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Suppression of the Phosphorylation of Receptor Tyrosine Phosphatase-α on the Src-Independent Site Tyrosine 789 by Reactive Oxygen Species

Qin Hao, Stacey A. Rutherford, Brad Low, and Hua Tang

Department of Biochemistry, the University of Texas Health Center at Tyler, Tyler, Texas

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ABSTRACT

Oxidation of receptor protein tyrosine phosphatase-α (RPTPα) is emerging as an important yet poorly characterized regulatory mechanism for RPTPα signaling in cells. RPTPα has been shown to be reversibly oxidized and inhibited by reactive oxygen species. However, it is not known whether oxidative stress could regulate the phosphorylation of Tyr789, a critical tyrosine residue for RPTPα signaling that modulates the function of Grb2 and the activation of Src family kinases. In the present study, we have taken advantage of a phosphospecific antibody against Tyr789-phosphorylated RPTPα and characterized the phosphorylation of RPTPα Tyr789 in various cultured cells, including SYF cells lacking all three ubiquitously expressed members (Src, Yes, and Fyn) of Src family kinases. We have obtained substantial evidence indicating that the phosphorylation of RPTPα Tyr789 is regulated predominantly by an Src kinase inhibitor, protein phosphatase 1 (PP1)-sensitive but Src/Yes/Fyn-independent tyrosine kinase, in cells. We further reported a novel finding that, besides the inhibition of RPTPα's activity, H_2O_2 at low to moderate concentrations (50–250 μM) markedly suppressed the phosphorylation of RPTPα Tyr789 and the association of RPTPα with Grb2 in cultured cells, which may result from inhibition of such a PP1-sensitive but Src/Yes/Fyn-independent tyrosine kinase. Because Tyr789 plays an important role in RPTPα signaling, our findings may provide new insights into the functional regulation of RPTPα by oxidative stress in cells.

Protein tyrosine phosphorylation is a fundamental mechanism for many signal transduction pathways that control cell growth, differentiation, and motility (Hunter, 1995). Although it is generally agreed that tyrosine phosphorylation is regulated by the equal and balanced actions of protein tyrosine kinases and protein tyrosine phosphatases (PTPs), relatively little is known about the regulation and signal transduction of most PTPs (Neel and Tonks, 1997). The receptor-like PTPα (RPTPα) is a widely expressed transmembrane PTP with a short, heavily glycosylated extracellular domain and two tandem cytoplasmic PTP domains (Kaplan et al., 1990). The membrane-proximal domain contains most catalytic activity, whereas the membrane-distal domain is catalytically inactive but has a regulatory role (Blanchetot et al., 2002). Several lines of evidence indicate that RPTPα is a positive regulator of Src family kinases and is required for integrin-mediated cell spreading and migration (Ponniah et al., 1999; Su et al., 1999; Zeng et al., 2003). Overexpression of RPTPα results in Src activation and neoplastic transformation (Zheng et al., 1992). Conversely, deficiency of RPTPα markedly impairs the catalytic activities of Src and Fyn and the integrin signaling (Ponniah et al., 1999; Su et al., 1999). In addition, RPTPα interferes with insulin receptor signaling (Moller et al., 1995) and regulates the Kv1.2 potassium channel upon the activation of m1 muscarinic acetylcholine receptor (Tsai et al., 1999).

RPTPα is phosphorylated on a critical tyrosine (Tyr789) located at the C terminus. It has been estimated that approximately 20% of RPTPα in NIH3T3 cells is phosphorylated on Tyr789 (den Hertog et al., 1994). The sequence on the C-terminal side of Tyr789 (Y^{789}ANF) fits the consensus binding site for the SH2 domain of adaptor protein Grb2 and Src

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ABBREVIATIONS: PTP, protein tyrosine phosphatase; PP1, protein phosphatase 1 [4-amino-5-(4-methylphenyl)-7-(*t*-butyl)pyrazolo[3,4-*d*]pyrimidine)]; RPTPα, receptor protein tyrosine phosphatase-α; ROS, reactive oxygen species; HAECs, human aortic endothelial cells; HUVECs, human umbilical vein endothelial cells; PAO, phenylarsine oxide; BAPTA-AM, 1,2-bis(2-aminophenoxy)ethane-*N*,*N*,*N*′,*N*′-tetraacetic acid-acetoxymethyl ester; PKC, protein kinase C; p130Cas, Tyr410-phosphorylated p130Crk-associated substrate; GF109203X, 2-(1-(3-dimethylaminopropyl)indol-3-yl)-3-(indol-3-yl)maleimide; AG-1295, 6,7-dimethyl-2-phenylquinoxaline; AG-1478, *N*-(3-chlorophenyl)-6,7-dimethoxy-4-quinazolinamine; GTP-14564, 3-phenyl-1*H*-benzofuro(3,2-*c*)pyrazole; AG-957, 4-amino-*N*-(2,5-dihydroxybenzyl)methyl benzoate.

family kinases (Songyang et al., 1993). Although Tyr789 is not involved in the regulation of the intrinsic phosphatase activity of RPTPα (Zheng et al., 2000), a body of evidence indicates that phosphorylation of Tyr789 negatively regulates Grb2-mediated signaling (den Hertog et al., 1994; Su et al., 1996). Moreover, phosphorylation of Tyr789 is required for RPTPα to dephosphorylate a negative regulatory site (Tyr529 in mammalian Src) in Src C terminus through a displacement of the phosphorylated Tyr529 from the Src SH2 domain (Zheng et al., 2000). The regulation of Tyr789 phosphorylation is not clear, although a previous study showed that Tyr789 was an autodephosphorylation site and that coexpression of RPTPα with Src enhanced Tyr789 phosphorylation in 293 cells (den Hertog et al., 1994).

