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Pim-1 kinase protects P-glycoprotein from degradation and enables its glycosylation and cell surface expression

Yingqiu Xie, Mehmet Burcu, Douglas E. Linn, Yun Qiu, Maria R. Baer

University of Maryland Greenebaum Cancer Center (YX, MB, YQ, MRB) and Departments of Medicine (MRB) and Pharmacology and Experimental Therapeutics (DEL, YQ), University of Maryland School of Medicine, Baltimore, Maryland

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Running title: Pim-1 enables Pgp glycosylation and cell surface expression

Correspondence to: Maria R. Baer, MD, University of Maryland Greenebaum Cancer Center, 22 South Greene Street, Baltimore, MD 21201. FAX: 410-328-6896; E-mail: mbaer@umm.edu

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Non-standard abbreviations:

ABC	ATP-binding cassette
BCRP	breast cancer resistance protein
ER	endoplasmic reticulum
AML	acute myeloid leukemia
ALL	acute lymphoblastic leukemia
Pgp	P-glycoprotein
PKC	protein kinase C
PKA	protein kinase A
FCS	fetal calf serum
shRNA	small hairpin RNA
siRNA	small interfering RNA
GFP	green fluorescent protein
GST	glutathione S-transferase
2-DG	2-deoxy-D-glucose
MG-132	carbobenzoxy-L-leucyl-L-leucyl-L-leucinal
KS	Kolmogorov-Smirnov
CHX	cycloheximide
CsA	cycosporin A

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ABSTRACT

The oncogenic serine/threonine kinase Pim-1 phosphorylates and activates the ATP-binding cassette transporter breast cancer resistance protein (BCRP; ABCG2). The ABC transporter P-glycoprotein (Pgp; ABCB1) also contains a Pim-1 phosphorylation consensus sequence, and we hypothesized that Pim-1 also regulates Pgp. Pgp is exported from the endoplasmic reticulum (ER) as a 150 kDa species that is glycosylated to 170 kDa Pgp, translocates to the cell surface and mediates drug efflux; alternatively, 150 kDa Pgp is cleaved to a 130 kDa proteolytic product by ER proteases or undergoes ubiquitination and proteasomal degradation. Pim-1 and Pgp interaction was studied in GST pull-down and phosphorylation in *in vitro* kinase assays. Pim-1 knockdown and inhibition effects on Pgp expression were studied by immunoblotting and flow cytometry and on Pgp stability by immunoblotting following cycloheximide treatment. Pim-1 directly interacted with and phosphorylated Pgp in intact cells and *in vitro*. Pim-1 knockdown or inhibition decreased cellular and cell surface 170 kDa Pgp, in association with both transient increase in 130 kDa Pgp and increased ubiquitination and proteasomal degradation. Pim-1 inhibition also decreased expression of 150 kDa Pgp in the presence of the glycosylation inhibitor 2-deoxy-D-glucose. Finally, Pim-1 inhibition sensitized Pgp-overexpressing cells to doxorubicin. Thus Pim-1 regulates Pgp expression by protecting 150 kDa Pgp from proteolytic and proteasomal degradation, and enabling Pgp glycosylation and cell surface translocation and thus Pgp-mediated drug efflux. Pim-1 inhibitors are entering clinical trials and may provide a novel approach to abrogating drug resistance.

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INTRODUCTION

The serine/threonine protein kinase Pim-1, encoded by a proto-oncogene originally identified as the proviral integration site in Moloney murine leukemia virus lymphomagenesis, is overexpressed in diverse malignances, including acute myeloid leukemia (AML), acute lymphoblastic leukemia (ALL), prostate cancer and gastric cancer (Amson et al., 1989; Dhanasekaran et al., 2001; Chen et al., 2005). Pim-1 has two protein isoforms, 33 kDa Pim-1S and 44 kDa Pim-1L, that are synthesized with alternative translation initiation sites (Saris et al., 1991) and differ in cellular localization, as 33 kDa Pim-1S is primarily intracellular, while 44 kDa Pim-1L is primarily localized to the plasma membrane (Xie et al., 2006). Pim-1 substrates include the pro-apoptotic protein BAD (Aho et al., 2004), the cell cycle regulatory proteins p21 (Zhang et al., 2007), p27 (Morishita et al., 2008), Cdc25A (Mochizuki et al., 1999) and Cdc25C (Bachmann et al., 2006) and the transcription factors SOCS-1 (Chen et al., 2002), RUNX3 (Kim et al., 2008) and c-myc (Zhang et al., 2008). Pim-1 also regulates drug resistance, as we recently demonstrated that it phosphorylates the G-subfamily ATP-binding cassette (ABC) transporter breast cancer resistance protein (BCRP; ABCG2) at threonine residue 362 (Thr-362), thereby promoting its multimerization and cell surface translocation (Xie et al., 2008).

