Podosome-type adhesions and focal adhesions, so alike yet so different.

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Contents:

Abstract

Cell-matrix adhesions are essential for cell migration, tissue organization, and differentiation, therefore playing central roles in embryonic development, remodeling and homeostasis of tissue and organs. Matrix adhesion dependent signals cooperate with other pathways to regulate biological functions such as cell survival, cell proliferation, wound healing and tumorigenesis. Cell migration and invasion are integrated processes requiring the continuous, coordinated assembly and disassembly of integrin-mediated adhesions. An understanding of how integrins regulate cell migration and invasiveness through the dynamic regulation of adhesions is fundamental to both physiological and pathological situations. A variety of cell-matrix adhesions has been identified, namely, focal complexes, focal adhesions, fibrillar adhesions, podosomes and invadopodia (podosome type adhesions). These adhesion sites contain integrin clusters able to develop specialized structures which are different in their architecture and dynamics although they share almost the same proteins. Here we compare recent advances and developments in the organization and dynamics of focal adhesions and podosome type adhesions, in order to understand how such subcellular sites so close in their composition can be structurally and functionally so different. The underlying question is how their respective physiological or pathological roles are related to their distinct organization.

Introduction

Many distinct types of adhesions between cells and the extracellular matrix have been described: focal complexes, focal adhesions, fibrillar adhesions, podosomes and invadopodia (Fig.1). These cell-extracellular matrix interactions are all mediated through different specialized subcellular sites that all contain specific adhesion receptors named integrins, cytoskeletal elements, and a wide variety of interconnecting adaptor proteins and signaling proteins. Some of those proteins can be specifically expressed at differentiation states such as RhoU/ Wrch1 which is induced during the differentiation of macrophages into osteoclasts (Brazier *et al.*, 2006). Although adhesive structures share almost the same proteins (Table 1), major structural differences are observed: podosomes contain a ring of adhesive molecules centered on an actin column and their general orientation is perpendicular to the substrate and the plasma membrane. This contrasts with the elongated structure of focal adhesions with a tangential orientation with respect to extracellular matrix (Fig. 1). Dynamics and tension associated to both structures are also different: podosome type adhesions (PTA) associated with podosomes and invadopodia being more dynamic and instable as compared to focal adhesions. In all cases, alteration of their dynamics results in modifications of cell differentiation and migration (Vicente-Manzanares *et al.*, 2005; Bouvard *et al.*, 2007). These distinct properties suggest specific functions: the most commonly admitted idea is that podosomes and invadopodia could be involved in matrix degradation and invasion, whereas focal adhesions are rather associated with matrix remodeling such as fibronectin fibrillogenesis (Larsen *et al.*, 2006; Linder, 2007).

Due to their involvement in physiological and pathological situations, cell-matrix adhesions are now receiving widespread attention. Indeed, podosomes and invadopodia could be involved in physiological events such as monocyte extravasation and tissue transmigration (Carman *et al.*, 2007) or in pathological conditions such as atheroma (Moreau *et al.*, 2003), osteoporosis or osteopetrosis. Cancer cells are also able to exploit cell-matrix adhesions such as focal adhesions and invadopodia (Paszek *et al.*, 2005; Marx, 2006). In the past few years, mutations on proteins located in focal adhesions and/or podosomes allowed to characterize some pathologies: for instance, WASP is associated with Wiskott-Aldrich syndrome causing a severe immunodeficiency, Kindlin is associated with Kindler syndrome (Siegel *et al.*, 2003) causing skin blistering, skin atrophy, photosensitivity, carcinogenesis, and palladin is causing familial pancreatic cancer (Pogue-Geile *et al.*, 2006). Nevertheless, the precise relationship between these pathologies and adhesion is still unclear.

Here, we will focus on the architecture, dynamics and tension of focal adhesions and podosome type adhesions (podosomes and invadopodia). The aim of this review is to point out the most convergent and divergent characteristics of these specific cell-matrix structures.

Architecture and signaling pathways of cell matrix contacts

Tangential cell matrix contacts: focal adhesion related structures

Focal adhesions are the best characterized type of such structures. They were initially described about 30 years ago by interference-reflection microscopy and electron microscopy (Abercrombie *et al.*, 1971). Although many investigators have thought that focal adhesions were artifactual structures only found in cells cultured on rigid surfaces, such structures have been described in vivo at cell-matrix junctions (Fuchs *et al.*, 1997; Cukierman *et al.*, 2001). In cell culture, a family of focal adhesion related structures has been identified and named focal complexes, focal adhesions and fibrillar adhesions, respectively (Zamir and Geiger, 2001). Focal complexes are 0.5-1 μm dot-like contacts localized along the lamellipodia. These structures are not connected to stress fibers although they have been shown to be linked to the actin network. Moreover, they do not contain Zyxin suggesting that they are subjected to moderate mechanical tensions (see next section). Focal complexes mature into focal adhesions (Fig. 1A), the elongated 3-10 μm structures associated with stress fibers. Those structures give rise to fibrillar adhesions enriched in tensin and involved in fibronectin fibrillogenesis (Fig. 1A) (Katz *et al.*, 2000). Up to 90 components have been reported to physically reside within these adhesions while 66 temporary players interact with the resident adhesion constituents and affect their activity and fate (Fig. 1B) (Zaidel-Bar *et al.*, 2007). Focal adhesions are mostly composed of β_1 and β_3 integrins. Moreover, some structural proteins found in focal adhesions and devoid of any catalytic activity are however involved in dynamics of the structure: for instance, talin controls integrin activation, vinculin is selectively activated by changes in head-tail interactions regulated by binding to talin (Izard *et al.*, 2004; Chen *et al.*, 2005; Humphries *et al.*, 2007), α-actinin forms a signaling complex with the Abl/Arg kinase adapter ArgBP2 (Ronty *et al.*, 2005) and paxillin integrates diverse signals from tyrosine kinases and Rho family GTPases (Brown and Turner, 2004). Another complex composed of integrin-linked kinase (ILK), PINCH and parvin also functions as a signaling platform for integrins (Legate *et al.*, 2006; Boulter *et al.*, 2006). Additionally, focal adhesions contain a rich diversity of enzymatically active proteins. Indeed, tyrosine phosphorylation is one of the key signaling events occurring at focal adhesions (Kirchner *et al.*, 2003). Two of the major protein tyrosine kinases found in focal adhesion are Src and focal adhesion kinase (FAK). The latter undergoes autophosphorylation that generates a docking

site for Src allowing further tyrosine phosphorylations on FAK and recruitment sites for potential substrates such as p130Cas or paxillin (Schaller *et al.*, 1994; Frame *et al.*, 2002). Other tyrosine kinases such as Abl, Csk and Pyk2 and ser/thr kinases such as ILK, PAK, and PKC are also found in focal adhesions.

