell Signaling, Danvers, MA) supplemented with complete protease and phosphatase inhibitor cocktail (Thermo Fisher Scientific, Rockford, IL). After centrifugation at 10000 rpm for 5 min, 30 µg of proteins were boiled in Roti Load 1 protein loading buffer (Carl Roth, Karlsruhe, Germany) at 100°C for 10 min. Proteins were separated on SDS-polyacrylamide gels and transferred to PVDF membranes [55, 57]. The membranes were incubated overnight at 4°C with rabbit phospho-FAK (Tyr397) antibody (1:1000, Cell Signaling, Danvers, MA), rabbit polyclonal FAK antibody (A-17) (1:1000, Santa Cruz, Dallas, Texas, USA) or rabbit anti-GAPDH antibody (1:1000; Cell Signaling, Danvers, MA) and then with secondary anti-rabbit HRP-conjugated antibody (1:1000; Cell Signaling, Danvers, MA) for 1 hour at room temperature. For loading controls, the membranes were stripped in stripping buffer (Thermo Scientific, USA) at RT for 10 min. Antibody binding was detected with the ECL Western Blotting Substrate (Pierce, Rockford, IL) and bands were quantified using Quantity One Software (Bio-Rad, München, Germany).

Immunocytochemistry and confocal microscopy

HUVECs grown on chamber slides were fixed for 15 min with 4% paraformaldehyde, washed with PBS and permeabilized for 10 min in 0.1% Triton X-100/PBS. The slides were blocked with 5% goat serum in 0.1% Triton X-100/PBS for 1 hour at RT. Actin was stained with rhodamine-phalloidin (1:100, Invitrogen, Karlsruhe, Germany) for 1 hour at RT, in the dark. The slides were mounted with ProLong Gold antifade reagent (Invitrogen, Karlsruhe, Germany). Confocal microscopy was performed as described previously [3, 58] with a confocal laser-scanning microscope (LSM 510, Carl Zeiss MicroImaging GmbH) using a water immersion A-Plan 40x/1.2W DICIII. At least 30 different fields were counted (about 70 cells), 8 independent experiments were performed and analysed.

AFM force mapping

AFM force mapping [59] was performed on live HUVECs plated onto fibronectin-coated Petri dishes and silenced with negative control siRNA or with *VPS13A* siRNA. The force mapping experiments were performed with a commercial AFM setup (MFP3D Bio, Asylum Research, Santa Barbara, CA) at 37°C about 48 hours after transfection. Right before the AFM experiments the cell culture medium was replaced with CO₂-independent Leibovitz's L-15 medium (Invitrogen, Life Technologies GmbH, Germany).

Two-dimensional arrays of force-distance-curves were recorded on the cells (with a scan area of 80 x 80 μm^2 , a force curve rate of 3 Hz corresponding to a vertical tip velocity of 20 $\mu\text{m/s}$, and a maximum force of 1 nN) using a single sphere-tip cantilever (Nanosensors SD-ST-CONT-M, NanoWorld, Neuchâtel, Switzerland) with a radius of $R = 1 \mu\text{m}$. The cantilever's spring constant was calibrated by the thermal noise method [60] to 0.38 N/m. The local mechanical stiffness in terms of Young's modulus E was obtained by fitting the force-indentation-curves with the spherical Hertz model [61]:

$$F = \frac{4}{3} \frac{E \sqrt{R} \delta^{3/2}}{1 - \nu^2},$$

where δ is the sample indentation and ν is the Poisson's ratio of the sample (assumed as $\nu = 0.5$). Two representative force curves and fits of the spherical Hertz model are shown in Fig. 2D and H.

A single value for the mechanical stiffness of a single cell was derived by averaging E over the cell area (exemplarily outlined by the dashed curves in Fig. 2C and G), where regions with a cell thickness below 1 μm were excluded to avoid an influence of the underlying substrate on the derived stiffness value. The average mechanical stiffness $\langle E \rangle$ was then obtained by averaging the stiffness values of 24 negative control siRNA silenced HUVECs and of 24 VPS13A siRNA silenced HUVECs, respectively. Since the mechanical stiffness of live cells is log-normally distributed [62] averaging and statistical tests were carried out with the logarithmic stiffness.

SICM topography imaging

SICM topography imaging [63, 64] was performed on HUVECs plated onto fibronectin-coated Petri dishes and silenced with negative control siRNA or with VPS13A siRNA. SICM allows non-contact and compression-free topography imaging of soft samples such as membranes [65] or cells [66, 67]. Recently, SICM has been used for stiffness mapping of living cells [68]. The images were recorded in backstep/hopping mode [66, 69] using a home-built SICM setup. The nanopipettes were fabricated from borosilicate glass capillaries (1B100F-4, World Precision Instruments Inc., Sarasota, FL) using a CO_2 -laser-based micropipette puller (P-2000, Sutter Instruments, Novato, CA) and had typical opening radii of 100-150 nm, providing a high signal-to-noise ratio while still allowing sub-micrometer lateral image resolution [70]. The SICM topography images were recorded on live cells at 37°C about 48 hours after transfection. Right before the SICM experiments the cell culture medium was replaced with CO_2 -independent Leibovitz's L-15 medium (Invitrogen, Life Technologies GmbH, Germany). Height profiles of the cells (from one edge of a cell through its center to its other edge) were obtained from the topography images (20 negative control siRNA silenced HUVECs and 20 VPS13A siRNA silenced HUVECs, 3 sections per cell). For each profile the cell height, h_{max} , was obtained as the maximum value of the profile; the lamellipodium height, h_{lam} , was obtained by averaging the outer 17% on each side of the profile (s. Fig. 3C and F). The relative lamellipodium height was defined as the ratio of lamellipodium height to cell height, $h_{\text{lam}}/h_{\text{max}}$.

Caspase 3 activity

The cultured HUVECs were detached from the 6-well plate by treatment with 1x trypsin-EDTA (PAA, Austria) for 5 minutes. The cells were washed with Vasculife complete VEGF medium (Lifescience Inc. Germany) with 10% FBS by centrifugation at 1600 rpm for 3 minutes. Active caspase-3 was measured by CaspGlow Fluorescein Active Caspase-3 Staining kit (BioVision, CA, USA) according to the manufacturer's instructions. Briefly, 10^5 cells were suspended in 100 μl Vasculife complete VEGF medium, stained for 1 hour with 0.1 μl active caspase-3-FITC antibody under cell culture conditions. Then the cells were washed once in 200 μl wash buffer supplied in the kit, resuspended in 200 μl wash buffer and fluorescence was determined by flow cytometry using a BD FACS Calibur (BD Biosciences, CA, USA).