Like BCRP, P-glycoprotein (Pgp), a B-subfamily ABC transporter (ABCB1) that is strongly associated with clinical drug resistance (Mahadevan et al., 2005), also

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has a Pim-1 phosphorylation consensus sequence (Palaty et al., 1997; Bullock et al., 2005), QDRKLS, located at S683, between nucleotide-binding domain 1 and transmembrane domain 1. We therefore hypothesized that Pim-1 might also be implicated in regulating drug resistance mediated by Pgp.

Regulation of Pgp expression is post-translational as well as transcriptional. Pgp is exported from the endoplasmic reticulum (ER) as a 150 kDa core-glycosylated intermediate species that is then glycosylated in the Golgi apparatus to yield the mature 170 kDa form that translocates to the cell surface and mediates cellular drug efflux (Gribar et al., 2000). Alternatively, 150 kDa Pgp may be cleaved by ER proteases to form a 130 kDa proteolytic product (Loo and Clarke, 1998a) or ubiquinated and thereby tagged for proteasomal degradation following export from the ER (Zhang et al., 2004). Pgp is phosphorylated by protein kinase C (PKC) at serines 661, 667 and 671 and by protein kinase A (PKA) at serines 667, 671 and 683 (Chambers et al., 1994), the latter of which is also the Pim-1 phosphorylation consensus site. Based on studies of phosphorylation-defective Pgp mutants, phosphorylation does not directly regulate Pgp transport function (Germann et al., 1996; Goodfellow et al., 1996), but the effect of phosphorylation on Pgp degradation and cell surface trafficking has not been characterized, and signaling pathways regulating these processes remain to be elucidated.

We demonstrate here that Pim-1 kinase phosphorylates Pgp and thereby protects core-glycosylated Pgp from proteolytic and proteasomal degradation

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and enables Pgp glycosylation and cell surface trafficking of glycosylated Pgp. Pim-1 is thus a novel signaling pathway regulating cellular and cell surface Pgp expression, and inhibiting Pim-1 kinase is a novel approach to abrogating Pgp-mediated drug resistance by promoting degradation of core-glycosylated Pgp and thereby inhibiting its glycosylation and cell surface expression.

MATERIALS AND METHODS

Cells

HL60/VCR leukemia cells (Ogretmen and Safa, 2000), 8226/Dox6 myeloma cells (Hazlehurst et al., 1999) and MCF7/AdrR ovarian carcinoma cells, re-designated NCI/ADR-RES, OVCAR-8-Pgp (Liscovitch and Ravid, 2007), all with Pgp overexpression and Pgp-mediated multidrug resistance, were obtained from Dr. Ahmad R. Safa, Indiana University, Indianapolis, IN, Dr. William S. Dalton, Moffitt Cancer Center, Tampa, FL, and Dr. Erasmus Schneider, Wadsworth Center, New York State Department of Health, Albany, NY, respectively. HL60/VCR cells were maintained in drug-free RPMI 1640 medium with 10% fetal calf serum (FCS), 8226/Dox6 cells in RPMI 1640 medium with 10% FCS and 60 nM doxorubicin, and MCF7/AdrR cells in RPMI 1640 medium with 10% FCS and 10 μM doxorubicin.

Pim-1 gene knockdown

Cells were infected with lentivirus containing Pim-1 small hairpin RNA (shRNA)

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or non-target control according to the manufacturer's protocol (Sigma-Aldrich, St. Louis, MO). Briefly, 2.5×10^5 cells were mixed with lentivirus in a 12-well plate, then cultured for 72 hours after infection. As a control, cells were also infected with equal amounts of plasmid expressing green fluorescent protein (GFP) (Sigma-Aldrich). As another approach to Pim-1 knockdown, cells were infected with lentivirus containing Pim-1 small interfering RNA (siRNA) and scrambled siRNA control under identical conditions, as described previously (Xie et al., 2006; Xie et al., 2008). Three days after infection with Pim-1 shRNA or siRNA or controls, Pim-1 expression was measured by immunoblotting, with glyceraldehyde 3-phosphate dehydrogenase (GAPDH) as a loading control, to confirm the expected effect or lack of effect on Pim-1 gene expression.