Reactive oxygen species (ROS), such as H_2O_2, superoxide ($O_2^{\cdot-}$), and hydroxyl radical (OH·), are constantly produced in the human body under physiological and pathophysiological conditions and are involved in the pathogenesis of cardiovascular diseases, cancer, and Alzheimer disease (Dreher and Junod, 1996; Knight, 1997; Madamanchi et al., 2005). PTPs are emerging as important redox sensors in cells. PTPs contain a catalytically essential cysteine residue in the signature active site motif, HCXXGXXR(S/T), which has a low pK_a and can be reversibly oxidized by ROS to inactivate PTPs (Rhee et al., 2000). Recent studies have shown that RPTPα can be oxidized and inhibited by H_2O_2 (Blanchetot et al., 2002). However, it is not known whether oxidative stress could regulate the phosphorylation of Tyr789, a critical residue for RPTPα signaling. In the present study, we report a novel finding that H_2O_2 at a low to moderate concentration (50–250 μM) markedly suppresses the phosphorylation of RPTPα Tyr789 in various cultured cells. Furthermore, our data suggest that inhibition of an Src/Yes/Fyn-independent tyrosine kinase may be involved in the suppression of Tyr789 phosphorylation by H_2O_2.

Materials and Methods

Reagents. H_2O_2 was from Sigma (St. Louis, MO) and Fisher Scientific (Houston, TX). Inhibitors for protein kinase C (PKC) and tyrosine kinase were from EMD Calbiochem (San Diego, CA). Reagents for chemiluminescence detection were from Cell Signaling (Beverly, MA).

Antibodies. Antibodies against phospho-RPTPα (Tyr789) and Tyr410-phosphorylated p130Crk-associated substrate (p130Cas) were from Cell Signaling. Phospho-Src (Tyr418) and phospho-Abl (Tyr412) antibodies were from Biosource (Camarillo, CA). RPTPα antibody was from Upstate Signaling Solutions (Charlottesville, VA). Antibodies against Src family kinases (SRC-2) and PKCδ were from Santa Cruz Biotechnology (Santa Cruz, CA).

Cell Culture. Human aortic endothelial cells (HAECs), human umbilical vein endothelial cells (HUVECs), and bovine aortic endothelial cells were from Cambrex Bio Science Walkersville, Inc. (Walkersville, MD); they were cultured in endothelial cell growth medium-2 or microvascular endothelial cell growth medium and were used for experiments within 10 passages. SYF (deficient for Src, Yes, and Fyn) cells and human embryonic kidney 293 cells were from American Type Culture Collection (Manassas, VA) and cultured in Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum. Murine embryonic E6-*RPTPα*$^{+/+}$ and E3-*RPTPα*$^{-/-}$ fibroblasts (Su et al., 1999) were kindly provided by Dr. Jan Sap (University of Copenhagen, Copenhagen, Denmark) and cultured in Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum.

Cell Transfection. SrcY529F (Tyr529 mutation to Phe) (Polte and Hanks, 1997) was kindly provided by Dr. Steven K. Hanks (Vanderbilt University, Nashville, TN), and v-Src (Wilkerson et al., 1985) was kindly provided by Dr. J. Thomas Parsons (University of Virginia Health System, Charlottesville, VA). Transient expression of these constructs was performed using FuGENE 6 (Roche Diagnostics, Indianapolis, IN) according to the manufacturer's protocol.

Immunoblotting. Immunoblotting was performed essentially as we described previously (Tang et al., 2000). Cells were washed twice with ice-cold phosphate-buffered saline and then lysed on ice in Nonidet P-40 lysis buffer (25 mM Tris-HCl, pH 7.5, 1% Nonidet P-40, 150 mM NaCl, 10 mM NaF, 1 mM Na_3VO_4, 1 mM phenylmethylsulfonyl fluoride, and 10 μg/ml each of leupeptin and aprotinin). The extract was clarified by centrifugation. Whole-cell lysates were subjected to SDS-polyacrylamide gel electrophoresis and transferred to polyvinylidene difluoride membrane. The membrane was probed with various primary antibodies as indicated and detected using the enhanced chemiluminescence system with horseradish peroxidase-conjugated secondary antibodies according to the manufacturer's protocol.

PTP Assay. Cells were washed twice with ice-cold phosphate-buffered saline and then lysed on ice in PTP lysis buffer (25 mM sodium acetate, pH 5.5, 1% Nonidet P-40, 150 mM NaCl, 10% glycerol, 1 mM phenylmethylsulfonyl fluoride, and 10 μg/ml each of leupeptin and aprotinin). The phosphatase activity was measured essentially as we described recently (Tang et al., 2005). In brief, the synthetic peptide Raytide (Oncogene, San Diego, CA) was labeled at its tyrosine residue using [γ-^{32}P]ATP and Src tyrosine kinase. RPTPα immunoprecipitates were mixed with ^{32}P-labeled tyrosine-Raytide in 50 μl of phosphatase reaction buffer (25 mM HEPES, pH 7.4, and 5 mM EDTA) and incubated at 37°C for 15 min. The reaction was terminated by the addition of acidic charcoal mixture [0.9 M HCl, 90 mM sodium pyrophosphate, 2 mM NaH_2PO_4, and 4% (w/v) Norit A]. After centrifugation in a microcentrifuge, the amount of radioactivity present in the supernatant was determined by scintillation counting. The phosphatase activity was evaluated by the extent of tyrosine-Raytide dephosphorylation in vitro.

