The Conserved Immunoglobulin Domain Controls the Subcellular Localization of the Homophilic Adhesion Receptor Protein-tyrosine Phosphatase μ*

Received for publication, September 3, 2004, and in revised form, October 13, 2004
Published, JBC Papers in Press, October 18, 2004, DOI 10.1074/jbc.M410181200

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The receptor protein-tyrosine phosphatase μ (PTPμ) is a homophilic adhesion protein thought to regulate cell-cell adhesion in the vascular endothelium through dephosphorylation of cell junction proteins. In subconfluent cell cultures, PTPμ resides in an intracellular membrane pool; however, as culture density increases and cell contacts form, the phosphatase localizes to sites of cell-cell contact, and its expression level increases. These characteristics of PTPμ, which are consistent with a role in cell-cell adhesion, suggest that control of subcellular localization is an important mechanism to regulate the function of this phosphatase. To gain a better understanding of how PTPμ is regulated, we examined the importance of the conserved immunoglobulin domain, containing the homophilic binding site, in control of the localization of the enzyme. Deletion of the immunoglobulin domain impaired localization of PTPμ to the cell-cell contacts in endothelial and epithelial cells. In addition, deletion of the immunoglobulin domain affected the distribution of PTPμ in subconfluent endothelial cells when homophilic binding to another PTPμ molecule on an apposing cell was not possible, resulting in an accumulation of the mutant phosphatase at the cell surface with a concentration at the cell periphery in the region occupied by focal adhesions. This aberrant localization correlated with reduced survival and alterations in normal focal adhesion and cytoskeleton morphology. This study therefore illustrates the critical role of the immunoglobulin domain in regulation of the localization of PTPμ and the importance of such control for the maintenance of normal cell physiology.

The physical interactions of individual cells with the local environment is critical to the control of their growth, differentiation, and fate within a multicellular organism. These responses are initiated by cell adhesion receptors, which bind either homophilic or heterophilic ligands on apposing cells or the extracellular matrix. A critical aspect in the cellular response to these interactions is reversible protein tyrosine phosphorylation of cell junction-associated proteins (1, 2). In fact, the bulk of the tyrosine-phosphorylated cellular proteins are localized to sites of cell-cell and cell-extracellular matrix adhesion. Several protein-tyrosine kinases and phosphatases have been implicated in the regulation of cell adhesion (3–6). In particular, receptor protein-tyrosine phosphatases (RPTPs), several of which possess extracellular domains with features characteristic of cell adhesion receptors, linked to a cytoplasmic PTP activity, are uniquely designed to mediate cellular responses to adhesive signals through protein tyrosine dephosphorylation (7, 8). Of particular interest is the potential for the extracellular domains of individual RPTPs to mediate interactions with, and control of, either cell-cell or cell-extracellular matrix adhesions. In this way, the targeting of RPTPs to specific junctions may be a key element in controlling the changes in cell junction-actin cytoskeleton interactions that occur as cells transition from a growing, migrating state, in which actin stress fibers are linked to cell-matrix junctions, to contact-inhibited cells, in which actin fibers are linked primarily to cell-cell junctions (9).

In this study, we focus on the receptor protein-tyrosine phosphatase PTPμ. PTPμ is synthesized as a single polyepitope chain, which is then glycosylated and proteolytically cleaved at a site N-terminal to the transmembrane segment to give two subunits that remain noncovalently associated (10, 11). The E-subunit (see Fig. 1A), which constitutes the majority of the extracellular segment, consists of one immunoglobulin (Ig) domain; four fibronectin type III repeats; and a MAM (Mu, A5, and meprin homology) domain, which is a conserved domain unique to PTPμ, PTPx, PTPβ, and PTPα and some cell adhesion molecules (12). The P-subunit (see Fig. 1A) contains a short extracellular segment; the transmembrane segment; and the entire cytoplasmic portion, including two PTP domains. PTPμ can function as a homophilic adhesion receptor whereby a PTPμ molecule on one cell can bind to an identical PTPμ molecule on an apposing cell (13, 14). It is this binding that is proposed to direct the localization of PTPμ to sites of cell-cell contact, where it is thought to interact with the cadherin-catenin cell adhesion complex (11, 15). Consistent with a role in cell-cell adhesion, the level of PTPμ protein increases as intercellular contacts are made and cell-cell junctions form (11). This phenomenon is seen with other RPTPs and may provide a means to control protein phosphorylation-based signaling in contact-inhibited cells (15–18). PTPμ is expressed predominantly in vascular endothelial cells and to a lesser extent in bronchial epithelium and may play a role in endothelium-dependent processes such as the control of vascular permeability and the angiogenic responses to tumor formation and wound healing (19).