Immunoblotting

Cells were lysed in buffer with protease (Roche Applied Science, Indianapolis, IN) and phosphatase (Pierce, Rockford, IL) inhibitor cocktails, as described previously (Xie et al., 2006; Xie et al., 2008), and immunoblotting was performed as described previously (Kim et al., 2004). Briefly, blots were incubated with primary antibodies, including 1:100 dilution of anti-phosphoserine (Calbiochem, San Diego, CA), 1:100 dilution of anti-Pim-1 (Santa Cruz Biotechnology, Inc., Santa Cruz, CA), 1:2000 dilution of anti-GAPDH (Calbiochem), 1:200 dilution of polyclonal anti-Pgp (H241, Santa Cruz), 1:200 dilution of monoclonal anti-Pgp (3C3.2, Chemicon International, Inc., Temecula**,** CA) and 1:200 dilution of monoclonal anti-ubiquitin (Santa Cruz) for 1 hour at room temperature or

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overnight at 4°C, followed by detection with horseradish peroxidase-conjugated secondary antibody.

Pgp cell surface expression

Pgp cell surface expression was measured with MRK16 antibody (Kamiya Biomedical Company, Seattle, WA) and IgG2a isotype control (Kamiya)**,** detected with phycoerythrin-labeled goat anti-mouse antibody (Caltag) and measured by flow cytometry (Minderman et al., 2004; Qadir et al., 2005).

Immunoprecipitation

Cells were lysed in lysis buffer, as above. Antibodies or control immunoglobulins were added to the lysates, followed by incubation at 4°C for 16 hours. Antibodies used for immunoprecipitation included 1 µg monoclonal anti-Pim-1, polyclonal anti-Pgp and monoclonal anti-Pgp. Immunocomplexes were collected using protein A- or protein G-sepharose beads, and the beads were then washed extensively with lysis buffer three times at 4°C.

Glutathione S-transferase pull-down assay

The glutathione S-transferase **(**GST) pull-down assay was performed as described previously (Xie et al., 2006; Xie et al., 2008), with minor modifications. Briefly, GST-tagged Pim-1 fusion protein or control GST (Cell Signaling, Danvers, MA) was pulled down by glutathione beads for 1 hour at 4°C, then washed three times with lysis buffer (20 mM Tris–HCl, pH 7.4, 150 mM NaCl, 1

mM EDTA, 1 mM EGTA, 1% Triton X-100) with protease inhibitor cocktail. The immobilized GST fusion protein or control GST was incubated with HL60/VCR cell lysates for 1 hour at 4°C. The beads were washed with the lysis buffer four times and the protein complexes were then loaded in a NuPage 4-12% Bis-Tris gel (Invitrogen, Carlsbad, CA), followed by immunoblotting with anti-Pgp antibody. Pgp and GST-Pim-1 fusion proteins in the reactions were also measured with anti-Pgp, anti-GST (Sigma-Aldrich) and anti-Pim-1 antibodies, respectively.

in vitro kinase assay

An *in vitro* kinase (IVK) assay of Pgp phosphorylation by Pim-1 was carried out as described previously (Xie et al., 2006; Xie et al., 2008). Briefly, immunoprecipitation was performed using anti-Pim-1. The protein A-immunoprecipitate complex was washed twice with 1x kinase buffer (Kim et al., 2006) and resuspended in 40 μl of 1x kinase buffer supplemented with 500 μM ATP and Pgp substrate protein (Upstate Biotechnology, Inc., Lake Placid, NY). To prepare the substrate, crude membrane protein (100 µg) extracted from High Five insect cells overexpressing human Pgp (Kerr et al., 2001) was resuspended in lysis buffer (Xie et al., 2006; Xie et al., 2008) with protease inhibitor cocktail (Roche). Insoluble material was removed by centrifugation, and 1 µg monoclonal anti-Pgp antibody or control immunoglobulin was added to lysates, followed by incubation at 4°C for 16 hours. Immunocomplexes were collected using protein G-sepharose beads, and the beads were then washed extensively with lysis