Analysis of necrosis

To determine necrosis, 10^5 cells/100 μl in complete Vasculife VEGF medium were incubated in 70% ethanol (Sigma, USA) on ice for 30 minutes, centrifuged at 1600 rpm for 3 minutes at 4°C and added to 200 μl of hypotonic buffer (0.1% sodium citrate, 0.1% triton X-100, 2mM CaCl_2 , 20U/ml RNase A in deionized water) together with 24 μl /ml Annexin V-FITC (Mabtag, Germany) and 50 μg /ml propidium iodide (Mabtag, Germany) and incubated on ice in the dark for 60 minutes. The cells were washed once at 1600 rpm for 3

Fig. 1. Effect of VPS13A silencing on actin polymerization in HUVECs. A. Representative original bands of *VPS13A* (upper bands) and calibrator/control *HPRT1* (lower bands) mRNA expression in HUVECs after 48 hours silencing with 5 nM negative control siRNA or with 5 nM VPS13A siRNA. B. Arithmetic means $\pm$ SEM ($n = 4$; arbitrary units) of *VPS13A* mRNA levels in HUVECs after 48 hours silencing with 5 nM negative control siRNA (Neg. siRNA) or with 5 nM VPS13A siRNA (VPS13A siRNA). ***($p < 0.001$) indicates statistically significant difference from HUVECs silenced with negative control siRNA; t-test. C. Representative original western blot of soluble G-actin over filamentous F-actin in HUVECs after 48 hours silencing with 5 nM negative control siRNA (Neg. siRNA) or with 5 nM VPS13A siRNA (VPS13A siRNA). D. Arithmetic means $\pm$ SEM ($n = 11$; arbitrary units) of soluble G-actin over filamentous F-actin ratio in HUVECs after 48 hours silencing with 5 nM negative control siRNA (Neg. siRNA) or with 5 nM VPS13A siRNA (VPS13A siRNA). **($p < 0.01$) indicates statistically significant difference from HUVECs silenced with negative control siRNA; Mann-Whitney test. E. Confocal microscopy of actin cytoskeleton in HUVECs after 48 hours silencing with 5 nM negative control siRNA (Neg. siRNA) or with 5 nM VPS13A siRNA (VPS13A siRNA). Images are representative of $n=8$ independent experiments.

minutes, resuspended in PBS/1% BSA and Annexin V-FITC fluorescence as well as PI fluorescence intensity were determined by flow cytometry using a BD FACS Calibur (BD Biosciences, CA, USA).

Statistics

Data are provided as means $\pm$ SEM, n represents the number of experiments. All data were tested for significance using Student's unpaired t-test or Mann-Whitney test, as indicated in the figure legends. Only results with p values < 0.05 were considered statistically significant.

Results

The present study explored whether chorein is expressed in vascular endothelial cells and whether it participates in the regulation of actin polymerization, cell shape and mechanical stiffness of those cells. Quantitative RT-PCR was employed to determine chorein expression. As illustrated in Fig. 1A, *VPS13A* transcript levels are detectable in human

Fig. 2. AFM stiffness analysis with or without VPS13A silencing in HUVECs. Representative optical image (A), AFM topography image (B), AFM stiffness map (C), and representative force curve (D) of HUVECs after 48 hours silencing with 5 nM negative control siRNA. Representative optical image (E), AFM topography image (F), AFM stiffness map (G), and representative force curve (H) of HUVECs after 48 hours silencing with 5 nM VPS13A siRNA. AFM scan area $80 \times 80 \mu\text{m}^2$ (indicated by the dashed box in A and E). To avoid an influence of the underlying substrate on the stiffness, only regions with a cell thickness above $1 \mu\text{m}$ (exemplarily outlined by dashed curve in C and G) were considered. I. Geometric means $\pm$ SEM ($n = 24/\text{group}$) of the averaged stiffness of HUVECs after 48 hours silencing with 5 nM negative control siRNA or with 5 nM VPS13A siRNA, showing that the VPS13A silenced HUVECs are softer by about 53% ($p = 1.5 \cdot 10^{-5}$). ***($p < 0.001$) indicates statistically significant difference from HUVECs silenced with negative control siRNA; t-test.

umbilical vein endothelial cells (HUVECs). Further experiments explored whether chorein influences the actin cytoskeleton organization in HUVECs. To this end, RNA interference was used to suppress endogenous *VPS13A* mRNA levels. To confirm the effects of silencing, *VPS13A* mRNA expression was examined by quantitative RT-PCR. As shown in Fig. 1A and B, *VPS13A* mRNA levels were significantly reduced in HUVECs silenced with VPS13A siRNA but not in HUVECs transfected with negative control siRNA. As illustrated in Fig. 1C and D, the ratio of soluble G-actin over filamentous F-actin was significantly higher in HUVECs silenced with VPS13A siRNA than in HUVECs silenced with negative control siRNA, an observation pointing to increased actin depolymerization. This was confirmed by confocal microscopy showing that HUVECs silenced with negative control siRNA had a clear filamentous actin network, which was markedly decreased in HUVECs silenced with VPS13A siRNA (Fig. 1E). Images are representative of 8 independent experiments. Filamentous actin network was reduced in approximately $\frac{3}{4}$ of investigated HUVECs silenced with VPS13A siRNA. Thus, in human umbilical vein endothelial cells, chorein influences the polymerization of actin filaments.

Fig. 3. SICM high-resolution topography imaging of HUVECs with or without VPS13A silencing. A-B. SICM topography images of representative negative control siRNA silenced HUVECs in a confluent monolayer. C. Cross section along the dashed line in (B). D-E. SICM topography images of representative VPS13A siRNA silenced HUVECs in a confluent monolayer. F. Cross section along the dashed line in (E). G. Means of the relative lamellipodium height of 20 negative control siRNA and 20 VPS13A siRNA treated HUVECs. ***($p < 0.001$) indicates statistically significant difference from HUVECs silenced with negative control siRNA; t-test. SICM scan areas: $200 \times 200 \mu\text{m}^2$ (A and D), $80 \times 80 \mu\text{m}^2$ (B) and $90 \times 90 \mu\text{m}^2$ (E). The three-dimensional relief is displayed to scale. The blue color marks regions where the underlying substrate is visible.