It is note worthy that most of data are issued from studies done on cells plated on 2D matrices and cell signalling seems to be different when comparing cells in 3D microenvironment to 2D matrices. In particular, adhesion in 3D microenvironment has to be found to be dependent solely on the $\alpha_5\beta_1$ integrin whereas the attachment of fibroblasts to 2D fibronectin is dependent on both $\alpha_5\beta_1$ and $\alpha_v\beta_3$ integrins (Cukierman *et al.*, 2001; Green and Yamada, 2007).

Perpendicular cell matrix contacts: podosome type adhesions

Migratory and invasive cells exhibit another type of integrin-mediated adhesion complexes called PTA, namely podosome type adhesions (Linder, 2007). Depending on their life time and structure, they have been referred to as podosomes or invadopodia. Podosomes have been observed in cells of the monocytic lineage such as osteoclasts, macrophages and dendritic cells whereas invadopodia have been identified in Src-transformed fibroblasts and carcinoma cells (Linder and Aepfelbacher, 2003). Podosomes and invadopodia architecture is defined by an actin-rich core (Marchisio *et al.*, 1984; Pfaff and Jurdic, 2001; Baldassarre *et al.*, 2006), where proteins involved in actin nucleation such as WASP (Linder *et al.*, 1999; Mizutani *et al.*, 2002), Arp2/3 and cortactin (Bowden *et al.*, 1999; Linder *et al.*, 2000; Pfaff and Jurdic, 2001; Artym *et al.*, 2006; Bowden *et al.*, 2006; Luxenburg *et al.*, 2006; Tehrani *et al.*, 2006; Webb *et al.*, 2007) have been identified (Fig. 1C, D). Podosome core is surrounded by a ring structure composed of integrin receptors including mostly β_2 and β_3 while β_1 integrins are generally excluded (Gaidano *et al.*, 1990). Integrin-associated protein also found in focal adhesions such as talin and paxillin (Bowden *et al.*, 1999; Pfaff and Jurdic, 2001; Buccione *et al.*, 2004) are also found around the actin core. This organization is not so well defined for invadopodia where the adhesive molecules may be mixed within the actin core. Invadopodia of Src-transformed cells were shown to self organize into podosomes ring named rosettes similarly to what was observed for podosomes in osteoclasts (Destaing *et al.*, 2003) and endothelial cells (Moreau *et al.*, 2003). Although FAK is expressed in many cells able to develop podosomes or invadopodia, Pyk2 appears to be the predominant mediator of integrin

$\alpha_v\beta_3$ signaling events in the hematopoietic lineage that influence podosome assembly in osteoclast (Wang *et al.*, 2003) or macrophage behavior (Okigaki *et al.*, 2003). However Pyk2 has also been observed in focal adhesion (Du *et al.*, 2001). Strikingly, Pyk2 is activated following increases in cytosolic free Ca^{2+}, (Lev *et al.*, 1995; Rucci *et al.*, 2005) due to voltage dependent channels (Miyauchi *et al.*, 1990). Pyk2 autophosphorylates on Tyr 402, creating a Src-homology-2 (SH2) binding site that recruits Src family kinases (SFK), which phosphorylate other tyrosine residues of Pyk2 and associated proteins (Dikic *et al.*, 1996; Park *et al.*, 2004). Interactions between the activated Pyk2-Src module and proteins such as the Grb2-Sos complex, p130Cas, paxillin and Graf regulate multiple intracellular signaling pathways reviewed in (Avraham *et al.*, 2000). Binding of $\alpha_v\beta_3$ integrin induces the formation of a Pyk2/Src/Cbl complex in which Cbl, an E3 ubiquitin ligase, is a key regulator of Src kinase activity, and of cell adhesion and osteoclast migration (Sanjay *et al.*, 2001).

Interplay between focal adhesions, podosome type adhesions and cell contractility.

During cell migration, adhesions at the front of the cell must be strong enough to withstand contractile forces generated by the cell front while adhesions at the rear must be weak enough to allow the cell to detach from its substrate. This means that asymmetry in the strength of adhesions at the cell front and rear is likely important for efficient cell migration. Several parameters may contribute to the strength of adhesion between a cell and its environment including ligand surface density, number of adhesion receptors, affinity of integrins towards their respective ligands, strength of receptor linkages, and organization of receptors on the cell surface (Huttenlocher *et al.*, 1996; Palecek *et al.*, 1998; Gallant *et al.*, 2005; Gupton and Waterman-Storer, 2006).

During cell attachment and spreading, initial adhesions evolve into small focal complexes that mature into focal adhesions connected to stress fibers. During this initial process, auto-assembly requires the application of a force on integrin receptors up to 2 pN. Formation of focal complexes results in a reinforcement of this mechanical link to 5 nN (Galbraith *et al.*, 2002; Giannone *et al.*, 2003; Buruinsma, 2005). This stage is under the control of the small GTPase Rac1 (Rottner *et al.*, 1999). Mature focal adhesions are adhesive structures of larger size and relative immobility with respect to the substrate. Their assembly is stimulated by the small GTPase RhoA (Ridley and Hall, 1992), and is mediated primarily via two of its immediate downstream effectors, RhoKinase and mDia (Kimura *et al.*, 1996; Watanabe *et al.*, 1999). RhoKinase stimulates myosin II-dependent contractility in smooth muscle and non-