* This work was supported by National Institutes of Health Grant GM55989. The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1754 solely to indicate this fact.

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1 The abbreviations used are: RPTPs, receptor protein-tyrosine phosphatases; PTP, protein-tyrosine phosphatase; BAE, bovine aortic endothelial cells; trBARE, transformed bovine aortic endothelial cells; MDCK, Madin-Darby canine kidney; BrdUrd, 5-bromo-2-deoxyuridine; WT, wild-type; Ig, immunoglobulin; MEM, minimum essential media; VE-cadherin, vascular endothelial cadherin.
Considering the importance of PTPs in the control of signal transduction, it is critical that they be tightly regulated to facilitate protein tyrosine phosphorylation (20). Based on studies with RPTPα, dimerization of RPTPs, which leads to occlusion of the active site, has been proposed as one mechanism for inhibition of phosphatase activity (21–23). However, it is not clear whether dimer-induced inhibition is widely applicable, as dimers formed in crystals of RPTP-LAR and RPTPβ are oriented such that the active sites are unobstructed (24, 25). A number of studies indicate that the control of localization and substrate accessibility by intrinsic targeting domains is another important way to modulate cellular dephosphorylation by PTPs (20) such as PTPμ. In contrast to the structurally related LAR-subtype RPTPs (LAR, PTPσ, and PTPδ), which can be found in both cell-matrix and cell-cell contacts (26–28), PTPμ is thought to function exclusively at sites of cell-cell adhesion, where it has the potential to regulate signaling events specific to contact-inhibited cells. In subconfluent cells, PTPμ is thought to cycle between the plasma membrane and membrane vesicles in the perinuclear region of the cell (11, 15). Although it has been proposed that stable surface expression is dependent upon homophilic binding of purified PTPμ fusion proteins as well as binding of the fusion proteins to the surface of cells expressing endogenous levels of PTPμ (10). Here, we have deleted the Ig domain of PTPμ and expressed the mutant protein in endothelial and epithelial cell lines to assess the role of this domain in regulating localization of the phosphatase. The results demonstrate the importance of the Ig domain for the localization of PTPμ to sites of cell-cell contact and also identify a role for this domain in localization of PTPμ in subconfluent cells in the absence of cell-cell contact.

EXPERIMENTAL PROCEDURES

Cell Culture—Bovine aortic endothelial cells (BAEC) and the derived cell lines GM7372 and GM7373 (referred to here as transformed BAEC (trBAEC)) (29) were obtained from the Coriell Institute for Medical Research (Camden, NJ). The cells were grown in basal medium (Sigma) supplemented with 10% fetal bovine serum (HyClone Laboratories), 1× MEM/essential and nonessential amino acid mixtures, 1× MEM/vitamins, 2 mM l-glutamine, and 10 μg/ml gentamycin (Invitrogen). Madin-Darby canine kidney (MDCK) cells (catalog no. CCL-34) were purchased from American Type Culture Collection (Manassas, VA) and grown in Dulbecco’s modified Eagle’s medium (Invitrogen) plus 10% fetal bovine serum, 2 mM l-glutamine, and 10 μg/ml gentamycin.

Construction of Retroviral Expression Plasmids—Human PTPμ (GenBank/EMBL accession number NM_002845) DNA constructs were cloned with a C-terminal T7 epitope tag (30) into the retroviral vector pWZL-hygromycin (provided by S. Lowe, Cold Spring Harbor Laboratory) by PCR with pBSKhF1 (31) as the template. pWZL/PTPμWT contains nucleotides 1–4359 of human PTPμ; pWZL/PTPμΔIg and pWZL/PTPμΔE have deletions of nucleotides 568–930 and 67–1914, respectively, in human PTPμ. The resulting constructs encoded proteins with a C-terminal extension of AMSMTGQQGMG, where the underlined amino acids define the T7 epitope tag. All constructs derived from PCR were confirmed by DNA sequencing.

Expression of PTPμ by Retroviral Infection—LinX-A retroviral packaging cells (32) were transfected with pWZL/PTPμ plasmid DNA using calcium phosphate. The resulting supernatants, containing recombinant retrovirus encoding PTPμ, were used to infect monolayer cultures of GM7372 cells, trBAEC, or MDCK cells. Two days following infection, cells were plated in the appropriate medium supplemented with 100 μg/ml (GM7372 cells) or 400 μg/ml (trBAEC and MDCK cells) hygromycin B (Invitrogen). The medium was changed every 2–3 days, and cultures were passaged when they reached ~70–90% confluence.