Statistical Analysis. All data were expressed as mean ± S.E.M. Differences between the mean values of two groups were analyzed by Student's *t* tests. Differences between mean values of multiple groups were analyzed by one-way analysis of variance with a Newman-Keuls post hoc analysis. $P < 0.05$ was considered statistically significant.

Results

H_2O_2 Inhibits RPTPα Activity and Suppresses the Phosphorylation of RPTPα on Tyr789. H_2O_2, the most stable form of ROS, can easily diffuse across the membrane and has been widely used to study the role of ROS in cells (Finkel, 2003). To determine effect of H_2O_2 on the catalytic activity of RPTPα, RPTPα was immunoprecipitated, and phosphatase activity of the immune complexes toward ^{32}P-labeled tyrosine-Raytide was measured. In agreement with a previous report (Blanchetot et al., 2002), we found that the activity of RPTPα was inhibited ~40% by H_2O_2 at 5 min, and then it gradually recovered to basal level at 30 min (Fig. 1A). An early study suggests that Tyr789 is an autodephosphorylation site of RPTPα (den Hertog et al., 1994). If so, inhibition of RPTPα activity by H_2O_2 should increase the phosphorylation of Tyr789. We next determined the effect of H_2O_2 on the phosphorylation of Tyr789, a critical tyrosine for RPTPα signaling, using a phosphospecific antibody against Tyr789-phosphorylated RPTPα (Cell Signaling). As shown in Fig. 1B, a 135-kDa protein band representing the phosphorylated RPTPα was detected with the phosphospecific antibody in

E6-*RPTPα*$^{+/+}$ but not in E3-*RPTPα*$^{-/-}$ fibroblasts (Su et al., 1999), indicating that the phospho-RPTPα (Tyr789) antibody specifically recognizes the phosphorylated RPTPα but not other receptor PTPs. We were surprised to find that the phosphorylation of RPTPα Tyr789 was suppressed 95% by a subcytolytic concentration of H_2O_2 (250 μM) within 10 min and gradually returned to 50% of basal level by 120 min in E6 fibroblasts (Fig. 1B). The time-dependent suppression of the phosphorylation of Tyr789 by H_2O_2 was also observed in HAECs and HUVECs but with a lower recovery rate compared with E6 fibroblasts (Fig. 1, C and D). We also found that the phosphorylation of RPTPα Tyr789 was markedly suppressed by H_2O_2 in bovine aortic endothelial cells and 293 cells (data not shown). Moreover, we found that the H_2O_2-induced suppression of Tyr789 phosphorylation was blocked by an antioxidant *N*-acetyl cysteine (Ferrari et al., 1995) (Fig. 1E). Because RPTPα associates with Grb2 through binding of the phosphorylated Tyr789 to Grb2 SH2 domain (den Hertog et al., 1994), we then determined the effect of H_2O_2 on the association of RPTPα with Grb2. As shown in Fig. 1F, treatment of HUVECs with H_2O_2 (250 μM) caused a rapid dissociation of RPTPα from Grb2, further confirming the inhibitory effect of H_2O_2 on Tyr789 phosphorylation. These findings suggest that the phosphorylation of Tyr789 by a kinase may be dominant over any Tyr789 autodephosphorylation and that the tyrosine kinase may be inhibited by H_2O_2 through a redox regulatory mechanism in cells.

We next determined the dose-dependent effect of H_2O_2 using the phospho-RPTPα (Tyr789) antibody. As shown in Fig. 2A, the Tyr789 phosphorylation was suppressed 60% by 10-min treatment of E6 fibroblasts with as low as 100 μM H_2O_2, 93% by 250 μM H_2O_2, and 91% by 500 μM H_2O_2, respectively. A similar dose-dependent inhibitory effect of H_2O_2 on Tyr789 phosphorylation was observed in HAECs (Fig. 2B). Thus, the maximal suppression of Tyr789 phosphorylation can be achieved by 250 μM H_2O_2 in both cells.

PP1-Sensitive but Src/Yes/Fyn-Independent Phosphorylation of RPTPα on Tyr789. We next characterized the phosphorylation of RPTPα Tyr789. As shown in Fig. 3A, the phosphorylation of Tyr789 was inhibited 80% by H_2O_2, 85% by the Src kinase inhibitor PP1 (Hanke et al., 1996), and 70% by the PKCδ inhibitor rottlerin (Gschwendt et al., 1994) in HAECs, respectively. In contrast, a general PKC inhibitor GF109203X or a membrane-permeable calcium chelator BAPTA-AM had virtually no effect. Furthermore, the H_2O_2-induced suppression of Tyr789 phosphorylation was slightly enhanced by both PP1 and rottlerin in HAECs (Fig. 3B).