muscle cells by inactivating myosin light chain phosphatase (Katoh *et al.*, 2001), whereas mDia is implicated in the regulation of actin polymerisation and the initiation of parallel arrays of actin filaments, probably through the recruitment of newly formed actin filaments to stress fibers (Burridge and Chrzanowska-Wodnicka, 1996; Rottner *et al.*, 1999). Myosin II exerts on focal adhesion a force of 5.2 $nN/\mu m^2$ (Schwarz *et al.*, 2002). Maturation of focal adhesions is a slow process that can take up to 60 min (Zamir *et al.*, 1999) corresponding to a 7 fold force reinforcement (Gallant *et al.*, 2005). This reinforcement is strictly dependent on talin and corresponds to the recruitment of vinculin and paxillin (Giannone *et al.*, 2003). Approximately, focal adhesion areas are proportional to the applied forces (Schwarz *et al.*, 2002; Gallant *et al.*, 2005). Internal tensions that promote focal adhesion assembly can be replaced by external forces application. Conversely, reduction of contractile forces is a prerequisite for remodeling of the actin cytoskeleton including focal adhesion disassembly (Riveline *et al.*, 2001). Tension will activate the tyrosine phosphatase RPTPα that in turn will activate SFK allowing its interaction with focal adhesion kinase (FAK). Phospho FAK will recruit paxillin that in turn will allow a negative feedback implying the activation of Rac1 and the simultaneous inactivation of RhoA (Schober *et al.*, 2007).

Conversely to what is observed with focal adhesions, podosome type adhesions seem to be promoted by decrease in local cellular contractility (Lener *et al.*, 2006; Linder, 2007). For instance A7r5 smooth muscle cells simultaneously display contractile activity in the cell center and motile activity in the cell periphery with reduced tension. This allows peripheral remodeling of actin cytoskeleton resulting of the dispersal of focal adhesions and the formation of dynamic podosomes at the same sites (Hai *et al.*, 2002; Kaverina *et al.*, 2003; Burgstaller and Gimona, 2004). This process is correlated with the local dispersion of contractile proteins including myosin, tropomyosin, and *h*1calponin, and the recruitment of p190RhoGAP to podosome sites (Lener *et al.*, 2006). The specific subcellular localization of p190RhoGAP, together with its tyrosine phosphorylation, is an important determinant for its activation (Brouns *et al.*, 2001; Haskell *et al.*, 2001) and the inhibition of RhoA which result in the subsequent decrease in contractility (Peacock, 2007). Consistent with the observation in smooth muscle cells, in neuroblastoma the activation of TRPM7, an α kinase coupled with a calcium channel, results in the phosphorylation of the heavy chain of myosin II and the transformation of focal adhesions into podosomes similarly to what is observed by pharmacodynamically inhibiting myosin II (Clark *et al.*, 2006). Although intracellular tensions seem not to be required for podosome assembly, their lifespan and mean minimum distance between them depend on the substrate flexibility as well as the speed of the

podosome ring expansion in GFP-actin transfected NIH 3T3 cells, suggesting that intracellular constraints may play a role in the collective dynamic of these structures (Collin *et al.*, 2006). Indeed, high-resolution scanning electron microscopy combined with fluorescence microscopy has allowed to resolve the molecular architecture of podosome arrays and to show that these adhesive structures communicate through a network of actin filaments parallel to the substrate suggesting the existence of tangential forces between podosome actin cores (Luxenburg *et al.*, 2007). Focal adhesion dynamics also appear to be tightly linked to matrix assembly and affected by the physical properties of the substrate. Indeed, formation of fibrillar adhesions and development of fibronectin fibrils occur when cells are plated on native fibronectin, whereas cells plated on covalently immobilized fibronectin do not form fibrillar adhesions (Katz *et al.*, 2000). Moreover, increase in substrate density accelerates focal adhesion assembly, a process that is dependent on ICAP-1. This allows the matrix surface density sensing by the cell permitting its adaptive response to changes in the properties of the ECM (Millon-Fremillon *et al.*, 2008).

Adhesion sites dynamics and cell migration

Individual versus collective dynamics

Because of their involvement in cell motility and matrix remodeling or matrix degradation, adhesion sites are necessarily dynamic structures able to assemble and disassemble (Fig. 2). To migrate, cells that develop focal adhesions initially extend a directed protrusion at the leading edge through the localized polymerization of actin and subsequent integrin-mediated stabilization of adhesions. After stabilization of the protrusion or lamellipodium, cells generate tensions and the contractile force is required for cell movement. The final step in the migratory cycle involves release of adhesions at the rear of the cell to allow forward progression. These classical steps are representative of the 2D migratory cycle of many adherent cells such as fibroblasts. In contrast, migrating leucocytes and more generally cells able to develop podosomes tend to display a more gliding movement. Disregarding the adhesion type assembled, the migration speed seems to be inversely proportional to the internal tension developed, i.e., 200 nN for a fibroblast speed of 0.5 µm/sec versus 20 nN for a keratinocyte migrating at 170 µm/sec (Isabey, D. personal communication). Focal adhesion lifetime is about 30-90 min (Fig. 2A). Assembly/disassembly of podosomes are much more dynamic than those of focal adhesions, with lifespan on the order of 2-12 minutes (Destaing *et al.*, 2003). Invadopodia found in

carcinoma are distinguishable from podosomes by a remarkable persistence going up to 1 hour or more (Yamaguchi *et al.*, 2005), and the induction of a more focused and deeper degradation of extracellular matrix (Table 1). Nevertheless invadopodia lifespan can be shortened by orthovanadate treatment up to the characteristic podosome lifetime (Fig. 2B). So far, studies addressing the dynamics of adhesions during migration have shed some light on the different adhesions processes. With a growing number of transgenic mice available, the role of individual adhesion molecule in the organization and dynamics of adhesive structure can be addressed *ex vivo*, and correlated with physiological functions *in vivo*. Such studies underline a spatiotemporal coordination of the adhesion structures between the front and the rear of migrating cells, and also between the external and internal rim of the rosettes. These observations emphasize two control levels: dynamics of individual focal adhesions or isolated podosomes, and collective dynamics of these adhesion structures (Table 1). For instance, collective dynamics can be imaged by the actin stress fibers mediated connection of "towing adhesions" in the front of the cell fibers with sliding trailing adhesions at the rear of the cell. Trailing adhesions actively generated at the rear of the cell are necessary for persistent forward movement of fibroblasts (Rid *et al.*, 2005). Collective dynamics allow also the organization of podosome clusters into rosettes or the coordination between focal adhesions at the front and those at the rear of migrating cells. It is noteworthy that increase in tyrosine phosphorylation most likely by Src kinase, results in both enhancement of podosome assembly and disassembly resulting in the acceleration of PTA rosette expansion while keeping the rosette width constant (Badowski *et al.*, 2008). These coordinated processes are required for efficient extracellular matrix degradation and transmigration through a cell monolayer (Saltel *et al.*, 2006; Badowski *et al.*, 2008). Actin dynamics is likely to play a major role in this organization and coordination as suggested by the actin cables able to maintain individual podosomes (Luxenburg *et al.*, 2007) or stress fibers that connect focal adhesions. Dynamics of adhesion structures is the common denominator that allows a fast adaptive response to external or internal stimuli, and supports cell shape and/or cell migration. Such response is regulated by several switches controlling signaling pathways such as GTPases, lipid, proteolytic and phosphorylation switches. Depending on the type of adhesions, the external stimuli transmitted by extracellular matrix is perceived differently and will induce a completely distinct cell response: matrix reorganization and fibronectin fibrillogenesis in case of fibrillar adhesions, or matrix degradation with podosome type adhesions.