Actin depolymerization indicates impaired filament stability [56] and is expected to modify the mechanical properties of HUVECs. In view of the impact of chorein silencing on actin polymerization we explored the possibility that chorein influences the stiffness and morphology of the human umbilical vein endothelial cells. Atomic force microscopy was thus employed to determine the stiffness of HUVECs following transfection with either negative control siRNA or with VPS13A siRNA (Fig. 2). Individual endothelial cells were localized using optical phase contrast microscopy and subsequently imaged with AFM force mapping (Fig. 2A-H). Chorein silencing results in a softer cell body (Fig. 2G and H) compared to the negative control silenced HUVECs (Fig. 2C and D). An analysis of the AFM force mapped cells revealed that chorein silenced HUVECs are, on average, significantly softer as compared to HUVECs transfected with negative control siRNA ($\langle E \rangle = 0.8 \pm 0.1$ kPa and 1.7 ± 0.2 kPa, respectively, Fig. 2I).

To analyse the cell morphology SICM topography imaging was performed on HUVECs in a confluent monolayer following transfection with either negative control siRNA or with VPS13A siRNA (Fig. 3). In comparison with the negative control siRNA treated HUVECs (Fig. 3A), the VPS13A siRNA silenced HUVECs (Fig. 3D) exhibited a distinct change in cell morphology, as their lamellipodium became more prominent and extended. Cross sections through single representative cells (Fig. 3B and E) revealed a smaller relative lamellipodium height for the VPS13A siRNA silenced HUVECs ($h_{lam}/h_{max} \approx 0.1$, Fig. 3F) as compared to the negative control siRNA silenced HUVECs ($h_{lam}/h_{max} \approx 0.3$, Fig. 3C). On average, the relative

Fig. 4. Phosphorylation of focal adhesion kinase (FAK) with or without VPS13A silencing in HUVECs. A. Representative original western blots showing phosphorylated-FAK (Tyr397), total FAK and GAPDH protein abundance in HUVECs after 48 hours silencing with 5 nM negative control siRNA (Neg. siRNA) or with 5 nM VPS13A siRNA (VPS13A siRNA). B. Arithmetic means $\pm$ SEM ($n = 8$, arbitrary units) of phosphorylated-FAK/total FAK protein ratio normalized to GAPDH in HUVECs after 48 hours silencing with 5 nM negative control siRNA (Neg. siRNA) or with 5 nM VPS13A siRNA (VPS13A siRNA). *($p < 0.05$) indicates statistically significant difference from HUVECs silenced with negative control siRNA; *t*-test.

Fig. 5. Effect of VPS13A silencing on apoptosis and necrosis of HUVECs. A. Representative dot plots and arithmetic means $\pm$ SEM ($n = 10$, %) of the percentage of HUVECs with active caspase 3 quantified by active caspase 3-FITC fluorescence in flow cytometry analysis after 48 hours silencing with 5 nM negative control siRNA (Neg. siRNA) or with 5 nM VPS13A siRNA (VPS13A siRNA); cleaved caspase3-FITC: FL1-Height. B. Representative dot plots and arithmetic means $\pm$ SEM ($n = 10$, %) of the percentage of necrotic HUVECs quantified by Annexin V/PI flow cytometry analysis after 48 hours silencing with 5 nM negative control siRNA (Neg. siRNA) or with 5 nM VPS13A siRNA (VPS13A siRNA); Annexin V: FL1-Height, PI: FL2-Height. *($p < 0.05$) indicates statistically significant difference from HUVECs silenced with negative control siRNA; Mann-Whitney test.

lamellipodium height of the VPS13A siRNA silenced HUVECs was significantly smaller than that of the negative control siRNA silenced HUVECs (Fig. 3G).

To gain some insight into the signaling involved in chorein-sensitive actin filament organization, cell shape and stiffness of HUVECs and in view of previous findings that focal adhesion kinase (FAK) is involved in cytoskeletal dynamics and organization as well as maintenance of cell stiffness [29], further experiments explored the role of chorein in the regulation of focal adhesion kinase. As illustrated in Fig. 4, VPS13A gene silencing was followed by a significant decrease of FAK phosphorylation in HUVECs pointing to a decrease of FAK activity.

In view of previous reports showing that loss of chorein leads to apoptosis of K562-erythrocytic cells [3] and that FAK signaling plays an important role in prevention of apoptosis [38, 39, 41], we explored the possibility that chorein influences HUVECs survival. As a result, VPS13A gene silencing was followed by a significant increase of caspase 3 activity in HUVECs (Fig. 5A). Furthermore, as shown in Fig. 5B, the percentage necrotic cells was significantly increased in HUVECs silenced with VPS13A siRNA as compared to negative control siRNA silenced HUVECs.

Discussion

The present observations disclose a novel function of chorein, i.e. regulation of cytoskeletal reorganization, cell morphology and mechanical stiffness of vascular endothelial cells. In human umbilical vein endothelial cells, decreased chorein expression markedly reduced the filamentous actin network which led to a distinct change in cell morphology with more prominent lamellipodium and softening of those cells. Furthermore, loss of chorein leads to caspase 3 activation and decreases survival of the human umbilical vein endothelial cells. The present observations provide compelling evidence that chorein is not only important for erythrocyte shape and neuronal function [3, 6-9] but may be effective in a wide variety of further functions.

At least in theory, endothelial cell stiffening may decrease the sensitivity of endothelial nitric oxide (NO) formation to shear stress and thus interfere with endothelial-dependent vasodilation [43]. For instance, aldosterone has been suggested to enhance endothelial cell stiffness and thus to decrease NO release and counteract vasodilation by up-regulating expression of the epithelial Na⁺ channel ENaC [44]. Along those lines, the mineralocorticoid receptor antagonist spironolactone reversed aldosterone induced endothelial cell stiffness and enhanced NO release [57]. Accordingly, endothelial cell stiffening was considered to predispose for decrease of NO release and increase of blood pressure [42]. In view of the present observations, not only decreased but as well increased chorein expression or function may be pathophysiologically relevant. According to the present observations increased chorein expression in endothelial cells could theoretically result in a "stiff endothelial cell syndrome" (SECS) [42] with potential impact on NO release and blood pressure regulation [43, 46]. Thus, our results suggest that endothelial chorein expression is involved in the regulation of endothelial function and may affect blood pressure regulation. Future studies are required, however, to test whether indeed excessive chorein influences endothelial NO release and systemic blood pressure.