Antibodies—The following primary antibodies were used in this study: anti-T7 epitope antibody (mouse IgG2b, Novagen); anti-VE-cadherin antibody 4506 (mouse IgG1, ICOS, Bothell, WA); anti-vinculin antibody VIN-11.5 (mouse IgG1; Sigma); anti-phosphotyrosine antibody G104 (mouse IgG1) (33); anti-panxillin antibody (mouse IgG1; Transduction Laboratories); and the PTPμ-specific antibodies SK7 (murine IgG2a), BK2 (mouse IgG1), and BK3 (murine IgG2a). The secondary antibodies were detected with isotype-specific secondary antibodies (Molecular Probes, Inc., Eugene, OR) to mouse IgG1 (labeled with Alexa 594) or to mouse IgG2b or IgG2a (labeled with Alexa 488).

RESULTS

Generation of Stable Lines of GM7372 Cells Expressing PTPμ Deletion Constructs—As an initial step in understanding the mechanisms involved in regulating PTPμ function in endothelial cells, we expressed various mutant constructs in GM7372 cells, a cell line derived from BAEC. GM7372 cells have similar morphology and growth properties compared with primary BAEC and express endothelium-specific cell junction
proteins (Fig. 1) (data not shown) (29). GM7372 cells expressed a similar level of endogenous PTP\(\mu\) compared with the parental BAEC (Fig. 1B). In agreement with previous findings (15, 19), PTP\(\mu\) was observed as a full-length ~200 kDa protein (Fig. 1B, EP) and as processed proteolytic fragments of ~110 kDa for the E-subunit (Fig. 1B, E) and P-subunit (data not shown). As described previously (19), at high cell density, PTP\(\mu\) co-localized at cell-cell contacts with the endothelial-specific VE-cadherin, and the level of PTP\(\mu\) protein was increased (Fig. 1, B and C). In subconfluent cells, PTP\(\mu\) was found in a perinuclear vesicular compartment (Fig. 1C).

Electrophoretic expression of PTP\(\mu\)WT, PTP\(\mu\)ΔIg (deletion of amino acids 190–310), and PTP\(\mu\)ΔE (deletion of amino acids 23–638) was achieved by infection of GM7372 monolayers with recombinant retrovirus encoding the T7 epitope-tagged PTP\(\mu\) constructs. We utilized a vector, pWZL, containing an internal ribosomal entry site, from which PTP\(\mu\) and the selection marker are separately translated from the same mRNA. Stable cells were selected in hygromycin as pooled populations from an ~90% confluent monolayer of infected GM7372 cells. Attempts to isolate clonal cell lines of GM7372 expressing PTP\(\mu\) from dilute cultures were unsuccessful. We reasoned that any inhibitory effects on growth or survival caused by ectopic expression of PTP\(\mu\) might be more pronounced at low cell density, when the normal level of PTP\(\mu\) is low, than at high cell density, when expression of the phosphatase is naturally up-regulated.

FIG. 1. Endogenous PTP\(\mu\) expression in bovine endothelial cells. A, the domain structure of PTP\(\mu\) is outlined with the signal sequence (Sig. seq.) and the MAM, immunoglobulin (Ig), fibronectin type III (FN III), and transmembrane (TM) domains indicated above the diagram. The positions of the E- and P-subunits (amino acids 23–638 and 639–1452, respectively) are indicated. B, lysates from confluent cultures of BAEC, trBAEC, and GM7372 cells (7372) (left panel) and sparse (sp; ~40% confluent) and confluent (con) GM7372 cells (right panel) were analyzed by immunoblotting with anti-PTP\(\mu\) antibody BK2. 40 \(\mu\)g of protein were loaded for each lysate. Brackets indicate the positions of the non-proteolytically processed protein (EP) and the proteolytically processed E-subunit (E). Pulse-chase labeling studies suggested that the lower band(s) for the EP protein represents the initial protein product prior to glycosylation and subsequent processing. The migration positions of relative molecular mass markers (in kilodaltons) are shown to the right of each panel. C, subconfluent GM7372 cells were fixed and stained with anti-PTP\(\mu\) antibody SK7 (upper panel), and confluent cells were stained sequentially with antibody SK7 (middle panel) and anti-VE-cadherin antibody 45CS (cad, lower panel) as described under “Experimental Procedures.” Scale bar = 10 \(\mu\)m.