Actin polymerization

Two distinct actin networks drive the protrusion of migrating cells (Ponti *et al.*, 2004). Extension of the leading edge is characterized by a cyclic process: the protrusion of lamellipodium associated with a dense network of branching actin filaments is followed by the formation of focal adhesions at the rear of the lamellipodium with the assembly of stress fibers in the lamellum area (Giannone *et al.*, 2007). Actin network undergoes a fast retrograde flow in the lamellipodium allowing actin polymerization and depolymerisation whereas a slower centripetal flow is observed in the actomyosin contraction associated lamellum. The transition between these two types of actin network is unknown but focal complexes are localized in the lamellipodium whereas newly formed focal adhesions are localized at the interface between the lamellipodia and lamella F-actin networks (Hu *et al.*, 2007) .

At this boundary, myosin II pulls the rear of the lamellipodial actin network, causing upward bending, edge retraction, and initiation of new adhesion sites (Giannone *et al.*, 2007). On the other hand, integrin occupancy in filopodia favors actin nucleation and dendritic polymerization through Rac signaling (Galbraith *et al.*, 2007; Guillou *et al.*, 2008). Additionally, a number of components of focal adhesions seem to promote actin nucleation such as paxillin, which couples the SH2/SH3 adaptor protein CrkII to N-WASp to allow its activation by the small GTPase cdc42 (Tang *et al.*, 2003; Tang and Gunst, 2004; Zhang *et al.*, 2005), FAK that associates with the Arp2/3 complex and colocalizes at transient structures formed early after adhesion in nascent lamellipodia (Serrels *et al.*, 2007), or vinculin that can bind and seems to regulate Arp2/3 nucleation activity (DeMali and Burridge, 2003). In spite of Arp2/3 interaction with proteins localized in focal adhesion, neither Arp2/3 nor WASP has been localized in focal adhesions structures (Table I). Interestingly, mature focal adhesions themselves seem not to be actual nucleation sites, and conversely to podosome type adhesions, they seem not to be so dependent on actin polymerization. Finally, specific actin-binding proteins within focal adhesions may link F-actin in the lamella to transmembrane integrins (Critchley *et al.*, 1999) that bind the extracellular matrix, stabilizing leading edge protrusions in the second step of migration.

During osteoclast polarization, podosomes undergo reorganization from a scattered distribution, through the formation of clusters and ring super-structures, to the assembly of a sealing zone at the cell periphery. The enhanced dynamic reorganization of podosomes during osteoclast polarization is inversely related to the local levels of tyrosine phosphorylation of the Src substrate, cortactin (Luxenburg *et al.*, 2006). Podosome belts are composed of two F-

actin-containing domains, namely, a diffuse actin cloud surrounding actin dots referred to as podosome cores. Comparisons between WT and $WIP^{-/-}$ osteoclast phenotypes allowed to separate these two F-actin domains and to show for the first time that they fulfill different roles (Chabadel *et al.*, 2007). The actin cloud linked to vinculin, paxillin, signaling phosphoproteins, together with the $\alpha_v\beta_3$ integrin interacts with extracellular matrix and regulates osteoclast contractility in part through myosin II. In contrast, podosome cores made of a dense F-actin network associated with cortactin, Arp2/3, WASp, and the transmembrane receptor CD44, which could establish an initial adhesion via CD44/hyaluronate. In parallel, in the absence of Src(s) activities in osteoclasts, podosomes cores are formed but are devoid of actin cloud. Thus, it appears that the main molecular regulator of the actin cloud is the tyrosine kinase activity of Src (Destaing *et al.*, 2008).

Assembly of cell matrix adhesions

Focal adhesions assembly starts with integrin occupancy and clustering to finally connect to actin stress fibers while at least assembly of podosome type adhesion of RSV transformed BHK cells is initiated by the nucleation of an actin column perpendicular to the plasma membrane that undergoes continuous cycles of polymerization and depolymerization (Badowski *et al.*, 2008) and constitutes the PTA core. Overexpression of cortactin, mutated at its major Src phosphorylation sites, enhanced actin turnover, suggesting that podosome dynamics in osteoclasts can be down regulated by Src dependent cortactin phosphorylation (Luxenburg *et al.*, 2006). On the other hand, it was recently shown that cortactin phosphorylation by Src enhances actin assembly and thereby could favor the appearance of new podosomes (Tehrani *et al.*, 2007). Conversely, it is also well known that cortactin does not accumulate in focal adhesions but in lamellipodia where the polymerized F-actin meshwork pushes the membrane of migrating cells (Bryce *et al.*, 2005). Therefore cortactin emerged as a key protein involved in the coordination of membrane dynamics with the actin cytoskeleton remodeling. Although the exact mechanisms underlying its fundamental roles remain to be defined, cortactin is likely to act via the Arp2/3 complex. Indeed, Arp2/3 knock down in osteoclast leads to an impairment in podosome formation (Hurst *et al.*, 2004).