The effects of chorein on actin cytoskeleton organization and cell stiffness are paralleled by the respective alterations of focal adhesion kinase (FAK) phosphorylation in HUVECs. FAK is a component of focal adhesions (FAs) considered as a point of convergence of integrin and growth factor mechanical signaling [58-62]. FAK is important for maintaining cell rigidity (stiffness) through promoting a static and highly aligned contractile cytoskeleton [29, 30, 34]. It is a powerful regulator of actin polymerization and distribution of microfilaments [21, 35-37] by activating downstream molecules such as: PI3K [18-20], paxillin [21, 35], PAK1 [23-25], Nhe1 [26, 27], Src [28, 32, 34], rho kinase [28-34] or α -actinin [22]. In FAK-deficient cells, reduced cytoskeletal stability is attributed to a compensatory increase of rhoA-kinase and ROCK activity [28, 29, 32, 33]. The FAK-sensitive regulation of cortical actin filament

architecture and dynamics impacts on exocytosis, membrane blebbing and receptor function [63-70].

Furthermore, focal adhesion kinase directly interacts with multiple cell surface receptors and signaling proteins [34, 60, 71-76] thus mediating a variety of physiological responses. As a regulator of focal adhesion dynamics, FAK plays an important role in vascular endothelial mechano-transduction induced by various stimuli [77-81] and contributes to the regulation of vascular cell proliferation and apoptosis [39, 41, 82-84], tissue remodelling [85, 86], angiogenesis and cell migration [82, 87, 88], leukocyte adhesion and vascular inflammation [89] as well as endothelial barrier function [82, 90]. Therefore, by regulating the activity of FAK, chorein may contribute to regulation of other physiological processes beyond regulating actin polymerization and cell stiffness. The present observations indeed reveal that chorein silencing leads to caspase 3 activation and increased necrosis in HUVECs. Thus, our results indicate that chorein is important for cell survival and that disruption of chorein-dependent signaling results in reduced viability of vascular endothelial cells.

In ChAc patients, the neuronal symptoms are most striking but possibly only the tip of the iceberg [5, 10]. However, additional studies are needed to define the physiological and pathophysiological role of chorein-dependent regulation of vascular endothelial cell stiffness and survival.

In conclusion, chorein is expressed in vascular endothelial cells and regulates endothelial cytoskeletal architecture and endothelial cell survival. Decreased chorein expression depolymerizes the actin filaments and thus leads to a distinct change in cell morphology and to softening of the vascular endothelial cells.

Abbreviations

AFM (atomic force microscopy); ChAc (chorea-acanthocytosis); EGF (epidermal growth factor); ENaC (amiloride-sensitive epithelial sodium channel); FAK (focal adhesion kinase); FGF (fibroblast growth factor); HPRT1 (hypoxanthine phosphoribosyltransferase 1); HUVECs (human umbilical vein endothelial cells); IGF (insulin-like growth factor); NHE1 (Na⁺/H⁺ exchanger 1); NO (nitric oxide); PAK1 (p21 protein-activated kinase); PI3K (Phosphoinositide 3-kinase); SECS (stiff endothelial cell syndrome); SICM (scanning ion conductance microscopy); siRNA (short interference RNA); Src (proto-oncogene tyrosine-protein kinase); ROCK (Rho-associated kinase); VEGF (vascular endothelial growth factor); VPS13A (vacuolar protein sorting 13 homolog A).

Conflict of Interests

The authors state that they have not any conflict of interests.

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References

- 1 Velayos-Baeza A, Vettori A, Copley RR, Dobson-Stone C, Monaco AP: Analysis of the human VPS13 gene family. *Genomics* 2004;84:536-549.
- 2 Kurano Y, Nakamura M, Ichiba M, Matsuda M, Mizuno E, Kato M, Agemura A, Izumo S, Sano A: In vivo distribution and localization of chorein. *Biochem Biophys Res Commun* 2007;353:431-435.