FIG. 2. Analysis of PTP\(\mu\) proteins expressed in GM7372 cells. Lysates from stable populations of confluent GM7372 cells expressing PTP\(\mu\)WT, PTP\(\mu\)ΔIg, PTP\(\mu\)ΔE, or the empty pWZL-hygro vector (V) were analyzed by immunoblotting with anti-P-subunit antibody SK7 (left panel) or anti-E-subunit antibody BK2 (right panel, lysate lanes). 18 \(\mu\)g of protein were loaded for each lysate. Immunoblotting conditions were chosen to demonstrate the overexpression of the ectopic proteins relative to endogenous PTP\(\mu\). The positions of the non-proteolytically processed protein (EP) and the processed P-subunit (P) and E-subunits of the PTP\(\mu\)WT (E(WT)) and PTP\(\mu\)ΔIg (E(ΔIg)) proteins are indicated to the left of the panels. Pulse-chase labeling studies suggested that the lower band(s) for the EP protein represents the initial protein product prior to glycosylation and subsequent processing. The band at 116 kDa in the PTP\(\mu\)ΔIg samples, which also appears in the vector samples, is from the endogenous PTP\(\mu\) E-subunit. Association of the two subunits of PTP\(\mu\)WT or PTP\(\mu\)ΔIg was demonstrated by immunoprecipitating the P-subunit from lysates of GM7372 cells with the anti-T7 epitope antibody and detecting the associated E-subunit by immunoblotting the immune complexes with antibody BK3 (right panel, IP lanes). The migration positions of the E-subunits from the PTP\(\mu\)WT and PTP\(\mu\)ΔIg proteins are indicated to the left of the right panel. The migration positions of relative molecular mass markers (in kilodaltons) are indicated to the right of each panel.

The use of the pWZL vector resulted in a tight correlation between hygromycin resistance and ectopic expression of PTP\(\mu\), producing cell populations in which 70–80% of the cells expressed detectable amounts of the specific PTP\(\mu\) mutant, as determined by detection with anti-PTP\(\mu\) antibodies (data not shown).

Immunoblotting of cell lysates with antibodies specific to the P-subunit (SK7) and the E-subunit (BK2) indicated similar levels of expression from each construct (Fig. 2). Furthermore, the wild-type EP protein migrated as a doublet on SDS-polyacrylamide gel, with the slower migrating band, previously shown to represent the glycosylated form (11), predominating. In contrast, the hypoglycosylated form of PTP\(\mu\)ΔIg predominated, which would contribute to the faster than expected migration of the E-subunit of this mutant on SDS-polyacrylamide gel. In addition, immunoprecipitation of the P-subunit of PTP\(\mu\)ΔIg with the antibody to the C-terminal T7 epitope followed by immunoblotting of the E-subunit with antibody BK3 demonstrated that the two intact segments of the processed protein were associated in the cell, as seen with the WT protein (Fig. 2).

The Ig Domain Is the Major Determinant of Localization of PTP\(\mu\) to Sites of Cell-Cell Contact—It has been proposed that
PTP pressing the empty pWZL vector, and therefore is not representative of samples stained with the anti-T7 epitope antibody, including cells ex-

talization at sites of cell-cell contact. Nuclear staining is seen in all samples, including cells expressing the empty pWZL vector, and therefore is not representative of PTP\textsubscript{\mu}-T7 localization at areas of cell-cell contact (PTP\textsubscript{\mu}WT and PTP\textsubscript{\mu}\Delta Ig). Scale bars = 10 \mu m.

Figure 3. Deletion of the Ig domain reduces localization of PTP\textsubscript{\mu} to sites of cell-cell contact in GM7372 cells. GM7372 cells expressing the empty pWZL-hygro vector, T7 epitope-tagged PTP\textsubscript{\mu}WT, PTP\textsubscript{\mu}\Delta Ig, or PTP\textsubscript{\mu}\Delta E were grown to confluence, fixed, and co-stained with antibodies to the T7 epitope and VE-cadherin (cad). Green (left panels) and red (right panels) channels for each field are shown side by side. Arrowheads indicate examples of PTP\textsubscript{\mu}-T7 and VE-cadherin localization at sites of cell-cell contact. Nuclear staining is seen in all samples stained with the anti-T7 epitope antibody, including cells expressing the empty pWZL vector, and therefore is not representative of PTP\textsubscript{\mu}-T7 localization. Scale bar = 10 \mu m.

homophilic binding may be responsible for localization of PTP\textsubscript{\mu} to cell-cell contacts (10, 11). To test this idea in a cellular context, GM7372 cells expressing T7 epitope-tagged PTP\textsubscript{\mu} mutants were analyzed by indirect immunofluorescence with the anti-T7 epitope antibody to determine the subcellular localiza-
tion of the phosphatase. Full-length PTP\textsubscript{\mu}-WT T7 localized to cell-cell contacts as indicated by co-localization with VE-cad-