CD44 was recently identified in podosome core of osteoclasts (Chabadel *et al.*, 2007) and seems to strengthen adhesion to the substrate through its affinity for hyaluronan, a glycosaminoglycan constituent of extracellular matrix, but also potentially through its affinity for other ligands such as osteopontin, collagens and matrix metalloproteases (Cichy and Pure,

2003). Since the actin core seems to appear before formation of the integrin rich surrounding ring in Src-transformed BHK cells, CD44 could play the role of an initial adhesion. Similarly, in addition to integrins, proteoglycan, glycosaminoglycan receptors were recently reported to localize at focal adhesions and induce an initial adhesion mediated by hyaluronate before the formation of adhesion structures driven by integrins (Cohen *et al.*, 2006). Another hyaluronan receptor named Layilin that interacts with talin and other ERM protein may play in the case of focal adhesions, a similar role than CD44 in podosomes (Borowsky and Hynes, 1998; Bono *et al.*, 2001; Bono *et al.*, 2005).

Genetic and biophysical analyses have also established important roles for talin in focal adhesion initiation, reinforcement and stabilization (Albiges-Rizo *et al.*, 1995; Priddle *et al.*, 1998; Giannone *et al.*, 2003; Jiang *et al.*, 2003), as well as in integrin activation and local phosphatidyl-4,5 bis-phosphate generation (Martel *et al.*, 2001; Yan *et al.*, 2001; Calderwood *et al.*, 2002; Tadokoro *et al.*, 2003). Indeed, integrin clustering requires the formation of the complex made of activated integrins, immobilized ligands, talin and PIP_2 (Cluzel *et al.*, 2005). Recent data suggest that the binding of a complex including talin, RIAM, Rap1 and VASP to the integrin cytoplasmic tail is a common final step in integrin activation (Han *et al.*, 2006). Recently, it has also been proposed a new model where vinculin has a key role in focal adhesion formation and turnover: vinculin head regulates integrin dynamics and clustering whereas the tail regulates the link to the mechantransduction force machinery (Humphries *et al.*, 2007). On the other hand, a low affinity switch of β_1 integrins is controlled by ICAP-1, a cytoplasmic partner, (likely by competing with talin). ICAP-1 delays focal adhesion assembly and, consequently, hampers cell spreading and migration (Bouvard *et al.*, 2003; Millon-Fremillon *et al.*, 2008). Integrin occupancy resulting in the recruitment of talin, vinculin, and paxillin is also observed in PTA as soon as the actin column has pushed the membrane in close contact with extracellular matrix (Badowski *et al.*, 2008).

The subsequent molecular mechanisms that lead to PTA and focal adhesions assembly have been partly characterized. They require Rho family GTPases, coordinated interaction between integrins and structural/signaling molecules, as well as actin-binding proteins (Chellaiah *et al.*, 2000; Moreau *et al.*, 2003; Raftopoulou and Hall, 2004; Destaing *et al.*, 2005; Yamaguchi *et al.*, 2005; Gimona and Buccione, 2006). The importance of these molecules as regulators is underscored by studies of knockout mice phenotypes showing abnormalities in cell migration and spreading.

In focal adhesions, PAK and PIX play a pivotal role in the maintenance of paxillin-containing focal adhesions (Stofega *et al.*, 2004) and their turnover (for review see

(Rosenberger and Kutsche, 2006). Further insight into the PIX-dependent molecular mechanisms required for actin reorganization and focal adhesion formation came from the identification of a novel protein family consisting of G protein-coupled receptor kinase-interacting target (GIT), paxillin kinase linker (p95PKL), ADP-ribosylation factor (Arf)-GAP-putative PIX-interacting, paxillin-interacting protein (p95-APP), and Cool-associated, tyrosine phosphorylated protein (CAT) (Bagrodia and Cerione, 1999; Turner *et al.*, 1999; Di Cesare *et al.*, 2000; Premont *et al.*, 2000; Paris *et al.*, 2003). Furthermore, complexes of GIT-PIX-PAK have been shown to cycle between at least three distinct subcellular compartments, including focal adhesions, a cytoplasmic (vesicular) compartment, and the leading edge (Di Cesare *et al.*, 2000; Matafora *et al.*, 2001; Manabe *et al.*, 2002).

Comparably, the RhoGTPase effector PAK4, a member of the p21 associated kinase family, and its regulator αPIX (PAK-interacting exchange factor), are important for podosome formation in primary human macrophages. Knockdown experiments, as well as expression of PAK4 truncation mutants, resulted in reduced numbers of podosomes per cell. Moreover, expression of kinase active or inactive PAK4 mutants enhanced or reduced the size of individual podosomes in macrophages, respectively, indicating an influence of PAK4 kinase activity on podosome size (Gringel *et al.*, 2006). Expression of active constructs of PAK1 is also able to induce the formation of dynamic, podosome-like F-actin columns in the A7r5 vascular smooth muscle cell line (Webb *et al.*, 2005).

Protein kinases and phosphatases regulate migration by modulating phosphorylation and dephosphorylation of key regulatory molecules. Podosome/invadopodia (PTA) dynamics and functions were reported to be regulated by Src-induced tyrosine phosphorylations (Marchisio *et al.*, 1984; Tarone *et al.*, 1985; Mueller *et al.*, 1992; Linder and Aepfelbacher, 2003; Bowden *et al.*, 2006). A key function of Src in osteoclasts is to promote the rapid assembly and disassembly of podosomes (Horne *et al.*, 2005). After integrin engagement, Pyk2 recruits Src and the adaptor protein Cbl, forming a molecular signaling complex that is critical for cell migration, and deletion of any molecule in this complex disrupts podosome ring formation and/or decreases osteoclast migration. The Cbl proteins in turn recruit and activate additional signaling effectors, including phosphatidylinositol 3-kinase (Fukazawa *et al.*, 1995; Soltoff and Cantley, 1996) and dynamin (Bruzzaniti *et al.*, 2005), which play key roles in the development of cell polarity and the regulation of cell attachment and motility.

