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Jurkat T cells activated by the phosphotyrosine phosphatase inhibitors H2O2 or vanadate were found to have a similar pattern of tyrosine phosphorylation when compared with T cells stimulated by anti-CD3 Ab cross-linking, suggesting that protein tyrosine phosphatase (PTP) inhibitors affect the early steps of TCR signaling. To study the role of PTPs in the most proximal membrane events of tyrosine phosphorylation, subcellular fractions of T cells were treated with the PTP inhibitors in the presence of ATP. In the membrane fraction, tyrosine phosphorylation of Lck, Fyn, and CD3ζ can be induced by PTP inhibitors, but not by anti-CD3. Detailed characterization of this cell-free system showed that the pattern and the order of induced tyrosine phosphorylation is similar to that induced in intact cells. Upon removal of the PTP inhibitor, the tyrosine-phosphorylated proteins, including Lck, Fyn, Syk, Zap70, and CD3ζ, are rapidly dephosphorylated. Preliminary characteristics indicate that a PTP distinct from CD45, SHP1, and SHP2 is present in T cell membranes and the inhibition of this yet unidentified PTP is most likely responsible for the Lck-dependent tyrosine phosphorylation triggered by PTP inhibitors. The Journal of Immunology, 1998, 161: 1743–1750.

The role of PTPs in the regulation of T cell activation is not as well elucidated as the role of the PTKs. Accumulating data indicate that PTPs have both positive and negative effects on T cell signaling (18–27). CD45, the receptor-like PTP, exerts primarily a positive effect through the dephosphorylation of negative regulatory tyrosyl residues of Src family PTKs (18–20). CD45-deficient T cell clones and cell lines are largely nonresponsive to CD3 stimulation (21, 22). Recently, two SH2-containing PTPs, SHP1 (also known as HCP, SHPTP1, PTP1C) and SHP2 (previously called Syp, SHPTP2) were proposed as negative regulators of T cell activation (23). T cells from SHP1-deficient me/me mice are hypersensitive to TCR stimulation, reflecting a possible negative regulation of TCR activation by SHP1 (24, 25). In Jurkat T cells, upon T cell stimulation, SHP1 was found associated with Zap70. This interaction resulted in a decrease in the kinase activity of Zap70 (26). Transient expression of dominant negative SHP1 appeared to decrease the activation threshold of Jurkat T cell toward CD3 or PMA stimulation. SHP2 was recently demonstrated to specifically associate with CTLA-4, a homologue of the T cell costimulator molecule CD28 (27). In T cells from CTLA-4−/− mice, Lck, Fyn, and Zap70 were found to be constitutively active, and Shc, an adapter molecule for the Ras/mitogen-activated protein kinase pathway, was found associated with tyrosine phosphorylated CD3ζ. These findings suggest that the recruitment of SHP2 to the T cell membrane through CTLA-4 negatively regulates T cell activation.

H2O2 has been described as a PTP inhibitor (28). Like other oxidants, H2O2 may oxidize the thiolate anion of a cysteine residue in the PTP-reactive center, blocking the formation of a phospho- cysteine intermediate, which is a critical step in dephosphorylation (29). In T lymphocytes, exposure to H2O2 induces a rapid tyrosine phosphorylation of a variety of proteins, including Src family and Syk family PTKs (30–32). H2O2 has also been reported to induce the tyrosine phosphorylation of mitogen-activated protein kinases and the activation of AP-1 and nuclear factor κB (NF-κB) (33–34). Thus, there are many similarities between CD3-mediated tyrosine phosphorylation and PTP inhibitor-induced T cell tyrosine phosphorylation. It is not clear, however, whether H2O2 mimics CD3 stimulation by triggering an ordered signaling cascade, or if H2O2 functions by inducing or maintaining random tyrosine phosphorylation as a consequence of the inhibition of PTPs.

To study the tyrosine phosphorylation triggered by inhibition of membrane PTPs, we developed a cell-free system by subcellular fractionation of T cells. We found that upon ATP/H2O2 induction,
target proteins in the T cell membrane fraction became tyrosine phosphorylated, whereas proteins in a cytosolic fraction did not. The inhibition of the membrane-associated PTPs triggered a cascade of tyrosine phosphorylation, which resembled that induced by TCR/CD3 stimulation in intact T cells. The tyrosine phosphorylation of the proteins in the T cell membrane fraction, including CD3-associated PTKs and CD3ζ, was rapidly reversed upon removal of H₂O₂. Lck is required for the H₂O₂ induction of tyrosine phosphorylation. Preliminary characterization indicates that a PTP distinct from CD45, SHP1, and SHP2 is present in T cell membranes, and may play a critical role in the negative regulation of TCR signaling.