Although PP1 is an inhibitor of Src kinase (Hanke et al., 1996), it has been shown that PP1 also inhibits Kit and Bcr-Abl tyrosine kinases (Tatton et al., 2003). As shown in Fig. 4A, the phosphorylation of RPTPα Tyr789 was inhibited 88% by PP1, whereas the phosphorylation of the Src activation loop-conserved tyrosine (Tyr418 in mammalian Src) that represents Src activation (Yamaguchi and Hendrickson,

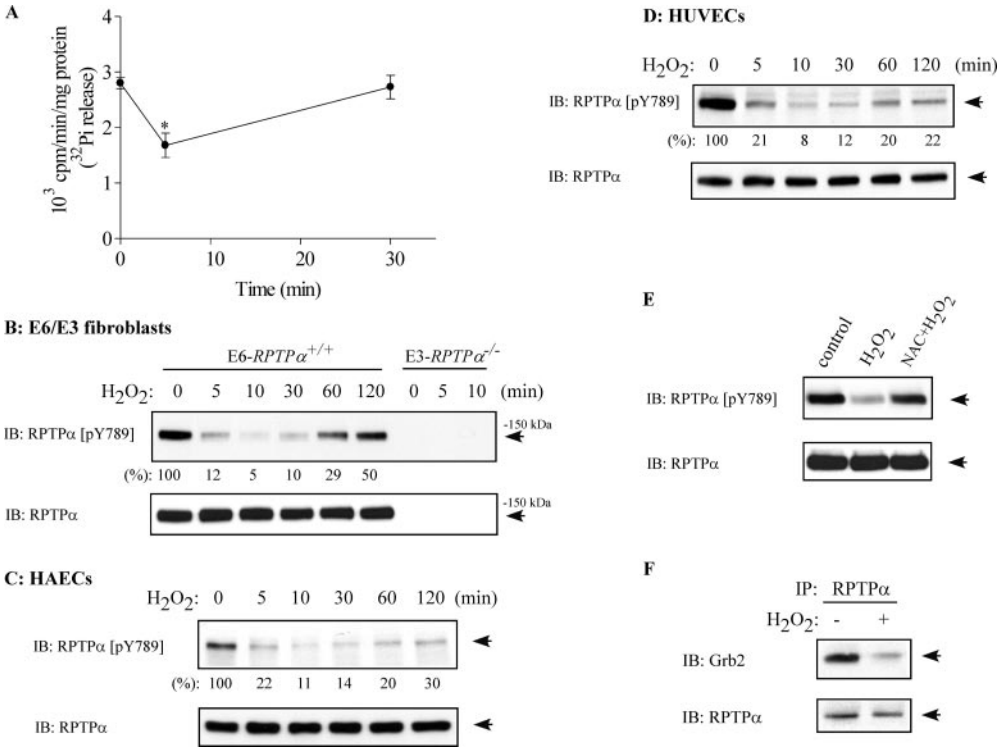

Fig. 1. H_2O_2 inhibits RPTPα activity and suppresses the phosphorylation of RPTPα on Tyr789 in various cultured cells. A, time-dependent effect of H_2O_2 (250 μM) on the catalytic activity of RPTPα in HUVECs. The phosphatase activity was evaluated by the extent of $^{32}P_i$ release from ^{32}P-labeled tyrosine-Raytide. Values are mean ± S.E.M. *, $P < 0.05$ versus control. B to D, E6-*RPTPα*$^{+/+}$ and E3-*RRPTPα*$^{-/-}$ fibroblasts (B), HAECs (C), and HUVECs (D) were treated with H_2O_2 (250 μM) for the indicated time periods. E, E6-*RPTPα*$^{+/+}$ cells were left untreated (control) or pretreated with *N*-acetyl cysteine (NAC, 6 mM) for 1 h and then incubated without or with H_2O_2 (250 μM) for 10 min. Lysates from B to E were subjected to immunoblotting (IB) with RPTPα (pTyr789) antibody that recognizes Tyr789-phosphorylated RPTPα. The phosphorylation of Tyr789 is also shown as a percentage of untreated individual control cells determined by densitometric analysis from three independent experiments. The same blot was stripped and reprobed with an RPTPα antibody to show the equal loading. F, HUVECs were treated without (−) or with (+) H_2O_2 (250 μM) for 10 min. RPTPα was immunoprecipitated (IP) and subjected to immunoblotting with Grb2 or RPTPα antibodies. Representative immunoblots of three (B–E) or two (F) independent experiments are shown.

