Role of lateral cell–cell border location and extracellular/transmembrane domains in PECAM/CD31 mechanosensation

David A. Kaufman, a,b,1 Steven M. Albelda, b Jing Sun, b and Peter F. Davies a,c,*

a Institute for Medicine and Engineering, University of Pennsylvania, Philadelphia, PA 19104, USA
b Division of Pulmonary, Allergy and Critical Care Medicine, Department of Medicine, University of Pennsylvania, Philadelphia, PA 19104, USA
c Department of Pathology and Laboratory Medicine, University of Pennsylvania, Philadelphia, PA 19104, USA

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Abstract

Phosphorylation of tyrosine residues on platelet–endothelial cell adhesion molecule-1 (PECAM-1), followed by signal transduction events, has been described in endothelial cells following exposure to hyperosmotic and fluid shear stress. However, it is unclear whether PECAM-1 functions as a primary mechanosensor in this process. Utilizing a PECAM-1–null EC-like cell line, we examined the importance of cellular localization and the extracellular and transmembrane domains in PECAM-1 phosphorylation responses to mechanical stress. Tyrosine phosphorylation of PECAM-1 was stimulated in response to mechanical stress in null cells transfected either with full length PECAM-1 or with PECAM-1 mutants that do not localize to the lateral cell–cell adhesion site and that do not support homophilic binding between PECAM-1 molecules. Furthermore, null cells transfected with a construct that contains the intact cytoplasmic domain of PECAM-1 fused to the extracellular and transmembrane domains of the interleukin-2 receptor also underwent mechanical stress-induced PECAM-1 tyrosine phosphorylation. These findings suggest that mechanosensitive PECAM-1 may lie downstream of a primary mechanosensor that activates a tyrosine kinase.

Keywords: Platelet endothelial adhesion molecule-1; Endothelial mechanotransduction; Hyperosmotic stress; Fluid shear stress

Mechanical stresses, including fluid shear stress (FSS), play an important role in determining endothelial cell (EC) behavior, modulating their physiology, gene expression, and morphology [1,2]. Transfer of FSS forces to the EC first occurs at the luminal cell surface where molecules whose conformations are directly affected by FSS may act as mechanosensors or mechanotransducers. In addition, sites remote from the initial stimulus may act as mechanosensors or mechanotransducers as the force of FSS is transmitted throughout the cell via the cytoskeleton [1]. One such location is the lateral cell–cell adhesion site [3].

Recently, investigators have identified a possible role for platelet–endothelial cell adhesion molecule-1 (PECAM-1, CD31) in the sensation of hyperosmotic stress (HOS) and FSS and subsequent signal transduction events [4–6]. PECAM-1 is a 130-kDa member of the immunoglobulin superfamily that is expressed abundantly on the cell surface of ECs, platelets, and many leukocytes. A striking feature of PECAM-1 is its localization at the cell–cell border between adjacent endothelial cells [7,8]. This specific localization may be important to the vascular function of PECAM-1, playing a role in leukocyte transmigration of EC monolayers [9]. In confluent endothelial cells, PECAM-1 molecules on adjacent cells bind homophilically to each other via extracellular domains 1 and 2 [10].

Abbreviation: PECAM-1, platelet–endothelial cell adhesion molecule-1.

* Corresponding author. Fax: 1-215-573-6815.
E-mail address: pfd@pobox.upenn.edu (P.F. Davies).
1 Present address: Division of Pulmonary and Critical Care Medicine, Mt. Sinai School of Medicine, New York, NY, USA.

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REN cells are endothelial-like cells derived from human malignant mesothelioma [11]. In culture, they form a confluent monolayer and adopt a “cobblestone” morphology reminiscent of ECs (Fig. 1). In addition, REN cells express several surface antigens in common with ECs but lack PECAM-1; they can be transfected stably with wild-type or mutant forms of PECAM-1 (Fig. 2A). We have previously used REN cells as an EC model, finding that many EC signaling processes may be reconstituted after PECAM-1 expression [12,13].

Utilizing this null cell, we reasoned that if PECAM-1 is a mechanosensor, force-induced PECAM-1 phosphorylation may require localization to, and organization at, the lateral cell–cell border. We also explored whether the cytoplasmic, extracellular or transmembrane domains of PECAM-1 are necessary for PECAM-1 mechanosignaling.

**Materials and methods**

**Antibodies, reagents, immunoprecipitation, and Western blotting.**

Antibodies included the following: mAb 4G6, a murine immunoglobulin (IgG) directed against the PECAM-1 extracellular Ig loop six domain [14]; mAb 1.3, a murine IgG directed against the PECAM-1 extracellular domain (a gift of Dr. Peter Newman, Blood Center of Southeastern Wisconsin, Milwaukee, WI); PCD, a rabbit polyclonal antibody directed against the PECAM-1 cytoplasmic domain; ab8325 (Abcam, Cambridge, UK), a murine mAb directed against the α-subunit of the interleukin-2 receptor (IL2R); anti-SHP-2 mAb (Cell Signaling Technology, Santa Cruz, CA); and PY20 (Transduction Laboratories, BD Biosciences, Palo Alto, CA), an anti-phosphotyrosine rabbit polyclonal Ab. Purified antibodies were obtained by protein G affinity chromatography of hybridoma supernatants or serum. Active binding of antibodies was confirmed by flow cytometry.