Material and Methods

Cells and antibodies

Jurkat T cell line J77, a variant of clone E6-1 (American Type Culture Collection (ATCC), Rockville, MD), was cultured in RPMI 1640 medium supplemented with 10% FCS at 37°C in a 5% CO₂-humidified atmosphere. JCAM (J.CaM1.6) and JCD45+ (J45.01) Jurkat T cells were obtained from the ATCC. Total thymocytes were obtained from 12- to 14-day-old normal male and female mice (C3HeB/FaJLe-ala-me strain; the Jackson Laboratory, Bar Harbor, ME). Anti-phosphotyrosine (anti-p Tyr) (RC20), anti-SHP-1, anti-SHP-2, and anti-Zap70 mAbs were purchased from Transduction Laboratories (Lexington, KY). Anti-CD3α monoclonal, anti-Fyn polyclonal, anti-Syk polyclonal, and anti-Zap70 polyclonal Abs were purchased from Santa Cruz Biotechnology (Santa Cruz, CA). Anti-Lck polyclonal Ab was purchased from Upstate Biotechnology (Lake Placid, NY). Anti-CD3 Ab (OKT3) was prepared from a hybridoma obtained from the ATCC.

Immunoprecipitation and Western blot analysis

Jurkat T cells (2 × 10⁷) were washed and resuspended in 1 ml of PBS. For CD3 stimulation, cells were incubated with OKT3 (2 μg/ml) for 5 min on ice, cross-linked by rabbit anti-mouse IgG (5 μg/ml) on ice for a further 5 min, then incubated at 37°C for 3 min. For H₂O₂ stimulation, cells were incubated with 5 mM H₂O₂ at 37°C for 3 min. After washing with PBS, cells were lysed in 1 ml of Nonidet P-40 (NP-40) lysis buffer (1% NP-40, 150 mM NaCl, 20 mM Tris, pH 7.4, 1 mM ATP and 5 mM Mg²⁺). The extract was centrifuged at 250,000 g for 15 min at 4°C. The supernatant (PNS) was centrifuged at 150,000 g for 15 min at 4°C. The postnuclear supernatant (PNS) was centrifuged at 250,000 g for 15 min at 4°C. The cells were then homogenized in a hypotonic buffer, then fractionated by differential centrifugation. The PNS, a fraction containing the cytosolic proteins, were resuspended in 0.5 ml hypotonic buffer, incubated at 37°C for varying times. After centrifugation, membranes were solubilized in NP-40 lysis buffer.

Subcellular fractionation of Jurkat T cells

After washing in PBS, T cells (2 × 10⁶) were incubated in 2 ml of hypotonic buffer (42 mM KCl, 10 mM HEPES (pH 7.4) and 5 mM MgCl₂) for 15 min at 4°C. The cells were then fractionated by differential centrifugation. The PNS, a fraction containing the cytosolic proteins, were resuspended in 0.5 ml hypotonic buffer, incubated at 37°C for varying times. After centrifugation, membranes were solubilized in NP-40 lysis buffer.

Induction of T cell membranes by PTP inhibitors and dephosphorylation assay

Membranes from 10⁷ T cells were resuspended in 0.5 ml hypotonic buffer containing 1 mM ATP, then stimulated with 10 mM H₂O₂ or 1 mM vanadate at 37°C for 3 min. The reaction mixtures were centrifuged at 12,000 × g for 5 min at 4°C. The membrane pellets were washed once with hypotonic buffer at 4°C. For the dephosphorylation assay, pelleted membranes were resuspended in 0.5 ml hypotonic buffer, incubated at 37°C for varying times. After centrifugation, membranes were solubilized in NP-40 lysis buffer.

In vitro kinase assay

Immunoprecipitates were incubated together with 0.1 μg of enolase and 1 μCi of [γ-³²P]ATP in 50 μl of reaction buffer (20 mM HEPES, pH 7.4, 10 mM MgCl₂) at room temperature for 30 min. The reaction was stopped by adding 25 μl of 2 × SDS sample buffer and boiling for 5 min. Proteins were then resolved by SDS-PAGE, transferred to polyvinylidene difluoride membrane, and autoradiographed.