- 3 Foller M, Hermann A, Gu S, Alesutan I, Qadri SM, Borst O, Schmidt EM, Schiele F, vom Hagen JM, Saft C, Schols L, Lerche H, Stournaras C, Storch A, Lang F: Chorein-sensitive polymerization of cortical actin and suicidal cell death in chorea-acanthocytosis. *FASEB J* 2012;26:1526-1534.
- 4 Hayashi T, Kishida M, Nishizawa Y, Iijima M, Koriyama C, Nakamura M, Sano A, Kishida S: Subcellular localization and putative role of VPS13A/chorein in dopaminergic neuronal cells. *Biochem Biophys Res Commun* 2012;419:511-516.
- 5 Saiki S, Sakai K, Murata KY, Saiki M, Nakanishi M, Kitagawa Y, Kaito M, Gondo Y, Kumamoto T, Matsui M, Hattori N, Hirose G: Primary skeletal muscle involvement in chorea-acanthocytosis. *Mov Disord* 2007;22:848-852.
- 6 Dobson-Stone C, Danek A, Rampoldi L, Hardie RJ, Chalmers RM, Wood NW, Bohlega S, Dotti MT, Federico A, Shizuka M, Tanaka M, Watanabe M, Ikeda Y, Brin M, Goldfarb LG, Karp BI, Mohiddin S, Fananapazir L, Storch A, Fryer AE, Maddison P, Sibon I, Trevisol-Bittencourt PC, Singer C, Caballero IR, Aasly JO, Schmierer K, Dengler R, Hiersemenzel LP, Zeviani M, Meiner V, Lossos A, Johnson S, Mercado FC, Sorrentino G, Dupre N, Rouleau GA, Volkmann J, Arpa J, Lees A, Geraud G, Chouinard S, Nemeth A, Monaco AP: Mutational spectrum of the CHAC gene in patients with chorea-acanthocytosis. *Eur J Hum Genet* 2002;10:773-781.
- 7 Dobson-Stone C, Velayos-Baeza A, Filippone LA, Westbury S, Storch A, Erdmann T, Wroe SJ, Leenders KL, Lang AE, Dotti MT, Federico A, Mohiddin SA, Fananapazir L, Daniels G, Danek A, Monaco AP: Chorein detection for the diagnosis of chorea-acanthocytosis. *Ann Neurol* 2004;56:299-302.
- 8 Ueno S, Maruki Y, Nakamura M, Tomemori Y, Kamae K, Tanabe H, Yamashita Y, Matsuda S, Kaneko S, Sano A: The gene encoding a newly discovered protein, chorein, is mutated in chorea-acanthocytosis. *Nat Genet* 2001;28:121-122.
- 9 Tomiyasu A, Nakamura M, Ichiba M, Ueno S, Saiki S, Morimoto M, Kobal J, Kageyama Y, Inui T, Wakabayashi K, Yamada T, Kanemori Y, Jung HH, Tanaka H, Orimo S, Afawi Z, Blatt I, Aasly J, Ujike H, Babovic-Vuksanovic D, Josephs KA, Tohge R, Rodrigues GR, Dupre N, Yamada H, Yokochi F, Kotschet K, Takei T, Rudzinska M, Szczudlik A, Penco S, Fujiwara M, Tojo K, Sano A: Novel pathogenic mutations and copy number variations in the VPS13A Gene in patients with chorea-acanthocytosis. *Am J Med Genet B Neuropsychiatr Genet* 2011;156:620-631.
- 10 Dobson-Stone C, Rampoldi L, Bader B, Velayos BA, Walker RH, Danek A, Monaco AP: Choreo-Acanthocytosis. *GeneReviews* 1993;updated 2010.
- 11 Tomemori Y, Ichiba M, Kusumoto A, Mizuno E, Sato D, Muroya S, Nakamura M, Kawaguchi H, Yoshida H, Ueno S, Nakao K, Nakamura K, Aiba A, Katsuki M, Sano A: A gene-targeted mouse model for chorea-acanthocytosis. *J Neurochem* 2005;92:759-766.
- 12 Schmidt EM, Schmid E, Munzer P, Hermann A, Eylich AK, Russo A, Walker B, Gu S, Muller Vom HJ, Faggio C, Schaller M, Foller M, Schols L, Gawaz M, Borst O, Storch A, Stournaras C, Lang F: Chorein sensitivity of cytoskeletal organization and degranulation of platelets. *FASEB J* 2013;27:2799-2806.
- 13 Wu C, Ma MH, Brown KR, Geisler M, Li L, Tzeng E, Jia CY, Jurisica I, Li SS: Systematic identification of SH3 domain-mediated human protein-protein interactions by peptide array target screening. *Proteomics* 2007;7:1775-1785.
- 14 Database Interactions found in IntAct: [<http://www.ebi.ac.uk/intact/pages/interactions/interactions.xhtml?conversationContext=1>]. EMBL EBI database 2011
- 15 Claesson-Welsh L, Welsh M: VEGFA and tumour angiogenesis. *J Intern Med* 2013;273:114-127.
- 16 Sen U, Moshal KS, Singh M, Tyagi N, Tyagi SC: Homocysteine-induced biochemical stress predisposes to cytoskeletal remodeling in stretched endothelial cells. *Mol Cell Biochem* 2007;302:133-143.
- 17 Zeller KS, Idevall-Hagren O, Stefansson A, Velling T, Jackson SP, Downward J, Tengholm A, Johansson S: PI3-kinase p110alpha mediates beta1 integrin-induced Akt activation and membrane protrusion during cell attachment and initial spreading. *Cell Signal* 2010;22:1838-1848.
- 18 Chen HC, Appeddu PA, Isoda H, Guan JL: Phosphorylation of tyrosine 397 in focal adhesion kinase is required for binding phosphatidylinositol 3-kinase. *J Biol Chem* 1996;271:26329-26334.
- 19 Gu S, Kounenidakis M, Schmidt EM, Deshpande D, Alkahtani S, Alarifi S, Foller M, Alevizopoulos K, Lang F, Stournaras C: Rapid activation of FAK/mTOR/p70S6K/PAK1-signaling controls the early testosterone-induced actin reorganization in colon cancer cells. *Cell Signal* 2013;25:66-73.
- 20 Yin HL, Janmey PA: Phosphoinositide regulation of the actin cytoskeleton. *Annu Rev Physiol* 2003;65:761-789.
- 21 Koukouritaki SB, Gravanis A, Stournaras C: Tyrosine phosphorylation of focal adhesion kinase and paxillin regulates the signaling mechanism of the rapid nongenomic action of dexamethasone on actin cytoskeleton. *Mol Med* 1999;5:731-742.