Disassembly of cell-matrix adhesions

Fibroblasts deficient in FAK, Src family kinases (Src, Yes, Fyn), (PTP)-PEST, or SHP2 expression exhibit a decrease in the rate of migration and spreading and an increase in the number and size of peripherally localized focal adhesions (Ilic *et al.*, 1995; Yu *et al.*, 1998; Angers-Loustau *et al.*, 1999; Klinghoffer *et al.*, 1999). In addition, live cell imaging studies underline the crucial role of some kinases and adaptor molecules, such as FAK, Src, p130Cas, paxillin, extracellular signal-regulated kinase (ERK) and myosin light-chain kinase (MLCK) in adhesion turnover at the cell front, a central process of cell migration (Webb *et al.*, 2004). In osteoclasts, the absence of a number of proteins components including Src, Cbl, Pyk2, β_3 integrin, RhoA and gelsolin reduces osteoclast bone-resorbing activity to various degrees and the ability to form podosomes rosettes and sealing zone (Soriano *et al.*, 1991; Chellaiah *et al.*, 2000; Chiusaroli *et al.*, 2003). In Src -/- osteoclasts, the peripheral podosome belt is absent and replaced by irregular podosome patches at the cell center, likely due to a decrease in podosome number and/or altered dynamics exemplified by the four fold increase in the average podosome life span (Destaing *et al.*, 2008). Indeed, Src is also a main regulator of the disassembly of focal adhesions and podosomes (Webb *et al.*, 2004; Luxenburg *et al.*, 2006; Destaing *et al.*, 2008). A similar pattern has been observed in case of knock-down of many components of podosome ring such as paxillin (Badowski *et al.*, 2008), meaning that the incapacity to form ring or belt is the signature of a defect in podosome type adhesion dynamics. Similarly to podosome distribution during osteoclast differentiation, in RSV-transformed BHK cells, invadopodia can also self-organize into rosettes and belts, under the control of tyrosine phosphorylation whereas in carcinoma cells invadopodia remain as individual structures. In the BHK-RSV model, it has been clearly established that the composition of individual invadopodia is spatiotemporally regulated and depends on invadopodia localization along the rosette section: the actin core assembly precedes the recruitment of surrounding integrins and integrin-linked proteins while the loss of the actin core was a prerequisite to invadopodia disassembly. Invadopodia rosette expansion is controlled by paxillin phosphorylations on tyrosine 31 and 118 by the FAK/Src complex which allows invadopodia disassembly. The lack of paxillin phosphorylation, or calpain or Erk inhibition result in similar phenotype, suggesting that these proteins belong to the same regulatory pathways (Badowski *et al.*, 2008). Surprisingly, this mechanism seems to be quite similar in focal adhesions where paxillin also plays a major role in their disassembly (Zaidel-Bar *et al.*, 2007). Indeed, recent studies have demonstrated that the calpain family has a

regulatory function in cell motility, partly through the capacity to down regulate integrin-mediated adhesion complexes (Glading *et al.*, 2000; Dourdin *et al.*, 2001; Bhatt *et al.*, 2002; Glading *et al.*, 2002). In that context, talin seems to be one of major target of calpain leading to a rate-limiting step critical for FA disassembly (Franco *et al.*, 2004). It has also been shown that the expression of a calpain-resistent cortactin impaired cell migration and increased transient membrane protrusion (Perrin *et al.*, 2006). Since cortactin is a major component of PTA, its degradation by calpain may play a key role in their disassembly. In addition, PTA turnover depends on degradation of WASP by calpain (Calle *et al.*, 2006) and on its stabilization by WIP (Chou *et al.*, 2006) . Lifetime and maturation of invadopodia are influenced by cofilin. Loss of cofilin leads to short-lived invadopodia and decreased matrix degradation in carcinoma cells (Yamaguchi *et al.*, 2005), suggesting cofilin as a key protein for transition between podosomes and invadopodia.

Microtubules have also been shown to stimulate focal adhesions disassembly (Kaverina *et al.*, 1999). More recently Ezratty et al (Ezratty *et al.*, 2005) have demonstrated that microtubule-induced focal adhesion disruption may occur independently of Rho A and Rac 1, but is dependent on FAK and dynamin, which might drive disassembly through integrin endocytosis. Microtubules also affect turnover of podosomes. The formation of the peripheral podosome belt in osteoclasts depends on an intact microtubule system involving Rho, the formin mDia2 and histone deacetylase (HDAC6), through regulation of the acetylation level of microtubules (Destaing *et al.*, 2005). Similarly to the targeting of focal adhesions by microtubules for their dissolution (Kaverina *et al.*, 1999; Krylyshkina *et al.*, 2003), macrophage podosomes are also targeted by microtubules plus ends influencing not only their breakdown but also podosome generation by a dissolution/fission process (Kopp *et al.*, 2006). However, other data although indicating a clear relationship between microtubules and podosomes suggest that podosomes fission/fusion may be influenced by nocodazole (a microtubules depolymerizing agent) or paclitaxel (a microtubules stabilizing agent) without any effect in dissolution of individual podosomes (Evans *et al.*, 2003). Microtubules probably deliver materials not yet identified in the case of focal adhesions. For podosomes, KIF1C may allow the delivery of lysosomal material (Poincloux *et al.*, 2006) or trafficking of MMPs (Schnaeker *et al.*, 2004). Moreover, KIF1C provides an interface together with Myosin IIA between microfilaments and microtubules (Gringel *et al.*, 2006).

Dynamin, a GTPase essential for endocytosis, is also involved in actin cytoskeleton remodeling and is localized to podosomes where it plays a role in actin turnover. Dynamin colocalizes with Cbl in the actin-rich podosome belt of osteoclasts (Bruzzaniti *et al.*, 2005).

Phosphorylated Cbl is also able to recruit Crk adapter proteins (Horne *et al.*, 2005) and the guanine nucleotide exchange factor vav (Marengere *et al.*, 1997), and possibly Src and other Src family kinases (Feshchenko *et al.*, 1998). In focal adhesions, it has also been suggested that Cbl-mediated ubiquitination plays an essential role in α_5 integrin proteasome degradation induced by FGFR2 activation (Kaabeche *et al.*, 2005). In addition, ArgBP2 interacts with Cbl and colocalizes with actin on stress fibers and at cell-adhesion sites. The ArgBP2 partners include dynamin, synaptojanin and WAVE isoforms, as well as WAVE regulatory proteins. ArgBP2/nArgBP2 knockdown in astrocytes produces a redistribution of focal adhesion proteins and an increase in peripheral actin ruffles, whereas nArgBP2 overexpression produces a collapse of the actin cytoskeleton. Thus, ArgBP2 is a scaffold protein that controls the balance between adhesion and motility by coordinating the function of multiple signaling pathways converging on the actin cytoskeleton (Cestra *et al.*, 2005).