Results

Tyrosine phosphorylation induced by H₂O₂, a PTP inhibitor, is similar to that induced by TCR stimulation

To determine the dose dependence of H₂O₂-induced tyrosine phosphorylation, Jurkat T cells were incubated with H₂O₂ at concentrations ranging from 0.1 mM to 10 mM for 2 min or for 5 min. Tyrosine-phosphorylated proteins were immunoprecipitated by an anti-p Tyr (4G10). After SDS-PAGE and transfer, proteins were immunoblotted with another anti-p Tyr (RC20). H₂O₂ at 0.2 mM induced detectable tyrosine phosphorylation while 5 to 10 mM induced maximal tyrosine phosphorylation. The time of incubation had little effect on tyrosine phosphorylation (Fig. 1A). H₂O₂-induced tyrosine phosphorylation is a rapid event that can be detected within 1 min (data not shown). The major tyrosine-phosphorylated proteins observed have the apparent molecular weights of 18 kDa, 38 kDa, 56 kDa, 70 kDa, and 100 kDa. To compare the patterns of tyrosine phosphorylation induced by H₂O₂ to that induced by CD3 stimulation, Jurkat T cells were stimulated either by 10 mM H₂O₂ or by anti-CD3 cross-linking followed by immunoprecipitation with anti-p Tyr or Abs specific for Lck, Fyn, Syk, Zap70, and CD3ζ. The tyrosine phosphorylation induced by H₂O₂ and by anti-CD3 appeared quite similar (Fig. 1B). Both modes of stimulation increased the tyrosine phosphorylation of Lck, Fyn, Syk, Zap70, and CD3ζ. Immunoprecipitation of Zap70 PTK with CD3ζ, as well as the coimmunoprecipitation of Zap70 with Lck, was also observed, indicating that both types of stimulation resulted in the association of Zap70 with CD3ζ and the association of Zap70 with Lck.

In isolated T cell membranes, protein tyrosine phosphorylation is also induced by PTP inhibitors

The above results demonstrated that incubation with H₂O₂ induces tyrosine phosphorylation of PTKs and TCR subunits involved in the early steps of TCR signaling, which suggested that H₂O₂ may be targeted at molecules on T cell membranes. To assess this possibility, Jurkat T cells were homogenized in a hypotonic buffer, then fractionated by differential centrifugation. The PNS, a fraction obtained by 250 × g centrifugation to remove the nuclei from homogenates, was further separated into crude membrane and cytosolic fractions by 150,000 × g centrifugation. After H₂O₂ stimulation, these fractions were subsequently solubilized by NP-40 lysis buffer and immunoprecipitated with an anti-p Tyr Ab. The results show that H₂O₂ induces strong protein tyrosine phosphorylation in the PNS, very weak tyrosine phosphorylation in the membrane fraction, and no tyrosine phosphorylation in the cytosolic fraction (Fig. 2A). When the cytosolic fraction was mixed with the membrane fraction, H₂O₂-induced tyrosine phosphorylation was reconstituted. Considering that some essential elements for tyrosine phosphorylation such as ATP and divalent ions, could be missing in the membrane fraction, it was supplemented with 1 mM ATP and 5 mM Mg²⁺. In the presence of 1 mM ATP, H₂O₂ induced strong tyrosine phosphorylation in the crude membrane fraction (Fig. 2B). In the PNS and cytosolic fractions, H₂O₂-induced tyrosine phosphorylation was not affected by adding exogenous ATP. In contrast, CD3 stimulation does not induce tyrosine phosphorylation.
phosphorylation in analogous experiments using subcellular fractions.

Two other PTP inhibitors, vanadate and pervanadate, were also used to treat T cell membrane fractions in the presence of ATP (Fig. 3). Vanadate (0.1 mM) was as potent as 2 mM H$_2$O$_2$ in the induction of tyrosine phosphorylation. Pervanadate was extremely potent, with 0.1 mM inducing maximal tyrosine phosphorylation. The pattern of tyrosine phosphorylation induced by H$_2$O$_2$, vanadate, and pervanadate appears quite similar.