buffer three times at 4°C and resuspended in 40 μl 1x kinase buffer (Kim et al., 2006) with 0.5 μg soluble Pim-1 protein kinase (Cell Signaling, Danvers, MA). After 30-minute incubation at 30°C, the reaction was terminated by adding an equal volume of 2X SDS sample buffer followed by immunoblotting with phosphoserine, Pgp and glutathione S-transferase (GST) (GE Healthcare Life Sciences, Piscataway, NJ) antibodies.

Inhibition of Pim-1 kinase

Pim-1 kinase was inhibited by incubation with the Pim-1-selective kinase inhibitor SGI-1776 (Chen et al. 2009, Mumenthaler et al., 2009), generously provided by SuperGen, Inc., Dublin, CA. SGI-1776 was used at 1 μM in 0.1% DMSO because it inhibits Pim-1 at a concentration of 7 + 1.8 nM and is selective for Pim-1, Pim-2, Pim-3, FLT3 and haspin in this concentration range, but is more than 95% bound to human plasma protein (Chen et al. 2009). Pim-1 inhibition was confirmed by measurement of phospho-BAD at S112 (Aho et al., 2004).

Inhibition of new protein synthesis

New protein synthesis was inhibited by culturing cells with 100 μg/ml cycloheximide (CHX; Sigma-Aldrich), and cellular protein was then measured at serial time points by immunoblotting.

Inhibition of glycosylation

Glycosylation inhibition was carried out by treating cells with 50 mM 2-deoxy-D-

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glucose (2-DG, Sigma-Aldrich), a nonmetabolizable glucose analog that inhibits glycosylation.

Proteasome inhibition

To evaluate the effect of proteasomal degradation on Pgp turnover, cells were incubated in the presence and absence of the proteasome inhibitor carbobenzoxy-L-leucyl-L-leucyl-L-leucinal (MG-132; Calbiochem) at 1μM.

Colony assay

To study sensitization of drug-resistant cells by Pim-1 inhibition, Pgp-overexpressing multidrug resistant MCF7/AdrR, or OVCAR-8-Pgp, cells were seeded in a 6-well plate at 1 x 10^5 cells per well with or without 10 μM doxorubicin, combined with 1 μM SGI-1776 or DMSO control. After 48 hours, the cells were gently washed three times and then cultured again in fresh medium with or without drug(s). After 120 hours, colonies were visualized by Coomassie Blue staining, and densitometric scanning was performed.

Statistical analyses

All experiments were repeated at least three times. Cell staining with MRK16 and isotype control was compared by the Kolmogorov-Smirnov (KS) statistic, which generates D-values ranging from 0 (no difference) to 1 (no overlap) (Qadir et al., 2005). Other comparisons were performed with the Wilcoxon rank test and the Student t-test, two-tailed.

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RESULTS

Pim-1 knockdown decreases Pgp expression

We first tested the effect of Pim-1 on Pgp expression in Pim-1 knockdown experiments. HL60/VCR cells were infected with lentivirus containing Pim-1 shRNA or non-target shRNA control (Figure 1A), or Pim-1 siRNA or Pim-1 scrambled siRNA control (Figure 1B). Three days after infection, expression of Pim-1, measured by immunoblotting, decreased in cells treated with Pim-1 shRNA or siRNA, in relation to controls, as expected, and expression of 170 kDa Pgp also decreased. A decrease in serine-phosphorylated Pgp, measured by immunoprecipitation and immunoblotting, was also seen, and was commensurate with the decrease in Pgp. Cell surface expression of Pgp, studied by flow cytometry with the MRK16 antibody, also decreased six days after infection with shRNA, in relation to control, though to a lesser degree than cellular Pgp expression. Thus Pim-1 promotes cellular and cell surface expression of 170 kDa Pgp. The lesser effect on cell surface, in relation to cellular, Pgp expression likely reflects the greater stability of cell surface, in relation to intracellular, Pgp (Pétriz et al., 2004).