-herin (Fig. 3, WT panels). Deletion of the Ig domain, containing the homophilic binding site, greatly reduced the localization of PTP\textsubscript{\mu} to cell-cell contacts (Fig. 3, \Delta Ig panels), resulting in a dispersed pattern consistent with expression at the cell surface. Therefore, the Ig domain, which contains the homophilic binding site (10), is a major determinant for localization to cell-cell contacts, suggesting that homophilic binding is important for this localization. Deletion of the entire E-subunit, containing most of the extracellular domain, completely elimi-
nated localization of PTP\textsubscript{\mu} to cell-cell contacts (Fig. 3, \Delta E panels), suggesting that this region may contain sequences in addition to the Ig domain that play a part in this localization.

A role has been proposed for the MAM domain in homophilic binding (11); however, we were unable to determine whether the MAM domain may contribute to the localization of PTP\textsubscript{\mu} because constructs with a deletion of this domain could not be stably expressed at levels comparable with the other mutants (data not shown). This is consistent with studies of the metalloprotease meprin A, which have suggested that the MAM domain may be critical for protein stability (34).

To verify that the localization of PTP\textsubscript{\mu}\Delta Ig in GM7372 cells is a property of the phosphatase and not a phenomenon unique to these cells, we examined the localization the PTP\textsubscript{\mu} deletion constructs in two additional cell types, a transformed endothelial cell line trBAEC and MDCK epithelial cells, the latter being a well established model for studying cell-cell adhesion. In trBAEC and MDCK cells, as seen in GM7372 cells, deletion of the Ig domain resulted in reduced localization to cell-cell contacts and a more dispersed distribution over the cell compared with the WT protein (Fig. 4). These results confirm that the Ig domain is a major determinant for the localization of PTP\textsubscript{\mu} to cell-cell contacts in multiple cell types.

The PTP\textsubscript{\mu}\Delta Ig Protein Is Present at the Cell Surface—As described above, deletion of the Ig domain led to a widespread distribution of PTP\textsubscript{\mu} over what appeared to be the cell surface. To confirm that the PTP\textsubscript{\mu}\Delta Ig protein was present at the cell surface, we used the extracellular domain-specific antibody BK2 to stain GM7372 cells that had not been permeabilized prior to antibody staining. PTP\textsubscript{\mu}WT was detected primarily at cell-cell contacts in intact non-permeabilized cells, whereas PTP\textsubscript{\mu}\Delta Ig was dispersed over the surface of the cell (Fig. 5). Staining of permeabilized cells revealed additional localization of both PTP\textsubscript{\mu}WT and PTP\textsubscript{\mu}\Delta Ig in a perinuclear region (Fig. 5) as described for the endogenous protein (Fig. 1). We were unable to determine whether PTP\textsubscript{\mu}\Delta E can reach the cell surface, as it did not react with the available antibodies directed against the extracellular region of PTP\textsubscript{\mu}.

To analyze the localization of the mutant PTP\textsubscript{\mu} proteins in
Deletion of the Ig Domain Affects Localization of PTP\(\mu\) in Subconfluent Cells—In contrast to what has been proposed for PTP\(\mu\)WT (11), the distribution of PTP\(\mu\)Ig in confluent cells (Figs. 3–6) suggested that stable surface expression of this mutant can be maintained independently of localization to cell-cell contacts. Therefore, we examined subconfluent GM7372 cells, which lack cell-cell contacts, to determine whether PTP\(\mu\)Ig was, in contrast to the WT protein (Fig. 1), stably expressed at the cell surface. Staining of non-permeabilized cells revealed that PTP\(\mu\)Ig was expressed over the surface of subconfluent cells with a high concentration seen at certain regions of the cell periphery (Fig. 7). In contrast, little surface staining could be observed in cells expressing PTP\(\mu\)WT (Fig. 7). Permeabilization of cells prior to staining revealed the intracellular localization of both PTP\(\mu\)WT and PTP\(\mu\)Ig (Fig. 6).
Control of Protein-tyrosine Phosphatase μ Localization

To confirm the presence of epitope-tagged PTPμΔlg at the cell periphery, we stained permeabilized cells with the anti-T7 epitope antibody in combination with anti-P-subunit antibody SK7. In 68 of 107 cells (64%) observed, PTPμΔlg showed a striking pattern of expression at regions of the cell periphery (Fig. 8), whereas peripheral localization of PTPμWT was seen in only 6 of 102 cells (6%). Deletion of the entire E-subunit eliminated the peripheral localization seen with the PTPμΔlg mutant, indicating that some features of the extracellular domain are required for targeting PTPμΔlg to the cell periphery (Fig. 8). Therefore, deletion of the Ig domain allowed PTPμ to concentrate at the cell periphery in subconfluent cells by a mechanism requiring some other elements of the E-subunit.