To determine the proteins phosphorylated in fractionated T cell membranes by inhibition of PTPs, we specifically examined the phosphorylation of CD3-associated PTKs and the CD3$\zeta$ subunit (Fig. 4A). In the membrane fraction, tyrosine phosphorylation of Lck, Fyn, and CD3$\zeta$ was induced by H$_2$O$_2$. In the presence of cytosolic components, as shown in the PNS fraction, the tyrosine phosphorylation of Zap70 and the coimmunoprecipitation of Zap70 with CD3$\zeta$ and Lck were observed. This indicated that Zap70 can be recruited into the TCR/CD3 complex in cell-free conditions in response to H$_2$O$_2$ stimulation. When the cytoplasmic fraction was stimulated by H$_2$O$_2$, tyrosine phosphorylation of Zap70 was not observed (Fig. 4B). These data indicate that H$_2$O$_2$ does not induce Zap70 tyrosine phosphorylation directly but, instead, through the activation of PTKs in the T cell membrane which, in turn, phosphorylate Zap70. Thus, the tyrosine phosphorylation induced by PTP inhibition is a membrane-related event.

**PTP inhibitor-induced tyrosine phosphorylation in isolated T cell membrane is rapidly reversed upon removal of inhibitors**

To study the inhibition of PTPs in the T cell membrane, we designed a dephosphorylation assay by using the fractionated T cell membranes. T cell membranes were stimulated by H$_2$O$_2$/ATP for 3 min, then H$_2$O$_2$ was removed from the reaction mixture by adding catalase and washing. Following additional incubation, the
In the presence of H₂O₂, the dephosphorylation required about 30 min, dephosphorylation was also completed within 5 min. In the presence of H₂O₂, dephosphorylation was also completed within 5 min. In the presence of H₂O₂, the dephosphorylation required about 30 min, demonstrating that T cell membranes contain PTP activity and that H₂O₂ inhibition of PTPs is reversible and incomplete. The membrane dephosphorylation assay was also performed following vanadate stimulation, and similar results were obtained (Fig. 5A). These reactions were performed in the presence of 1 mM ATP and reflect an equilibrium between phosphorylation and dephosphorylation. By contrast, when ATP was removed after stimulation, a rapid dephosphorylation was observed (Fig. 5B). In the absence of H₂O₂, dephosphorylation was also completed within 5 min. In the presence of H₂O₂, the dephosphorylation required about 30 min, demonstrating that T cell membranes contain PTP activity and that H₂O₂ inhibition of PTPs is reversible and incomplete. The membrane dephosphorylation assay was also performed following vanadate stimulation, and similar results were obtained (Fig. 5C). To further characterize this observation, the dephosphorylation of Lck, Syk, Zap70, and CD3ζ was studied in a similar way by specific immunoprecipitation. The results showed that all TCR-associated PTKs studied and CD3ζ were rapidly dephosphorylated in isolated T cell membrane upon removal of PTP inhibitors (Fig. 5D).

We next assessed the dephosphorylation of Lck since it appears to play a critical role in tyrosine phosphorylation in T cells (4–8). Upon the removal of H₂O₂/ATP, the dephosphorylation of Lck was as rapid as the general dephosphorylation seen in membranes (Fig. 6A). When blotted with anti-Lck, a similar amount of Lck protein was observed, confirming that there is no apparent loss of Lck protein in these assays (Fig. 6A). To determine whether Lck is inactivated by dephosphorylation, Lck activity was determined in an in vitro kinase assay following its dephosphorylation (Fig. 6C). Lck is almost completely inactivated 15 min after removal of H₂O₂, while most of the Lck activity is maintained in the presence of H₂O₂. These results indicate that the inhibition of membrane-associated PTPs triggers the tyrosine phosphorylation in T cells.