1996) was inhibited only 40% by PP1 in HAECs, suggesting the involvement of an Src-independent mechanism for Tyr789 phosphorylation. The phosphorylation of RPTPα Tyr789 and Src Tyr418 was inhibited 82 and 90% by H_2O_2 in HAECs, respectively (Fig. 4A), which may result from the H_2O_2-induced inhibition of a novel kinase other than Src, as we hypothesized (Tang et al., 2005). To determine whether Src kinase is involved in the phosphorylation of RPTPα Tyr789, HAECs were transiently transfected with SrcY529F (Polte and Hanks, 1997), a constitutively activated form of Src, and lysates were immunoblotted with the phospho-RPTPα (Tyr789) antibody. As shown in Fig. 4A, transient expression of the SrcY529F mutant had virtually no effect on the phosphorylation of Tyr789 in HAECs, although it apparently enhanced (2.65-fold) Src activation detected with a phospho-Src (Tyr418) antibody that recognizes the activated form of Src (Biosource). We next performed similar experiments using 293 cells that can be transfected with a high efficiency. As shown in Fig. 4B, transient expression of v-Src (Wilkerson et al., 1985) virtually did not affect the phosphorylation of RPTPα Tyr789 in 293 cells, although it apparently enhanced (4-fold) Src activation detected with the phospho-Src (Tyr418) antibody (Biosource). Furthermore, activation of Src to an extremely high level (>30-fold) with expression of the SrcY529F mutant only slightly (1.3-fold) increased the phosphorylation of RPTPα Tyr789 in 293 cells (Fig. 4B). It is remarkable that we found RPTPα Tyr789 to be strongly phosphorylated in SYF cells lacking all three ubiquitously expressed members (Src, Yes, and Fyn) of Src family kinases (Klinghoffer et al., 1999) (Fig. 4C). Reintroducing the activated Src (SrcY529F) into SYF cells only slightly (1.2-fold) increased the phosphorylation of RPTPα Tyr789, whereas it markedly augmented the phosphorylation of p130Cas Tyr410, an Src phosphorylation site (Tang et al., 2005). The phosphorylation of p130Cas Tyr410 was unable to detect in vector-transfected (control) SYF cells (Fig. 4C). In addition, we found that the phosphorylation of RPTPα Tyr789 was suppressed 51% by genistein (Spinozzi et al., 1994), a general inhibitor for protein tyrosine kinases and 70% by PP1, but only 10% by another Src kinase inhibitor, herbimycin A (Ogino et al., 2004), in SYF cells, respectively (Fig. 4D). In contrast, piceatannol (Oliver et al., 1994), an Syk tyrosine kinase inhibitor, AG-1295 (Levitzki and Gazit, 1995), a selective inhibitor of platelet-derived growth factor receptor, AG-1478 (Levitzki and Gazit, 1995), a selective inhibitor of epidermal growth factor receptor, GTP-14564 (Murata et al., 2003), a selective inhibitor of class III receptor tyrosine kinases including Kit, and terreic acid (Kawakami et al., 1999), a selective inhibitor of Bruton's tyrosine kinase, did not significantly affect the phosphorylation of Tyr789 in SYF cells (Fig. 4, D and E). We found that AG-957 (Anafi et al., 1992), a potent inhibitor of Bcr-Abl and c-Abl, caused a mobility shift of RPTPα and apparently suppressed the phosphorylation of Tyr789 in a dose-dependent manner in SYF cells (Fig. 4E). Taken together, these findings demonstrated that, in contrast to Tyr410 of p130Cas, Tyr789 of RPTPα is not a primary target site of Src kinase. Thus, the phosphorylation of RPTPα Tyr789 is predominantly regulated by a PP1-sensitive but Src/Yes/Fyn-independent tyrosine kinase in cells.

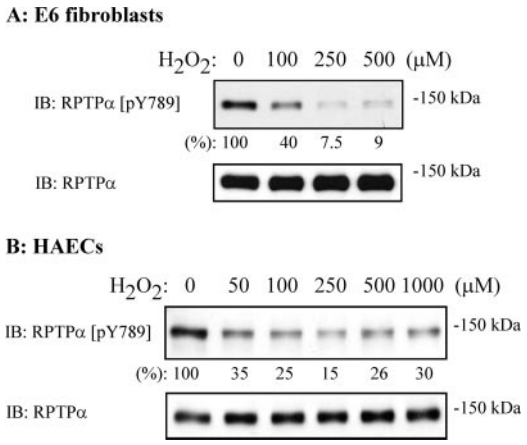

Fig. 2. Dose-dependent suppression of RPTPα Tyr789 phosphorylation by H_2O_2. E6-*RPTPα*$^{+/+}$ fibroblasts (A) or HAECs (B) were treated with various concentrations of H_2O_2 for 10 min, and lysates were subjected to immunoblotting (IB) with RPTPα (pTyr789) antibody. The phosphorylation of Tyr789 is also shown as the percentage of untreated control cells determined by densitometric analysis. The same blot was stripped and reprobed with an RPTPα antibody to show the equal loading. Representative immunoblots of three independent experiments are shown.

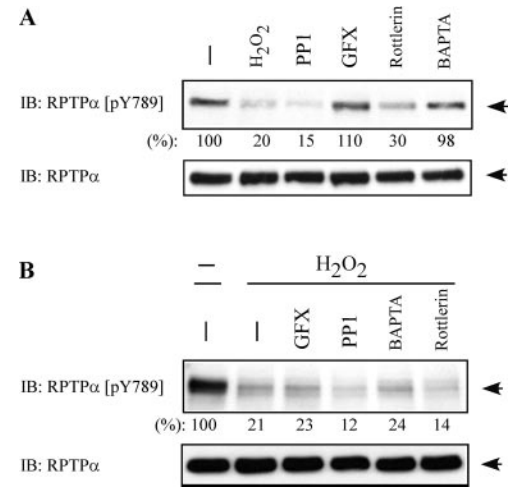

Fig. 3. PP1-sensitive phosphorylation of RPTPα on Tyr789. A, HAECs were treated for 15 min with H_2O_2 (250 μM) or 30 min with PP1 (10 μM), GFX109203X (GFX, 10 μM), rottlerin (10 μM), or BAPTA-AM (50 μM). B, HAECs were left untreated (−) or were pretreated with various inhibitors as shown in Fig. 3A and then incubated without (−) or with H_2O_2 (250 μM) for 15 min. Lysates were subjected to immunoblotting (IB) with RPTPα (pTyr789) antibody. The phosphorylation of Tyr789 is also shown as the average percentage of untreated control cells determined by densitometric analysis from two independent experiments. The same blot was stripped and reprobed with an RPTPα antibody to show the equal loading. Representative immunoblots of two independent experiments are shown.