Ectopic Expression of PTPμ Induces Alterations in Focal Adhesion and Actin Cytoskeleton Morphology—The aberrant localization of PTPμΔlg in subconfluent GM7372 cells suggested that this protein may modulate events that occur at the cell periphery such as the formation of nascent cell-matrix junctions. Consistent with this idea, the morphology of focal adhesions and cytoskeleton components was affected by overexpression of PTPμΔlg in sparse cultures of GM7372 cells. Vector control cells (Fig. 9, vector panels) showed the characteristic punctate pattern of vinculin-containing focal adhesions (1). In cultures expressing PTPμΔlg, many cells displayed a broad region of vinculin staining that co-localized with the phosphatase at the cell periphery (Fig. 9, Δlg panels, arrowheads).

The presence of PTPμΔlg at the cell periphery correlated with the redistribution of phosphotyrosine proteins from discrete punctate areas, as seen in vector control cells (Fig. 9, vector panels), to continuous broad regions of staining that coincided with the mutant PTP at the cell periphery (Δlg panels, arrowheads). Again, the changes in phosphotyrosine localization in PTPμWT cells were minor compared with those seen with PTPμΔlg (Fig. 9). These results, in combination with the redistribution of vinculin, suggest that the aberrant localization of PTPμΔlg results in specific changes that affect the formation of focal contacts at the cell periphery, rather than the large-scale dephosphorylation of phosphotyrosine proteins in general. The specific PTP activities of PTPμΔlg and PTPμWT immunoprecipitated from lysates of GM7372 cells were similar (data not shown), suggesting that the effects caused by PTPμΔlg correlate with the unique localization of this mutant and are not caused by a change in activity.

Further analysis by immunoblotting lysates with anti-phosphotyrosine antibodies did not reveal consistent changes in the pattern of protein tyrosine phosphorylation in response to expression of PTPμWT or PTPμΔlg, reinforcing the idea that the ectopic expression of the phosphatase causes limited changes in tyrosine phosphorylation. We tested several potential targets of PTPμ, including β-catenin and p120ctn (35), as well as the major focal adhesion phosphotyrosine proteins focal adhesion kinase, c-Src, paxillin, and p130cas, as suggested by the localization of PTPμΔlg. In the presence of ectopic PTPμWT or PTPμΔlg, we did not detect consistent changes in the state of tyrosine phosphorylation of these proteins by immunoblotting with anti-phosphotyrosine antibodies or phospho-specific antibodies.

To examine further the state of cell-matrix contacts, we visualized the distribution of the focal adhesion protein paxillin (1). In cells expressing empty vector or PTPμWT, paxillin was visualized in a punctate staining pattern at regions at the cell-matrix interface characteristic of focal adhesions (Fig. 10). The sizes of the punctate regions observed in WT cells were not as uniformly large as those of the vector control cells. Cells expressing PTPμΔlg exhibited a diffuse pattern of paxillin localization with some punctate staining at the cell periphery (Fig. 10). Similarly, PTPμΔlg cells displayed numerous tensin-containing contacts, but they were not as large as those seen with cells expressing empty vector or PTPμWT (data not shown). In light of the interdependence of focal adhesions and the actin cytoskeleton, the morphology of F-actin was also

**FIG. 7.** The PTPμΔlg protein is present at the surface of subconfluent GM7372 cells. GM7372 cells expressing either PTPμWT-T7 or PTPμΔlg were grown to confluence and fixed. Cells were either permeabilized as described under “Experimental Procedures” (perm.) or left intact (non-perm.) and then stained with anti E-subunit antibody. Asterisks indicate a PTPμWT-expressing cell displaying little detectable PTPμ surface expression and a PTPμΔlg-expressing cell showing elevated levels of PTPμ surface expression with localized concentration at the periphery (arrowheads). Scale bar = 10 μm.