The inhibition of CD45, SHP1, or SHP2 is not responsible for the PTP inhibitor-induced tyrosine phosphorylation in isolated T cell membrane

CD45 is a known transmembrane phosphatase that regulates Lck activity (18–22). In order to study the role of CD45 in PTP inhibitor-induced tyrosine phosphorylation, we used a CD45− Jurkat T cell line. As in Jurkat T cells, H₂O₂- and vanadate-induced tyrosine phosphorylation was observed in CD45− T cells and their membrane preparation, indicating that CD45 is not involved in H₂O₂-induced tyrosine phosphorylation (Fig. 7, A and B). When a similar experiment was performed by using JCAM, a Lck− variant of the Jurkat T cell line, it was very interesting that neither H₂O₂ nor vanadate induced strong tyrosine phosphorylation (Fig. 7, A and B). This indicates that, in the absence of Lck, inhibition of PTPs is not sufficient to trigger tyrosine phosphorylation. This was confirmed by showing that tyrosine phosphorylation in a JCAM cell line transfected with Lck was H₂O₂ inducible (data not shown). These data suggested that the PTPs inhibited in T cell membranes could be involved in the negative regulation of Lck signaling.

SHP1 and SHP2, two SH2-containing PTPs, have been reported to be involved in the dephosphorylation of T cell membrane-associated proteins such as Lck, Zap70, and CD3ζ (23–27). As cytosolic PTPs, SHP1 and SHP2 may associate with phosphorylated membrane proteins, and therefore be present in T cell membrane. To study the role of SHP1 and SHP2 in the regulation of tyrosine phosphorylation, we examined the subcellular distribution of SHP1 and SHP2. The membrane and cytosolic fractions were prepared from T cells, as well as fibroblasts, as a control. Western blot analysis with anti-SHP1 and anti-SHP2 showed that both SHP1 and SHP2 were expressed in T cells and fibroblasts predominantly as cytosolic proteins with only a small amount of SHP1 detectable in the T cell membrane preparation (Fig. 8A). The presence of SHP2 in the T cell membrane fraction was not detected in our experiment. This suggested that SHP1 may be the membrane-associated PTP which, when inhibited, triggers tyrosine phosphorylation. Neither SHP1 nor SHP2 was detected in 3T3 cell membrane preparations. Therefore, the PTP activity observed in our membrane preparations is unlikely to be due to cytosolic contaminants.
To study whether the inhibition of T cell membrane-associated SHP1 is related to the initiation of tyrosine phosphorylation, T cell membranes were prepared from thymocytes of motheaten mice, a genetic model for SHP1 deficiency. The results showed that H2 O2 and vanadate induced similar tyrosine phosphorylation in both me/me mice and normal littermate control mice (Fig. 8, B and C). Without stimulation, the basal tyrosine phosphorylation in me/me mice is at a low level, and is only slightly above that in normal littermate mice. The exception is an 18-kDa protein determined to be CD3ζ, which is constitutively tyrosine phosphorylated in me/me mice. In normal mice, tyrosine phosphorylation of CD3ζ was induced by H2O2 and vanadate stimulation. This indicates that SHP1 does play a role in the regulation of protein tyrosine phosphorylation of CD3ζ. However, it is clear that additional PTPs are present in me/me T cell membranes, whose activity affects the tyrosine phosphorylation observed in isolated T cell membranes.

**Discussion**

Although it is known that tyrosine phosphorylation can be induced by PTP inhibitors in T cells, the signals triggered by PTP inhibitors and the targets of PTP inhibitor have not been fully defined. We report here that the tyrosine phosphorylation of proteins induced by H2O2 or vanadate is very similar to that induced by TCR stimulation (Fig. 1). These results suggest that the PTP inhibitors H2O2 and vanadate specifically affect the early steps of TCR signaling. To further study this question, we established a cell-free system by subcellular fractionation of Jurkat T cells. In cell-free conditions, tyrosine phosphorylation of proteins in the T cell membrane fraction can be induced by PTP inhibitors, H2O2, or vanadate, but not by TCR/CD3 stimulation (Figs. 2 and 3). In cell-free conditions,
we found that membrane-associated Lck, Fyn, Zap70, and CD3ζ were phosphorylated by ATP/H₂O₂ (Fig. 4). Furthermore, the regulation of tyrosine phosphorylation in isolated membrane was studied by a dephosphorylation assay (Fig. 5). Lck and other TCR-associated PTKs and CD3ζ were rapidly dephosphorylated in T cell membranes upon removal of PTP inhibitors (Figs. 5 and 6). The dephosphorylation of Lck also resulted in the inactivation of Lck kinase activity (Fig. 6). Therefore, we established a cell-free system in which tyrosine phosphorylation may be regulated by the addition or removal of PTP inhibitors.