- 22 Izaguirre G, Aguirre L, Hu YP, Lee HY, Schlaepfer DD, Aneskievich BJ, Haimovich B: The cytoskeletal/non-muscle isoform of alpha-actinin is phosphorylated on its actin-binding domain by the focal adhesion kinase. *J Biol Chem* 2001;276:28676-28685.
- 23 Manser E, Leung T, Salihuddin H, Zhao ZS, Lim L: A brain serine/threonine protein kinase activated by Cdc42 and Rac1. *Nature* 1994;367:40-46.
- 24 Manser E, Huang HY, Loo TH, Chen XQ, Dong JM, Leung T, Lim L: Expression of constitutively active alpha-PAK reveals effects of the kinase on actin and focal complexes. *Mol Cell Biol* 1997;17:1129-1143.
- 25 Castro-Castro A, Ojeda V, Barreira M, Sauzeau V, Navarro-Lerida I, Muriel O, Couceiro JR, Pimentel-Muinos FX, Del Pozo MA, Bustelo XR: Coronin 1A promotes a cytoskeletal-based feedback loop that facilitates Rac1 translocation and activation. *EMBO J* 2011;30:3913-3927.
- 26 Ilic D, Mao-Qiang M, Crumrine D, Dolganov G, Larocque N, Xu P, Demerjian M, Brown BE, Lim ST, Ossovskaya V, Schlaepfer DD, Fisher SJ, Feingold KR, Elias PM, Mauro TM: Focal adhesion kinase controls pH-dependent epidermal barrier homeostasis by regulating actin-directed Na⁺/H⁺ exchanger 1 plasma membrane localization. *Am J Pathol* 2007;170:2055-2067.
- 27 Tominaga T, Barber DL: Na-H exchange acts downstream of RhoA to regulate integrin-induced cell adhesion and spreading. *Mol Biol Cell* 1998;9:2287-2303.
- 28 Chen BH, Tzen JT, Bresnick AR, Chen HC: Roles of Rho-associated kinase and myosin light chain kinase in morphological and migratory defects of focal adhesion kinase-null cells. *J Biol Chem* 2002;277:33857-33863.
- 29 Fabry B, Klemm AH, Kienle S, Schäffer TE, Goldmann WH: Focal adhesion kinase stabilizes the cytoskeleton. *Biophys J* 2011;101:2131-2138.
- 30 Ilic D, Furuta Y, Kanazawa S, Takeda N, Sobue K, Nakatsuji N, Nomura S, Fujimoto J, Okada M, Yamamoto T: Reduced cell motility and enhanced focal adhesion contact formation in cells from FAK-deficient mice. *Nature* 1995;377:539-544.
- 31 Raftopoulou M, Hall A: Cell migration: Rho GTPases lead the way. *Dev Biol* 2004;265:23-32.
- 32 Ren XD, Kiosses WB, Sieg DJ, Otey CA, Schlaepfer DD, Schwartz MA: Focal adhesion kinase suppresses Rho activity to promote focal adhesion turnover. *J Cell Sci* 2000;113:3673-3678.
- 33 Schober M, Raghavan S, Nikolova M, Polak L, Pasolli HA, Beggs HE, Reichardt LF, Fuchs E: Focal adhesion kinase modulates tension signaling to control actin and focal adhesion dynamics. *J Cell Biol* 2007;176:667-680.
- 34 Webb DJ, Donais K, Whitmore LA, Thomas SM, Turner CE, Parsons JT, Horwitz AF: FAK-Src signalling through paxillin, ERK and MLCK regulates adhesion disassembly. *Nat Cell Biol* 2004;6:154-161.
- 35 Gerthoffer WT, Gunst SJ: Invited review: focal adhesion and small heat shock proteins in the regulation of actin remodeling and contractility in smooth muscle. *J Appl Physiol* 2001;91:963-972.
- 36 Koukouritaki SB, Vardaki EA, Papakonstanti EA, Lianos E, Stournaras C, Emmanouel DS: TNF-alpha induces actin cytoskeleton reorganization in glomerular epithelial cells involving tyrosine phosphorylation of paxillin and focal adhesion kinase. *Mol Med* 1999;5:382-392.
- 37 Papakonstanti EA, Stournaras C: Association of PI-3 kinase with PAK1 leads to actin phosphorylation and cytoskeletal reorganization. *Mol Biol Cell* 2002;13:2946-2962.
- 38 Boosani CS, Nalabothula N, Munugalavadla V, Cosgrove D, Keshamoun VG, Sheibani N, Sudhakar A: FAK and p38-MAP kinase-dependent activation of apoptosis and caspase-3 in retinal endothelial cells by alpha1(IV)NC1. *Invest Ophthalmol Vis Sci* 2009;50:4567-4575.
- 39 Lu Q, Rounds S: Focal adhesion kinase and endothelial cell apoptosis. *Microvasc Res* 2012;83:56-63.
- 40 Paoli P, Giannoni E, Chiarugi P: Anoikis molecular pathways and its role in cancer progression. *Biochim Biophys Acta* 2013;
- 41 Zhao X, Peng X, Sun S, Park AY, Guan JL: Role of kinase-independent and -dependent functions of FAK in endothelial cell survival and barrier function during embryonic development. *J Cell Biol* 2010;189:955-965.
- 42 Lang F: Stiff endothelial cell syndrome in vascular inflammation and mineralocorticoid excess. *Hypertension* 2011;57:146-147.
- 43 Fels J, Oberleithner H, Kusche-Vihrog K: Menage a trois: aldosterone, sodium and nitric oxide in vascular endothelium. *Biochim Biophys Acta* 2010;1802:1193-1202.
- 44 Jeggle P, Callies C, Tarjus A, Fassot C, Fels J, Oberleithner H, Jaisser F, Kusche-Vihrog K: Epithelial Sodium Channel Stiffens the Vascular Endothelium In Vitro and in Liddle Mice. *Hypertension* 2013;61:1053-1059.
- 45 Kusche-Vihrog K, Oberleithner H: An emerging concept of vascular salt sensitivity. *F1000 Biol Rep* 2012;4:20.
- 46 Oberleithner H, Kusche-Vihrog K, Schillers H: Endothelial cells as vascular salt sensors. *Kidney Int* 2010;77:490-494.