H_2O_2 Suppresses the Phosphorylation of RPTPα Tyr789 in Src/Yes/Fyn-Deficient SYF Cells. Consistent with the data obtained using fibroblasts and endothelial cells (Fig. 1), we found that the phosphorylation of RPTPα Tyr789 was also markedly suppressed by H_2O_2 in SYF cells lacking all three ubiquitously expressed members (Src, Yes, and Fyn) of Src family kinase (Fig. 5A). The phosphorylation of Tyr789 was inhibited 85% by H_2O_2 at 10 min and then gradually recovered to near basal level at 60 min. Of note, the phosphorylation of c-Abl on the kinase activation loop Tyr412 (Brasher and Van Etten, 2000), which represents c-Abl activation, was not altered by H_2O_2 treatment in SYF cells (Fig. 5A, bottom). The H_2O_2-induced suppression of Tyr789 phosphorylation was mimicked by a PTP inhibitor, phenylarsine oxide (PAO) (Garcia-Morales et al., 1990) but not by the

serine/threonine phosphatase inhibitor NaF in SYF cells (Fig. 5B). Furthermore, pretreatment of SYF cells with PAO enhanced the suppression of Tyr789 phosphorylation by H_2O_2. These findings suggest that a novel tyrosine kinase (but not Src, Yes, Fyn, or c-Abl) phosphorylating RPTPα Tyr789 may be inhibited by H_2O_2 treatment in cells and that the inhibition of a PTP(s) may be involved in the process.

Discussion

In the present study, we characterized the phosphorylation of RPTPα on Tyr789 using different approaches and obtained substantial evidence indicating that the phosphorylation of RPTPα Tyr789 is regulated by a PP1-sensitive but Src/Yes/Fyn-independent tyrosine kinase in cells. We further show that, besides the inhibition of RPTPα activity, H_2O_2 at low to moderate levels (50–250 μM) markedly suppresses the phosphorylation of Tyr789 and the association of RPTPα with Grb2 in cultured cells, which may be through the inhibition of such an Src/Yes/Fyn-independent tyrosine kinase. Because Tyr789 plays an important role in RPTPα signaling, our findings may provide new insights into the functional regulation of RPTPα by H_2O_2, a stable form of ROS.

It has been demonstrated that phosphorylation of RPTPα Tyr789 modulates Grb2-mediated signaling and the activation of Src family kinases, although Tyr789 is not involved in the regulation of the intrinsic phosphatase activity of RPTPα (den Hertog et al., 1994; Su et al., 1996; Zheng et al., 2000). However, the regulation of RPTPα Tyr789 phosphorylation remains unclear. An early study suggests that Tyr789 is an autodephosphorylation site of RPTPα (den Hertog et al., 1994). If so, inhibition of RPTPα activity should increase the phosphorylation of Tyr789. We were surprised to find that besides the inhibition of RPTPα activity, H_2O_2 markedly suppressed the phosphorylation of Tyr789 in cells, leading to the dissociation of RPTPα from Grb2. These data suggest that the phosphorylation of Tyr789 by a tyrosine kinase may be dominant over any Tyr789 autodephosphorylation and that the tyrosine kinase may be inhibited by H_2O_2. A model for the RPTPα-mediated Src activation describes that binding of the phosphorylated Tyr789 to Src SH2 domain induces displacement of the Src negative regulatory site (Tyr529) from its SH2 domain, which facilitates the dephosphorylation of Tyr529 by RPTPα and thereby promotes Src activation (Zheng et al., 2000). If the phosphorylation of Tyr789 is mediated by Src in cells, as suggested by an early study in which coexpression of RPTPα with Src enhanced Tyr789 phosphorylation in 293 cells (den Hertog et al., 1994), the activated Src will phosphorylate RPTPα Tyr789 and the phosphorylated Tyr789 will bind to Src SH2 domain to activate Src, thereby causing hyperactivation of Src and hyperphosphorylation of RPTPα through cycles of the positive-feedback loop. Apparently, this conflicts with the fact that only a small fraction of Src is activated in cells, suggesting the involvement of an Src-independent mechanism for Tyr789 phosphorylation. In the present study, we provided substantial evidence indicating that the phosphorylation of RPTPα Tyr789 is regulated predominantly by an Src/Yes/Fyn-independent tyrosine kinase. Transient expression of SrcY529F (Polte and Hanks, 1997), a constitutively activated form of Src, or v-Src (Wilkerson et al., 1985), which led to a