For immunoprecipitation, thawed lysates were preabsorbed with protein A-conjugated Sepharose beads (Amersham–Pharmacia). After removal from the beads, the precleared supernatants were transferred to fresh microtubes and immunoprecipitated by incubation with mAb 4G6 (for WT PECAM-1 and the K151A/R152A mutant) or...
Hyperosmotic stress and fluid shear stress. Cells were seeded onto gelatin-coated glass microscope slides 48 h prior to the experiment and grown to confluence. For experiments with HAECs, EBM-2 (Clonetics) containing 2% fetal bovine serum and Bullet kit reagents (Clonetics), supplemented with 1% dextran, was used. To enhance the PY-PECAM-1 signal, this medium was supplemented with 5 mM NaVO₃ (pH 7.4); HAECs incubated for 3 h in NaVO₃-containing medium were used as a positive PY-PECAM-1 control.

REN cells were incubated in R10 medium containing 1% dextran and 5 mM NaVO₃ (pH 7.4) for 15 min of fluid shear stress (FSS) lead to tyrosine phosphorylation of PECAM-1 in HAECs and REN cells transfected with wild-type PECAM-1.

In order to explore the role of PECAM-1 as a mechanosensitive molecule in depth, we chose the REN cell model as a null cell. Because wild-type-PECAM-1 is expressed abundantly on all known lines of ECs, detecting the effects of mutations to PECAM-1 is difficult. Some investigators have employed anti-sense oligo techniques to knock down the expression of wt-PECAM-1, but such techniques only suppress the expression of wt-PECAM-1 to approximately 70% of normal [5]. Thus, we subjected REN cells transfected with wt-PECAM-1 (REN-HP) to FSS and HOS. In order to strengthen the PECAM-1–tyr-P signal in Western blotting, phosphatase activity was inhibited by incubating the cells with growth media containing 5 mM NaVO₃ for 2 h prior to FSS or HOS (control samples were incubated with growth media containing 5 mM NaVO₃ for 2 h 15 min). FSS or HOS stimulated tyr-P of PECAM-1 in cultured bovine aortic endothelial cells (HAECs) and REN cells transfected with wild-type PECAM-1.

Results and discussion

Fluid shear stress leads to tyrosine phosphorylation of PECAM-1 in HAECs and REN cells transfected with wild-type PECAM-1.

FSS and HOS induce tyrosine phosphorylation of PECAM-1 in cultured bovine aortic endothelial cells [5,6]. To confirm this observation, and to ascertain whether this phenomenon is present in human EC, physiologic FSS (13 dyn/cm²) was applied for 15 min, or HOS for 10 min, to cultured HAECs. PECAM-1 purified from HAECs subjected to FSS demonstrated significantly higher levels of tyr-P than controls (Fig. 3).

We also confirmed the observation that PECAM-1–tyr-P co-immunoprecipitated with SHP-2, as observed by other investigators (data not shown) [19].

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217 The extracellular and transmembrane domains of PECAM-1 are not required for mechanically induced tyrosine phosphorylation

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these molecules modulates or is modulated by PECAM-1 has not been elucidated.

Mechanical stress is an important determinant of endothelial cell behavior [1,2]. Areas of disturbed flow, for example, are more prone to atheroma formation [25,26]. Abnormal mechanical stress may also play a role in the pathogenesis of pulmonary hypertension [27], ventilator-induced lung injury [28,29] or glomerulonephropathy [30]. PECAM-1 is expressed abundantly on endothelial cells, platelets, and most leukocytes. It is believed to play a role in mediating adhesion between adjacent endothelial cells, angiogenesis, and neutrophil adhesion to, and migration through, the endothelial monolayer [9,31,32]. PECAM-1-null mice, however, do not display developmental abnormalities or significant vascular defects, although bleeding time is increased, leukocyte transendothelial migration is slowed, and the blood–brain barrier may be weakened [33–35].

In summary, utilizing EC-like REN cells stably transfected with wild-type and mutant PECAM-1 constructs to elucidate which domains of PECAM-1 confer mechanosensitivity, we demonstrate that in the confluent monolayer, phosphorylation does not depend upon lateral membrane localization of the protein and cell-cell homophilic PECAM-1 binding. The transmembrane and extracellular domains of PECAM-1 are not necessary for mechano-responsiveness. The kinase, which remains to be identified, appears to be activated by a more direct effect of mechanical stress on the cells.

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References