Conclusions

Although extensively studied, focal adhesions and podosomes have rarely been compared. While they exhibit very distinct structures, recent data in the literature suggest surprisingly convergent regulatory mechanisms of their dynamics. However, the study of different matrix adhesions with distinct morphologies, compositions and dynamics may shed light on their capacity to activate or respond to distinct signaling pathways and their specific functions. Nevertheless, interplay between both structures has been evidenced. Future challenges will include the determination of how dynamic processes are involved in the formation and transformation or conversion of matrix adhesions highlighting the plasticity of cell matrix contacts in a variety of biological responses in different tissue, under physiological and pathological situations. One will have to address how regulatory molecules or external constraints in cell-matrix adhesion may contribute to promote or impair distinct adhesive structures. Finally, it will be important to understand how focal adhesions, podosomes and invadopodia function cooperatively during tumor invasion.

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Figures legend :

Figure 1 : Architecture and composition of adhesive structures.

A. Tangential adhesive structures. MEF cells spread on a fibronectin matrix were stained to visualize either β1 integrin containing focal adhesion (Fa) and focal complex (Fx) or fibronectin to localize fibrillar adhesion (Fb). **B.** Schema representing Fa organization. IAP: Integrin Associated Protein (CD47) **C.** Perpendicular adhesive structures. RSV-transformed BHK cells were transfected with cortactin-DsRed and stained for vinculin and paxillin phosphorylated on Y118 (P-Paxillin). Confocal analysis displays a rosette of PTA (Podosome-type adhesion). One structural unit (PTA) is presented on zoom pictures and is made by one core surrounded by adhesion proteins. **D.** Schema representing the architecture of PTA.

Figure 2: Dynamics of adhesion structures.

A. Turnover of Fa. VASP-GFP expressing MEF cells spread on a fibronectin matrix were monitored over a 6 hours period. At the birth of a nascent Fa (white arrow), the clustering of integrins and the recruitment of focal adhesion proteins induce an increase of GFP-VASP fluorescence until it reaches a brief plateau denoting the mature adhesion which is immediately follows by the decrease of GFP fluorescence and the dissociation of proteins leading to the disassembly of adhesion site. **B.** Turnover of PTA. Cortactin-GFP transfected BHK-RSV cells were treated with sodium orthovanadate 5mM to allow rosette expansion and observed over a 130 min period. Ring expansion is allowed by new PTA formation at the rosette periphery (white circle) and disassembly of PTA at the rosette center.

Table 1: Comparison of PTA and Fa associated proteins.

Non exhaustive listing of proteins directly linked to Fa and PTA, signalling proteins and actin-binding regulators, all associated with these adhesive structures. Focal complexes (Fx) and PTA structures present both branched actin organization and extracellular matrix is necessary for both focal adhesion structures and podosome-type adhesion structures formation. However, their dynamics and functions are quite distinct.

	Adhesion structures		
Composition	Focal adhesion (Fa, Fx, Fb)	Podosome type Adhesion (PTA)	
		Podosome	Invadopodia
Talin	+ (Fa, Fx)	+	+
Vinculin	+ (Fa, Fx)	+	+
Paxillin	+ (Fa, Fx)	+	+
α-actinin	+ (Fa)	+	+
Zyxin	+ (Fa)	?	?
Tensin	+ (Fb)	-	-
Integrins	+	+	+
CD44	?	+	+
Kindlin	+	+	?
Src	+	+	+
FAK/Pyk2	+	+	+
PI3K	+	+	+
PAK	+	+	+
PIX	+	+	+
Cdc42	-	+	+
Rac1	-	+	+
P130cas	+	+	+
P120RasGAP	+	+	+
P190RhoGAP	+	+	+
Cbl	+	+	+
Actin organisation	bundle (Fa, Fb) + branched (Fx)	bundle (cloud) + branched (core)	?
WASP/N-WASP	-	+	+
WIP	-	+	+
Arp2/3 complex	-	+	+
Cortactin	-	+	+
Dynamin-2	?	+	+
VASP	+	+	+
Fimbrin	+	+	+
Cofilin	+	+	+
Gelsolin	+	+	+
Filamin	-	?	?
Plectin	+	+	+
AFAP 110	+	+	+
Myosin 2	+	+	+
ECM-dependent formation	+	+	+
Dynamics			
Individual	++	+++	+
Collective	migration	Rosette formation/expansion	Rosette formation/expansion (Src-BHK cells)
Functions			
Adhesion	+++	++	?
Migration	+++	?	?
ECM remodeling (FN fibrillogenesis)	+++ (Fb)	?	?
ECM degradation	+/-	++	+++