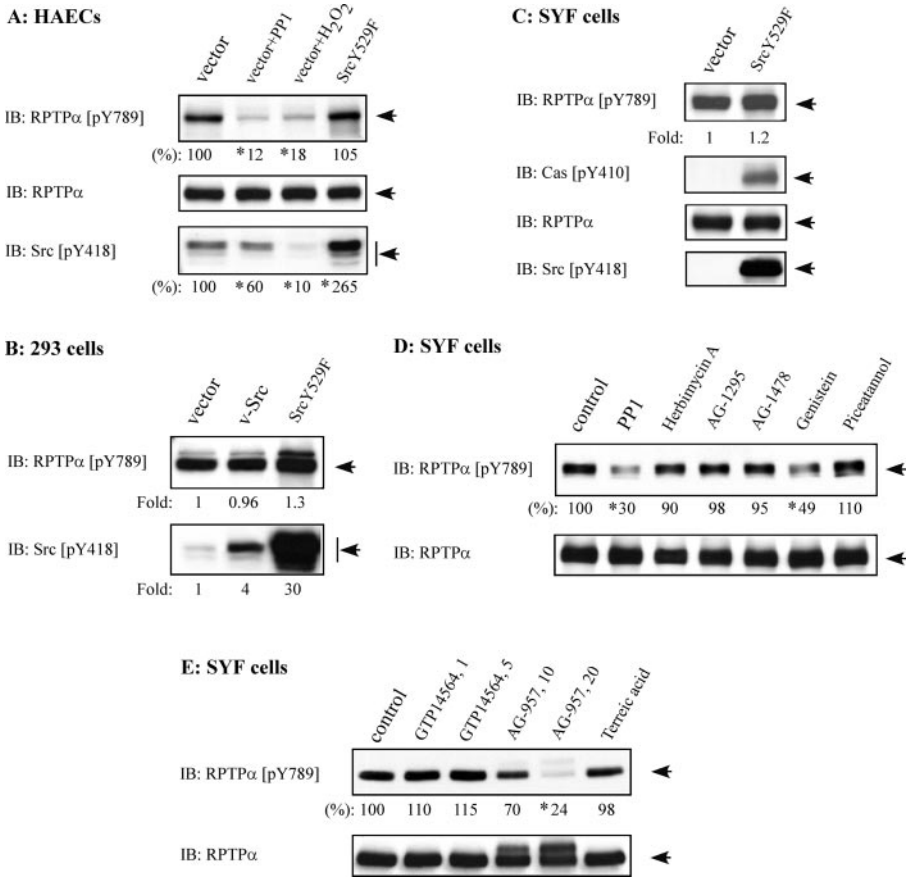

Fig. 4. PP1-sensitive but Src/Yes/Fyn-independent phosphorylation of RPTPα on Tyr789. A, HAECs were transiently transfected with vector alone or SrcY529F mutant and then treated without or with PP1 (10 μM) for 30 min or H_2O_2 (250 μM) for 10 min. B and C, 293 cells or SYF cells were transiently transfected with vector alone, v-Src, or SrcY529F as indicated. D and E, SYF cells were left untreated (control) or treated for 30 min with PP1 (10 μM), herbimycin A (10 μM), AG-1295 (50 μM), AG-1478 (250 nM), genistein (300 μM), peceatannol (50 μM), GTP-14564 (1 or 5 μM), AG-957 (10 or 20 μM), or terreic acid (50 μM) as indicated. Lysates from A to E were subjected to immunoblotting (IB) with antibodies against RPTPα (pTyr789), Src (pTyr418), Cas (pTyr410), or RPTPα. The phosphorylation of RPTPα Tyr789 or Src Tyr418 is also shown as the mean percentage or fold over untreated control cells determined by densitometric analysis from three independent experiments. Representative immunoblots of three independent experiments are shown. $*$, $P < 0.05$ versus control.

moderate Src activation (2.6- to 4-fold), had virtually no effect on the phosphorylation of Tyr789 in HAECs and 293 cells, respectively. The phosphorylation of Tyr789 was only slightly increased (1.3-fold) in 293 cells when Src was activated to an extremely high level (>30-fold) with the expression of SrcY529F mutant. It should be noted that RPTPα Tyr789 was strongly phosphorylated in SYF fibroblasts lacking Src, Yes, and Fyn (Klinghoffer et al., 1999). Furthermore, reintroducing the activated Src (SrcY529F) into SYF cells only slightly (1.2-fold) increased the phosphorylation of RPTPα Tyr789, whereas it remarkably augmented the phosphorylation of an Src substrate, p130Cas, on Tyr410 that was not detected in control SYF cells. These findings demonstrated that, in contrast to Tyr410 of p130Cas, the Tyr789 of RPTPα is not a primary target site of Src family kinases in cells. It is likely that the phosphorylation of RPTPα Tyr789 is regulated predominantly by an Src/Yes/Fyn-independent tyrosine kinase. Nine members of Src family kinases have been identified to date. In contrast to Src, Yes, and Fyn that are expressed ubiquitously, Hck, Fgr, Blk, Yrk, and Lck are restricted to hematopoetic cell lineages, and Lyn is expressed in both hematopoetic and neuronal cells (Brown and Cooper, 1996). The defective integrin signaling phenotype of the SYF cells also argues against the expression of other cell type-specific Src family members in SYF cells (Klinghoffer et al., 1999). Indeed, no band was detected in SYF fibroblasts by using an SRC-2 antibody that recognizes the C terminus of Src family kinases (data not shown). It seems that a non-Src family kinase may be responsible for the phosphorylation of RPTPα Tyr789.