**FIG. 8.** Localization of PTPμ-T7 proteins in subconfluent GM7372 cells. GM7372 cells expressing PTPμWT-T7, PTPμΔlg, or PTPμΔE were plated on glass coverslips, fixed, and co-stained with the anti-T7 epitope antibody (green) and anti-PTPμ P-subunit antibody SK7 (red). Green (left panels) and red (right panels) channels for each field are shown side by side. Arrowheads indicate unique localization of the PTPμΔlg protein seen in 68 of 107 cells examined. Shown is an example of a typical PTPμWT-expressing cell exhibiting no peripheral localization for PTPμ. Scale bar = 10 μm.
and could explain the difficulties in generating stable clones of GM7372 cells expressing PTPµ. To test this hypothesis, GM7372 cells infected with recombinant retrovirus encoding pWZL/PTPµ mutants were plated at various densities from ~50% confluence (1 × 10⁴ cells/cm²) to ~5% confluence (0.11 × 10⁴ cells/cm²) and incubated for 15 days, and the cell number was estimated by staining with crystal violet. Comparison of cells expressing empty vector with those expressing different PTPµ constructs indicated that at each given plating density, expression of PTPµ∆Ig had the greatest inhibitory effect on cell number compared with the PTPµWT and PTPµΔE proteins (Fig. 11A). The four cell lines exhibited similar rates of proliferation represented by the percentage of cells progressing through the cell cycle as indicated by the incorporation of BrdUrd (Fig. 11B). However, PTPµ∆Ig-expressing cultures exhibited increased levels of apoptosis compared with the other cell lines (Fig. 11B). As cells complete apoptosis, they dissociate from the culture dish and are not counted in the assay we used. As a result, the percentage of apoptotic cells presented in Fig. 11 likely under-represents the rate of apoptosis of the cultures. Therefore, consistent with the changes in focal adhesions and the actin cytoskeleton, expression of PTPµ∆Ig reduced the survival of GM7372 cells.

**FIG. 9.** Aberrant localization of vinculin and phosphotyrosine proteins at the cell periphery of GM7372 cells expressing PTPµ∆Ig. GM7372 cells expressing PTPµ constructs were plated on glass coverslips, fixed, and co-stained with the anti-T7 epitope (green) and anti-vinculin (red) antibodies or stained with the anti-phosphotyrosine antibody (PTyr; red). The constructs expressed are indicated to the left. The small frames show additional examples from the PTPµWT and PTPµ∆Ig samples with focus on the cell periphery. Arrowheads and dashed ovals point out the unique patterns of PTPµ∆Ig, vinculin, and phosphotyrosine proteins. Scale bar = 10 μm.

**FIG. 10.** Expression of PTPµ∆Ig affects formation of focal adhesions and actin stress fibers in subconfluent GM7372. GM7372 cells expressing the empty pWZL-hygro vector (V), PTPµWT, or PTPµ∆Ig were plated on glass coverslips, fixed, and stained with either the anti-paxillin antibody or Alexa 594-labeled phalloidin to detect F-actin (actin). Irregular localization of actin in PTPµ∆Ig-expressing cells is indicated by arrowheads. Scale bar = 10 μm.

**DISCUSSION**

The precise consequence of ligand binding is not understood for most RPTPs, but the structural relationship of enzymes such as PTPµ to cell adhesion molecules suggests that one purpose of the extracellular segment may be to position the phosphatase at sites of cell adhesion. In this regard, it has been suggested that homophilic binding, the engagement of a PTPµ molecule on one cell by another PTPµ molecule on an opposing cell, directs localization of PTPµ to sites of cell-cell contact. At this location, PTPµ is thought to regulate the cell junction complexes that control cell-cell adhesion (11, 15). We examined the role of the conserved Ig domain, which contains the homophilic binding site, in regulating PTPµ in cultured cells. Recent studies have conveyed the importance of Ig domains in the extracellular segments of RPTP-LAR and PTPγ, which are in a different structural class from PTPµ. In *Drosophila*, the three Ig domains of PTP-LAR have been shown to be important for survival (38). The N-terminal Ig domain of PTPγ mediates binding to heparin sulfate proteoglycans and may be critical in targeting the phosphatase to sites of cell-matrix interaction (39). Mutations in the Ig domain of the *Caenorhabditis elegans* RPTP CLR-1 compromise the ability of the phosphatase to control axonal guidance (40). Our results indicate that the Ig
domain of PTP\(_\mu\) not only is involved in localization of the enzyme to cell-cell contacts, but may also control localization in the absence of cell-cell contact.