- 47 Kusche-Vihrog K, Urbanova K, Blanque A, Wilhelmi M, Schillers H, Kliche K, Pavenstadt H, Brand E, Oberleithner H: C-reactive protein makes human endothelium stiff and tight. *Hypertension* 2011;57:231-237.
- 48 Fernandes D, Assreuy J: Nitric oxide and vascular reactivity in sepsis. *Shock* 2008;30 Suppl 1:10-13.
- 49 Virdis A, Ghiadoni L, Plantinga Y, Taddei S, Salvetti A: C-reactive protein and hypertension: is there a causal relationship? *Curr Pharm Des* 2007;13:1693-1698.
- 50 Li M, Wang X, Fu W, He S, Li D, Ke Q: CD4+CD25+Foxp3+ regulatory T cells protect endothelial function impaired by oxidized low density lipoprotein via the KLF-2 transcription factor. *Cell Physiol Biochem* 2011;28:639-648.
- 51 Molinari C, Uberti F, Grossini E, Vacca G, Carda S, Invernizzi M, Cisari C: 1 α ,25-dihydroxycholecalciferol induces nitric oxide production in cultured endothelial cells. *Cell Physiol Biochem* 2011;27:661-668.
- 52 Sztelyn K, Schmid E, Nurbaeva MK, Yang W, Munzer P, Kunzelmann K, Lang F, Shumilina E: Expression and functional significance of the Ca²⁺-activated Cl⁻ channel ANO6 in dendritic cells. *Cell Physiol Biochem* 2012;30:1319-1332.
- 53 Alesutan I, Daryadel A, Mohebbi N, Pelzl L, Leibrock C, Voelkl J, Bourgeois S, Dossena S, Nofziger C, Paulmichl M, Wagner CA, Lang F: Impact of bicarbonate, ammonium chloride, and acetazolamide on hepatic and renal SLC26A4 expression. *Cell Physiol Biochem* 2011;28:553-558.
- 54 Alesutan I, Sopjani M, Dërmaku-Sopjani M, Munoz C, Voelkl J, Lang F: Upregulation of Na-coupled glucose transporter SGLT1 by Tau tubulin kinase 2. *Cell Physiol Biochem* 2012;30:458-465.
- 55 Voelkl J, Pasham V, Ahmed MS, Walker B, Sztelyn K, Kuhl D, Metzler B, Alesutan I, Lang F: Sgk1-dependent stimulation of cardiac Na/H⁺ exchanger nhe1 by dexamethasone. *Cell Physiol Biochem* 2013;32:25-38.
- 56 Papakonstanti EA, Stournaras C: Actin cytoskeleton architecture and signaling in osmosensing. *Methods Enzymol* 2007;428:227-240.
- 57 Pelzl L, Pakladok T, Pathare G, Fakhri H, Michael D, Wagner CA, Paulmichl M, Lang F: DOCA sensitive pendrin expression in kidney, heart, lung and thyroid tissues. *Cell Physiol Biochem* 2012;30:1491-1501.
- 58 Eyleinstein A, Gehring EM, Heise N, Shumilina E, Schmidt S, Sztelyn K, Munzer P, Nurbaeva MK, Eichenmuller M, Tyan L, Regel I, Foller M, Kuhl D, Soboloff J, Penner R, Lang F: Stimulation of Ca²⁺-channel Orai1/STIM1 by serum- and glucocorticoid-inducible kinase 1 (SGK1). *FASEB J* 2011;25:2012-2021.
- 59 Radmacher M, Fritz M, Kacher CM, Cleveland JP, Hansma PK: Measuring the viscoelastic properties of human platelets with the atomic force microscope. *Biophys J* 1996;70:556-567.
- 60 Cook S, Schäffer T, Chynoweth K, Wigton M, Simmonds R, Lang K: Practical implementation of dynamic methods for measuring atomic force microscope cantilever spring constants. *Nanotechnology* 2006;17:2135-2145.
- 61 Hertz H: Über die Berührung fester elastischer Körper. *J Reine Angew Math* 1882;92:156-171.
- 62 Rotsch C, Braet F, Wisse E, Radmacher M: AFM imaging and elasticity measurements on living rat liver macrophages. *Cell Biol Int* 1997;21:685-696.
- 63 Hansma PK, Drake B, Marti O, Gould SA, Prater CB: The scanning ion-conductance microscope. *Science* 1989;243:641-643.
- 64 Korchev YE, Bashford CL, Milovanovic M, Vodyanov I, Lab MJ: Scanning ion conductance microscopy of living cells. *Biophys J* 1997;73:653-658.
- 65 Böcker M, Muschter S, Schmitt EK, Steinem C, Schäffer TE: Imaging and patterning of pore-suspending membranes with scanning ion conductance microscopy. *Langmuir* 2009;25:3022-3028.
- 66 Novak P, Li C, Shevchuk AI, Stepanyan R, Caldwell M, Hughes S, Smart TG, Gorelik J, Ostanin VP, Lab MJ, Moss GW, Frolenkov GI, Klenerman D, Korchev YE: Nanoscale live-cell imaging using hopping probe ion conductance microscopy. *Nat Methods* 2009;6:279-281.
- 67 Rheinlaender J, Geisse NA, Proksch R, Schäffer TE: Comparison of scanning ion conductance microscopy with atomic force microscopy for cell imaging. *Langmuir* 2011;27:697-704.
- 68 Rheinlaender J, Schäffer T: Mapping the mechanical stiffness of live cells with the scanning ion conductance microscope. *Soft Matter* 2013;9:3230-3236.
- 69 Mann SA, Hoffmann G, Hengstenberg A, Schuhmann W, Dietzel ID: Pulse-mode scanning ion conductance microscopy--a method to investigate cultured hippocampal cells. *J Neurosci Methods* 2002;116:113-117.
- 70 Rheinlaender J, Schäffer T: Image formation, resolution, and height measurement in scanning ion conductance microscopy. *J Appl Phys* 2009;105:094905.