We found that the phosphorylation RPTPα Tyr789 was profoundly inhibited by the Src kinase inhibitor PP1 (Hanke et al., 1996) in HAECs and even in SYF cells lacking Src family kinases but was not affected by another Src kinase inhibitor, herbimycin A (Ogino et al., 2004), in SYF cells. It is noteworthy that the phosphorylation of RPTPα Tyr789 was inhibited 88% by PP1, whereas the phosphorylation of Src activation loop conserved Tyr418 that represents Src activation (Yamaguchi and Hendrickson, 1996) was inhibited only 40% by PP1 in HAECs, suggesting the involvement of an Src-independent mechanism. Indeed, PP1 also inhibits other tyrosine kinases, including Kit and Bcr-Abl tyrosine kinases (Tatton et al., 2003). We found that AG-957 (Anafi et al., 1992), a potent inhibitor of Bcr-Abl and c-Abl, but not GTP-14564 (Murata et al., 2003), a selective inhibitor of class III receptor tyrosine kinases including Kit, markedly inhibited the phosphorylation of Tyr789 in SYF cells through a distinct mechanism from PP1 by causing a mobility shift of RPTPα. Whether c-Abl is directly involved in Tyr789 phosphorylation remains to be investigated. Moreover, the pharmacological studies revealed that platelet-derived growth factor receptor kinase, epidermal growth factor receptor kinase, Syk, and Bruton's tyrosine kinases may not be involved in the phosphorylation of RPTPα Tyr789. These findings suggest that a PP1-sensitive but Src-independent tyrosine kinase (probably not Kit) may be responsible for the phosphorylation of RPTPα Tyr789. This notion was further supported by the finding that the phosphorylation of Tyr789 was inhibited by the general tyrosine kinase inhibitor genistein in SYF cells. In addition, we found that the phosphorylation of RPTPα Tyr789 was also sensitive to rottlerin in cells. Although rottlerin was identified originally as an inhibitor of PKCδ (Gschwendt et al., 1994), it readily suppresses cellular ATP levels (Soltoff, 2001). We found that neither PKCδ wild type nor the kinase-dead mutant (kindly provided by Dr. Trevor Biden) affected the phosphorylation of RPTPα Tyr789, indicating that the phosphorylation of Tyr789 is regulated by rottlerin in a PKCδ-independent mechanism (data not shown).

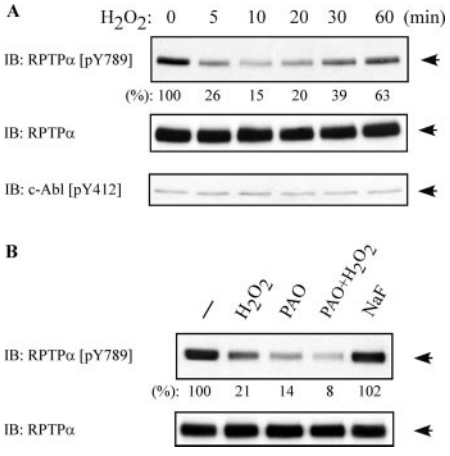

Fig. 5. H_2O_2 suppresses the phosphorylation of RPTPα Tyr789 in SYF cells lacking Src/Yes/Fyn. A, SYF cells lacking Src/Yes/Fyn were treated with H_2O_2 (250 μM) for the indicated time periods. B, SYF cells were left untreated (−) or were treated for 10 min with H_2O_2 (250 μM) or 20 min with PAO (20 μM) or NaF (10 mM). PAO + H_2O_2 indicates that SYF cells were pretreated for 10 min with PAO and then incubated with H_2O_2 (250 μM) for 10 min in the presence of PAO. Lysates were subjected to immunoblotting (IB) with RPTPα (pTyr789) or Abl (pTyr412) antibodies. The phosphorylation of Tyr789 is also shown as the mean percentage of untreated control cells determined by densitometric analysis from three independent experiments. The same blot was stripped and reprobed with an RPTPα antibody to show the equal loading. Representative immunoblots are shown.

RPTPα that can be oxidized and inhibited by H_2O_2 is emerging as an important redox sensor in cells (Blanchetot et al., 2002). However, it is not known whether oxidative stress could regulate the phosphorylation of Tyr789, a critical residue for RPTPα signaling that modulates the function of Grb2 and the activation of Src family kinases. In the present study, we reported a novel finding that, besides the inhibition of RPTPα activity, H_2O_2 at low to moderate concentrations (50–250 μM) markedly suppressed the phosphorylation of RPTPα Tyr789 in endothelial cells, E6 fibroblasts, and Src/Yes/Fyn-deficient SYF cells. It is remarkable that the phosphorylation of Tyr789 was inhibited 65% by 5-min treatment of HAECs with as low as 50 μM H_2O_2 and was almost abolished by 250 μM H_2O_2 in all cells examined. Thus, H_2O_2 suppresses RPTPα signaling not only through inhibition of its catalytic activity but also through a reduction in the phosphorylation of Tyr789. Because the phosphorylation of Tyr789 is predominantly regulated by a PP1-sensitive but Src/Yes/Fyn-independent tyrosine kinase, it seems that such a tyrosine kinase phosphorylating RPTPα Tyr789 may be inhibited by H_2O_2, leading to a reduction in Tyr789 phosphorylation. Moreover, our data suggest that inhibition of a PTP(s) may be involved in the process because the H_2O_2-induced suppression of Tyr789 phosphorylation was mimicked by the PTP inhibitor PAO (Garcia-Morales et al., 1990). The hypothesis merits further investigation.

In summary, we obtained substantial evidence indicating that H_2O_2 suppresses the phosphorylation of RPTPα on an Src-independent phosphorylation site, Tyr789, which may

offer new insights into the redox regulation of RPTPα signaling.

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Address correspondence to: Dr. Hua Tang, Department of Biochemistry, The University of Texas Health Center at Tyler, 11937 US Highway 271, Tyler, TX 75708. E-mail: hua.tang@uthct.edu