To explore the function of the Ig domain in PTP\(_\mu\), we generated a construct, termed PTP\(_\mu\)ΔIg, in which this domain had been deleted. The integrity of this mutant protein is supported by several observations. As in the case with the wild-type enzyme, the mutant protein was processed normally into a P-subunit (containing the intracellular PTP domains), which was associated with the E-subunit, here comprising the mutated extracellular segment. In addition, the enzymatic activity and half-life of PTP\(_\mu\)ΔIg were unaffected compared with those of the wild-type enzyme. Furthermore, the data in Fig. 3, showing that regions of the E-subunit other than the Ig domain contribute to the residual localization of PTP\(_\mu\)ΔIg to cell-cell contacts, also suggest that some function is retained in either the MAM domain or fibronectin type III repeats when the Ig domain is deleted. In contrast to what has been proposed for the MAM domain or fibronectin type III repeats when the Ig domain is deleted, the normal cycling of PTP\(_\mu\)Ig domain deletion mutant may be a result of the mislocalized some cell adhesion molecules such as cadherin and LICAM participate in combinations of cis- and trans-homophilic interactions often involving multiple conserved domains, including Ig domains (41, 42). One function for the cis-interactions is to mediate the formation of multimeric receptor complexes that increase the avidity of the trans-interactions, thereby strengthening cell-cell adhesion complexes (41). Furthermore, cis-interactions may also affect the transport of adhesion proteins to and from the cell surface and, as a result, may control localization in the absence of cell adhesion (42). In light of these precedents, it is possible that elements of the PTP\(_\mu\) extracellular domain may participate in both trans- and cis-homophilic interactions, controlling localization of the phosphatase either in the presence or absence of cell-cell contact.

Previous studies have demonstrated that PTP\(_\mu\) associates with classical cadherins such as E-cadherin, N-cadherin, and cadherin-4 (43) and that PTP\(_\mu\) can modulate cell adhesion to culture surfaces coated with N- or E-cadherin (44, 45). However, PTP\(_\mu\)ΔIg did not induce major changes in the localization of VE-cadherin, suggesting that the integrity of cell-cell contacts was maintained (Figs. 3 and 5). Instead, the consequences of PTP\(_\mu\)ΔIg expression were most apparent in subconfluent cells in the absence of cadherin-dependent cell-cell adhesion and suggested that this mutant acts on a component of cell-matrix junctions or the associated actin cytoskeleton. Considering that many potential targets of PTP\(_\mu\) in cell-cell junctions are also found in cell-matrix junctions, the effects caused by the Ig domain deletion mutant may be a result of the mislocalized phosphatase acting on a normal PTP\(_\mu\) substrate in the wrong context, that of the focal adhesion in subconfluent cells. We were unable to detect changes in the global pattern of tyrosine phosphorylation, implying that the expressed forms of PTP\(_\mu\) did not act in a broad, nonspecific manner, but instead exhibited selectivity in action, leading to the effects on focal adhesions and cell survival. Although p120\(^ctn\), a phosphorylase protein that may function in both cell-cell and cell-matrix adhesions, could be such a substrate (35, 46), we did not detect consistent changes in the tyrosine phosphorylation of this or other potential substrates following expression of either the PTP\(_\mu\)WT or PTP\(_\mu\)ΔIg protein.
In defining a role for the Ig domain in regulating PTP\(\mu\), we have illustrated the importance of this region in positioning the phosphatase at its proposed site of action, cell-cell junctions. In addition, this analysis has also brought to light the importance of the Ig domain in restricting PTP\(\mu\) to cell-cell junctions. In subconfluent GM7372 cells, internalization of PTP\(\mu\) is shown to the right of the nucleus. Cadherin-containing cell-cell junctions are indicated by the orange bars that bridge two apposing confluent cells, and cell-matrix junctions are shown in red at the basal surface of the cell. It has been proposed that stable surface expression of PTP\(\mu\) is dependent upon its localization to sites of cell-cell contact as directed by homophilic binding to another PTP\(\mu\) molecule on an apposing cell. Deletion of the Ig domain disrupts the normal localization of PTP\(\mu\), significantly reducing the amount PTP\(\Delta\)Ig at regions of cell-cell contact and allowing for the stable surface expression of PTP\(\mu\)Ig. One possibility is that the Ig domain is required for the internalization of PTP\(\mu\) (arrow from the plasma membrane for PTP\(\mu\)WT) that occurs when homophilic binding is not possible, and therefore, PTP\(\mu\)Ig remains at the surface, allowing for aberrant localization to the cell periphery in the area occupied by cell-matrix junctions.

Acknowledgments—We thank K. Pennino, M. Daddario, and M. Ye for technical assistance; S. Hearn for help with confocal microscopy; G. J. Hannon and D. Conklin for providing LiNX-A cells; and A. Piccini, D. Buckley, and S. Muthuswamy for advice on the manuscript.

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