Table I. Block et al

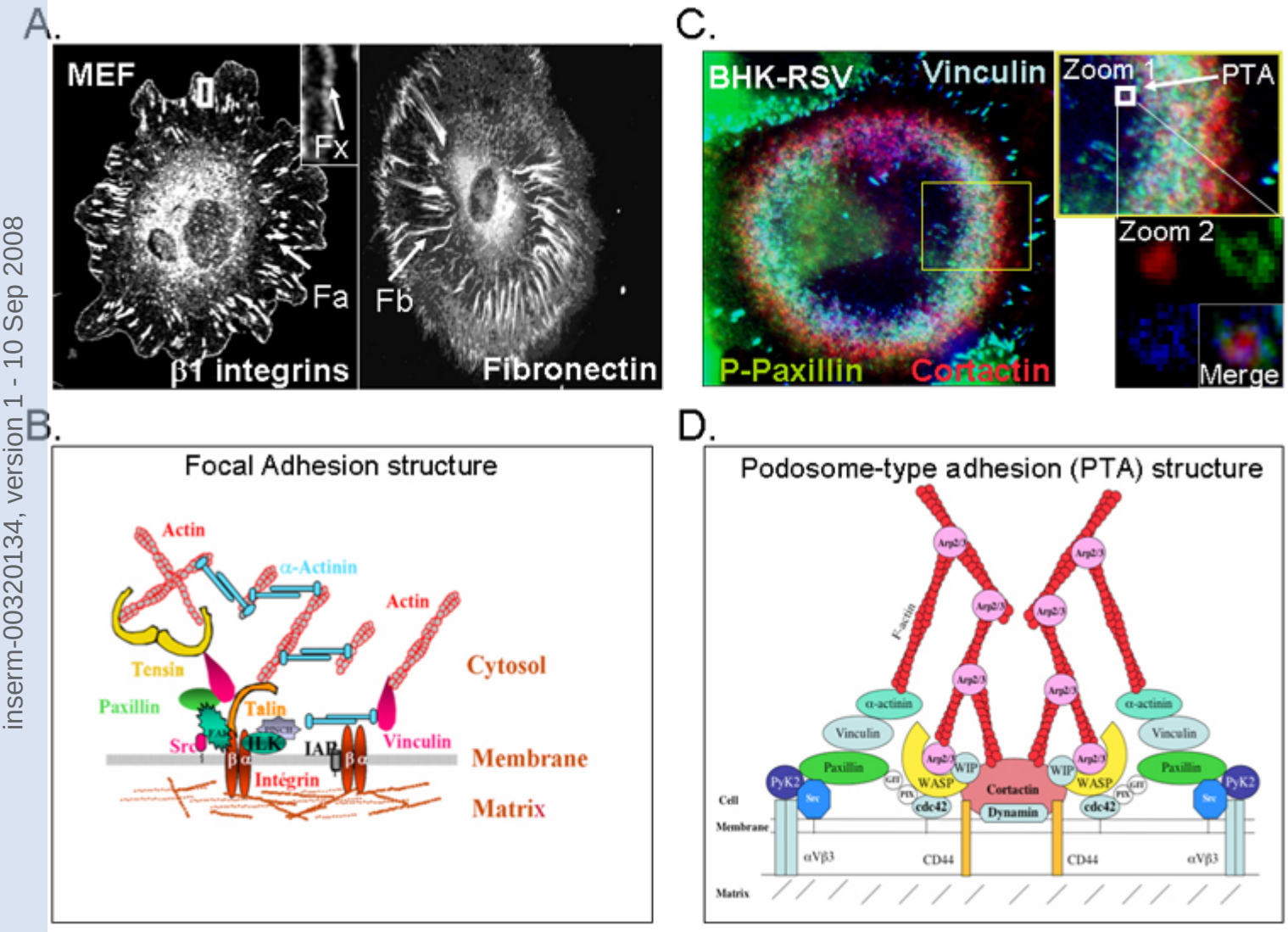

Figure 1.Block et al.

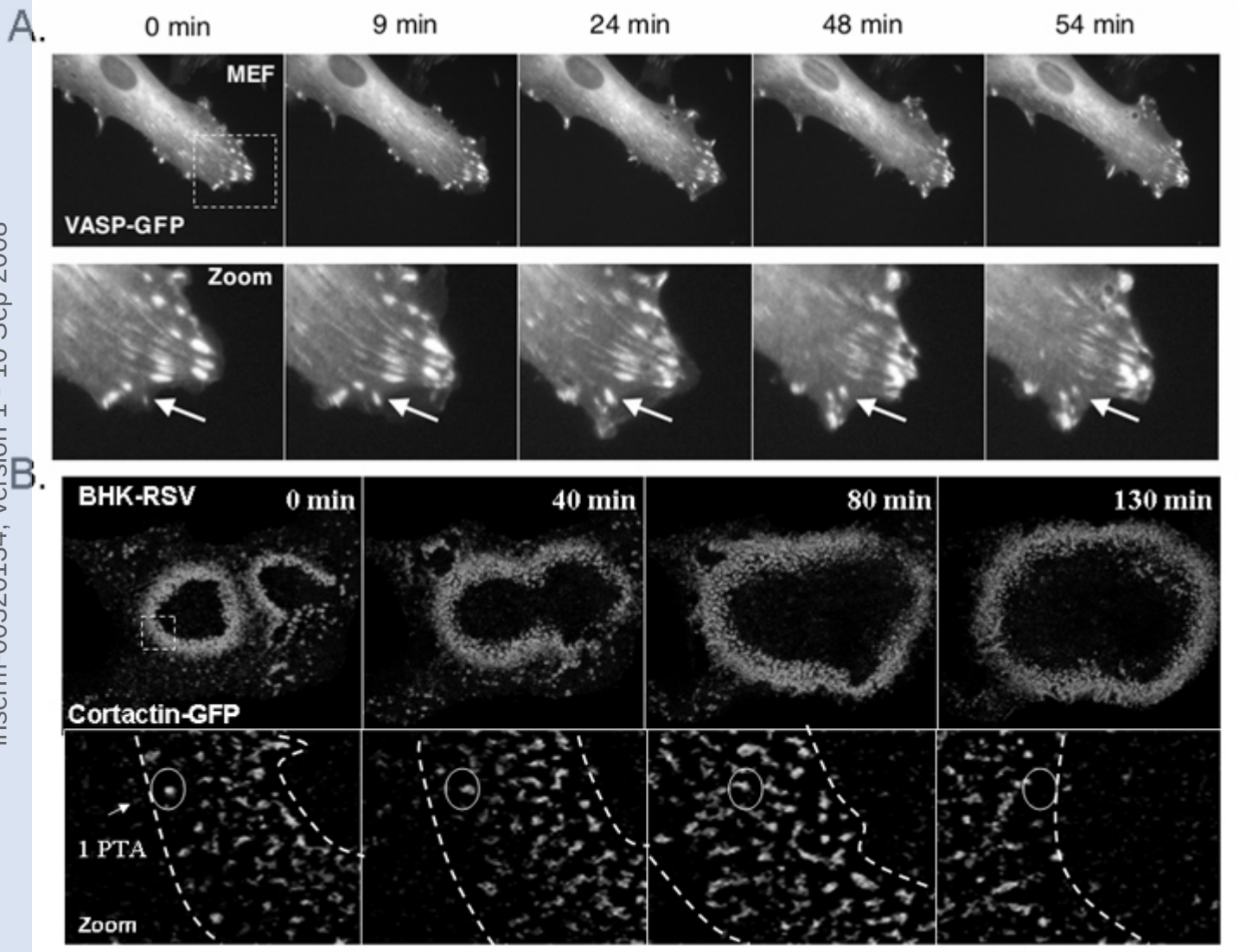

Figure 2, Block et al.