- 71 Stournaras C, Stiakaki E, Koukouritaki SB, Theodoropoulos PA, Kalmanti M, Fostinis Y, Gravanis A: Altered actin polymerization dynamics in various malignant cell types: evidence for differential sensitivity to cytochalasin B. *Biochem Pharmacol* 1996;52:1339-1346.
- 72 Druppel V, Kusche-Vihrog K, Grossmann C, Gekle M, Kasprzak B, Brand E, Pavenstadt H, Oberleithner H, Kliche K: Long-term application of the aldosterone antagonist spironolactone prevents stiff endothelial cell syndrome. *FASEB J* 2013;
- 73 Cabodi S, Di Stefano P, Leal MP, Tinnirello A, Bisaro B, Morello V, Damiano L, Aramu S, Repetto D, Tornillo G, Defilippi P: Integrins and signal transduction. *Adv Exp Med Biol* 2010;674:43-54.
- 74 Chen SY, Chen HC: Direct interaction of focal adhesion kinase (FAK) with Met is required for FAK to promote hepatocyte growth factor-induced cell invasion. *Mol Cell Biol* 2006;26:5155-5167.
- 75 Long W, Yi P, Amazit L, LaMarca HL, Ashcroft F, Kumar R, Mancini MA, Tsai SY, Tsai MJ, O'Malley BW: SRC-3Delta4 mediates the interaction of EGFR with FAK to promote cell migration. *Mol Cell* 2010;37:321-332.
- 76 Zebda N, Dubrovskiy O, Birukov KG: Focal adhesion kinase regulation of mechanotransduction and its impact on endothelial cell functions. *Microvasc Res* 2012;83:71-81.
- 77 Eduardsen K, Larsen SL, Novak I, Lambert IH, Hoffmann EK, Pedersen SF: Cell volume regulation and signaling in 3T3-L1 pre-adipocytes and adipocytes: on the possible roles of caveolae, insulin receptors, FAK and ERK1/2. *Cell Physiol Biochem* 2011;28:1231-1246.
- 78 Eliyahu E, Tsaadon A, Shtraizent N, Shalgi R: The involvement of protein kinase C and actin filaments in cortical granule exocytosis in the rat. *Reproduction* 2005;129:161-170.
- 79 Keller H, Rentsch P, Hagmann J: Differences in cortical actin structure and dynamics document that different types of blebs are formed by distinct mechanisms. *Exp Cell Res* 2002;277:161-172.
- 80 Malacombe M, Bader MF, Gasman S: Exocytosis in neuroendocrine cells: new tasks for actin. *Biochim Biophys Acta* 2006;1763:1175-1183.
- 81 Mitchell T, Lo A, Logan MR, Lacy P, Eitzen G: Primary granule exocytosis in human neutrophils is regulated by Rac-dependent actin remodeling. *Am J Physiol Cell Physiol* 2008;295:C1354-C1365.
- 82 Onabajo OO, Seeley MK, Kale A, Qualmann B, Kessels M, Han J, Tan TH, Song W: Actin-binding protein 1 regulates B cell receptor-mediated antigen processing and presentation in response to B cell receptor activation. *J Immunol* 2008;180:6685-6695.
- 83 Insall RH, Machesky LM: Actin dynamics at the leading edge: from simple machinery to complex networks. *Dev Cell* 2009;17:310-322.
- 84 Papakonstanti EA, Stournaras C: Cell responses regulated by early reorganization of actin cytoskeleton. *FEBS Lett* 2008;582:2120-2127.
- 85 Gillies K, Wertman J, Charette N, Dupre DJ: Anterograde Trafficking of CXCR4 and CCR2 Receptors in a Prostate Cancer Cell Line. *Cell Physiol Biochem* 2013;32:74-85.
- 86 Baillat G, Siret C, Delamarre E, Luis J: Early adhesion induces interaction of FAK and Fyn in lipid domains and activates raft-dependent Akt signaling in SW480 colon cancer cells. *Biochim Biophys Acta* 2008;1783:2323-2331.
- 87 Cance WG, Golubovskaya VM: Focal adhesion kinase versus p53: apoptosis or survival? *Sci Signal* 2008;1:e22.
- 88 Golubovskaya VM, Finch R, Cance WG: Direct interaction of the N-terminal domain of focal adhesion kinase with the N-terminal transactivation domain of p53. *J Biol Chem* 2005;280:25008-25021.
- 89 Golubovskaya VM, Finch R, Zheng M, Kurenova EV, Cance WG: The 7-amino-acid site in the proline-rich region of the N-terminal domain of p53 is involved in the interaction with FAK and is critical for p53 functioning. *Biochem J* 2008;411:151-160.
- 90 Holinstat M, Knezevic N, Broman M, Samarel AM, Malik AB, Mehta D: Suppression of RhoA activity by focal adhesion kinase-induced activation of p190RhoGAP: role in regulation of endothelial permeability. *J Biol Chem* 2006;281:2296-2305.
- 91 Morales SA, Mareninov S, Wadehra M, Zhang L, Goodlick L, Braun J, Gordon LK: FAK activation and the role of epithelial membrane protein 2 (EMP2) in collagen gel contraction. *Invest Ophthalmol Vis Sci* 2009;50:462-469.
- 92 Coyer SR, Singh A, Dumbauld DW, Calderwood DA, Craig SW, Delamarche E, Garcia AJ: Nanopatterning reveals an ECM area threshold for focal adhesion assembly and force transmission that is regulated by integrin activation and cytoskeleton tension. *J Cell Sci* 2012;125:5110-5123.
- 93 Hirakawa M, Oike M, Watanabe M, Karashima Y, Ito Y: Pivotal role of integrin alpha5beta1 in hypotonic stress-induced responses of human endothelium. *FASEB J* 2006;20:1992-1999.

- 94 Provenzano PP, Inman DR, Eliceiri KW, Keely PJ: Matrix density-induced mechanoregulation of breast cell phenotype, signaling and gene expression through a FAK-ERK linkage. *Oncogene* 2009;28:4326-4343.
- 95 Yano Y, Saito Y, Narumiya S, Sumpio BE: Involvement of rho p21 in cyclic strain-induced tyrosine phosphorylation of focal adhesion kinase (pp125FAK), morphological changes and migration of endothelial cells. *Biochem Biophys Res Commun* 1996;224:508-515.
- 96 Young SR, Gerard-O'Riley R, Kim JB, Pavalko FM: Focal adhesion kinase is important for fluid shear stress-induced mechanotransduction in osteoblasts. *J Bone Miner Res* 2009;24:411-424.
- 97 Mehta D: Focal adhesion kinase regulation of endothelial barrier function, apoptosis, and neovascularization. *Microvasc Res* 2012;83:1-2.
- 98 Wang JG, Miyazu M, Xiang P, Li SN, Sokabe M, Naruse K: Stretch-induced cell proliferation is mediated by FAK-MAPK pathway. *Life Sci* 2005;76:2817-2825.
- 99 Ward KK, Tancioni I, Lawson C, Miller NL, Jean C, Chen XL, Uryu S, Kim J, Tarin D, Stupack DG, Plaxe SC, Schlaepfer DD: Inhibition of focal adhesion kinase (FAK) activity prevents anchorage-independent ovarian carcinoma cell growth and tumor progression. *Clin Exp Metastasis* 2013;30:579-594.
- 100 Hsu HJ, Lee CF, Locke A, Vanderzyl SQ, Kaunas R: Stretch-induced stress fiber remodeling and the activations of JNK and ERK depend on mechanical strain rate, but not FAK. *PLoS One* 2010;5:e12470.
- 101 Sai X, Naruse K, Sokabe M: Activation of pp60(src) is critical for stretch-induced orienting response in fibroblasts. *J Cell Sci* 1999;112:1365-1373.
- 102 Cabrita MA, Jones LM, Quizi JL, Sabourin LA, McKay BC, Addison CL: Focal adhesion kinase inhibitors are potent anti-angiogenic agents. *Mol Oncol* 2011;5:517-526.
- 103 Lechertier T, Hodiola-Dilke K: Focal adhesion kinase and tumour angiogenesis. *J Pathol* 2012;226:404-412.
- 104 Petzold T, Orr AW, Hahn C, Jhaveri KA, Parsons JT, Schwartz MA: Focal adhesion kinase modulates activation of NF-kappaB by flow in endothelial cells. *Am J Physiol Cell Physiol* 2009;297:C814-C822.
- 105 Chen XL, Nam JO, Jean C, Lawson C, Walsh CT, Goka E, Lim ST, Tomar A, Tancioni I, Uryu S, Guan JL, Acevedo LM, Weis SM, Cheresh DA, Schlaepfer DD: VEGF-induced vascular permeability is mediated by FAK. *Dev Cell* 2012;22:146-157.