To our knowledge, this is the first report that regulation of tyrosine phosphorylation/dephosphorylation may be studied in cell-free conditions. Characterization of this new system indicates that isolated T cell membranes keep the dynamic balance between tyrosine phosphorylation and dephosphorylation and demonstrates an ordered pattern of tyrosine phosphorylation. We expect this system to prove useful to explore early signal transduction cascades. By reconstitution of membranes and cytosol from different cell types or different tissues, it may be possible to determine the specific cytosolic substrates of membrane-associated kinases and the interactions between cytosolic factors and membrane proteins. In cell-free conditions, these factors may be conveniently added into the assay mixture or specifically removed by Abs. Also, these cell-free systems may be useful to test drugs or reagents that are not permeable to the cell membranes.

The presence of Lck in T cell membranes is required for H₂O₂- and vanadate-induced tyrosine phosphorylation. Lck is activated when T cells are treated with H₂O₂ (Fig. 7). It has been hypothesized that H₂O₂ and other oxidants may activate Src family kinases by changing the intracellular redox state. Redox state is coupled to the oxidation of cysteine residues in proteins by a complex thiol/disulfide exchange mechanism that may result in the conformational change and activation of the Src family kinases (35–37). However, H₂O₂ and all other in vivo-effective oxidants and alkylating agents fail to activate Src family kinases in vitro (36, 37). Only HgCl₂ can activate Src family kinases in vitro, presumably by bridging two adjacent sulfydryl groups to form an R-S-Hg-S-R bond (36, 37). Currently, there is no evidence that such an intramolecular or intermolecular disulfide bridge could be formed through the H₂O₂ induction. Our results showed that tyrosine phosphorylation of Lck is induced by vanadate or H₂O₂ in a cell-free system, but is not induced when isolated Lck is treated with H₂O₂ or vanadate (data not shown). It supports the hypothesis that the activation of Src family kinases by H₂O₂ and vanadate is indirect, and a common mechanism, the inhibition of PTPs, is the most likely explanation for H₂O₂, and other oxidants such as phenylarsine oxide- and diamide-induced tyrosine phosphorylation in T cells (38).

The identity of the PTPs inhibited by H₂O₂ and vanadate that associate with T cell membranes and regulate Lck and other TCR-associated PTKs is currently under investigation. In JCAM T cells, which are deficient in Lck, tyrosine phosphorylation was not induced by H₂O₂ (Fig. 7) (8). Therefore, the membrane-associated
PTPs targeted by PTP inhibitors are most likely to be involved in negative regulation of Lck. This is consistent with previous reports that H2O2 may activate Lck (30–32). CD45, a transmembrane PTP, has been reported to regulate Lck (20, 21). However, there must be PTPs other than CD45 in T cell membranes, as our results show that CD45-deficient T cells respond to H2O2 with a signal similar to J77 T cells (Fig. 7). A role for SHP1 and SHP2 in the negative regulation of T cell activation has been reported (23). T cells deficient in SHP1 are hypersensitive to TCR stimulation (26, 27). SHP1 can dephosphorylate and inactivate bacterially produced Lck (39). Lck, Zap70, and CD3ζ were dephosphorylated by SHP1 when cotransfected in a Spodoptera frugiperda cell line (40). SHP1, a primarily cytosolic PTP, could be present in T cell membranes via an interaction with CD3ζ and CD5 (25). SHP2 may also be present in the T cell membrane in association with tyrosine phosphorylated CTLA-4 (27). We have studied the subcellular distributions of SHP1 and SHP2 and found a small amount of SHP1, but not SHP2, in T cell membrane preparations. To further study the potential role of SHP1 in regulating tyrosine phosphorylation, the membranes from thymocytes of SHPTP1 deficient me/me mice were stimulated by H2O2 (Fig. 8). Strong tyrosine phosphorylation was induced by H2O2 in both me/me mice and normal littermate control mice, although CD3ζ was found to be constitutively tyrosine phosphorylated in me/me mice but not in normal control mice, consistent with previous reports (24, 25). These data indicate that, in addition to SHP1 and CD45, a novel PTP may be present in T cell membranes, the inhibition of which is more likely related to the overall tyrosine phosphorylation observed upon H2O2 stimulation. The further characterization and identification of this membrane-associated PTP is of great interest and will be facilitated by the ability to study the regulation of tyrosine phosphorylation in this cell-free system.

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References