Pim-1 stabilizes Pgp

Based on Pim-1 enhancement of the stability of other substrate proteins, we

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hypothesized that Pim-1 might increase Pgp stability as a mechanism for increasing its expression. To test this hypothesis, HL60/VCR cells infected with lentivirus containing shPim-1 or non-target control for 72 hours were treated with 100 μg/ml CHX to block new protein synthesis, and expression of Pgp was measured at serial time points by immunoblotting. Compared to treatment with shRNA control, Pim-1 knockdown resulted in a significantly decreased half-life of total cellular Pgp (Figure 1D), 5 versus 9 hours ($p=0.04$; Wilcoxon rank test).

Pim-1 interacts with and phosphorylates Pgp

To determine the mechanism by which Pim-1 promotes Pgp expression, we tested whether Pim-1 physically interacts with Pgp, using a co-immunoprecipitation assay. Lysates of drug-resistant HL60/VCR, 8226/Dox6 and OVCAR-8-Pgp cells overexpressing Pgp were immunoprecipitated with anti-Pim-1 antibody, then immunoblotted with anti-Pgp antibody, or immunoprecipitated with anti-Pgp antibody, then immunoblotted with anti-Pim-1 antibody. The Pim-1 antibody used recognizes both the 33 kDa isoform of Pim-1, or Pim-1S, which is primarily intracellular (Xie et al., 2006) and the 44 kDa isoform, or Pim-1L, which is primarily localized to the plasma membrane. Interaction between Pim-1 and Pgp was demonstrated in HL60/VCR, 8226/DOX6 and OVCAR-8-Pgp cells (Figure 2A). Of note, Pim-1 interacted predominantly with 150 kDa Pgp in 8226/Dox6 cells and OVCAR-8-Pgp cells, but interacted primarily with 170 kDa Pgp in HL60/VCR cells, possibly reflecting the fact that Pgp expression requires ongoing drug exposure in 8226/DOX6 and OVCAR-8-Pgp, while 170 kDa Pgp is

expressed in the absence of ongoing drug exposure in HL60/VCR cells.

To test whether Pim-1 direct interacts with Pgp, a GST pull-down assay was then performed. Purified GST-tagged recombinant Pim-1 protein or GST control pulled down by glutathione beads was incubated with lysates of HL60/VCR cells, which overexpress Pgp. Immunoblotting demonstrated specific and direct interaction of Pim-1 and Pgp (Figure 2B).

Finally, to test whether Pim-1 directly phosphorylates Pgp, Pgp immunoprecipitated from High Five insect cell membranes (100 µg) expressing Pgp was incubated with GST-tagged recombinant Pim-1 (GST-Pim-1) protein in an *in vitro* kinase assay, and Pgp phosphorylation was measured by immunoblotting with anti-phosphoserine (pSer). Pim-1 phosphorylation of Pgp was demonstrated (Figure 2C).

Pim-1 protects Pgp from proteolysis

We sought to determine whether Pim-1 binding stabilizes Pgp at least in part by inhibiting its proteolytic degradation. To address this question, we measured the effect of Pim-1 knockdown on the 130 kDa Pgp proteolytic species by immunoblotting with anti-Pgp following Pim-1 knockdown, with prolonged exposure to detect the proteolytic species. In addition to causing decreased expression of 170 kDa mature Pgp, Pim-1, knockdown also caused an increase in the 130 kDa proteolytic Pgp species (Figure 3A), suggesting that Pim-1

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enhances expression of 170 kDa mature Pgp in association with protecting it from degradation by ER proteases to form 130 kDa Pgp.

We then investigated the dynamic effects of Pim-1 inhibition by the Pim-1-selective inhibitor SGI-1776 on expression of 170 kDa Pgp and its 130 kDa proteolytic product in Pgp-overexpressing cells. It is expected that the effects of Pim-1 knockdown and Pim-1 inhibition will be different, since Pim-1 knockdown affects cell signaling by a genomic pathway and represents a stable cellular signaling change, while Pim-1 inhibition reflects a transient signaling change by a non-genomic effect. OVCAR-8-Pgp cells were treated with 1 μM SGI-1776, and expression of Pgp was measured by immunoblotting after 15 and 30 minutes and 1, 3, 8, 16 and 24 hours. SGI-1776 treatment resulted in a transient increase in 130 kDa Pgp, followed by a decrease in expression of 170 kDa Pgp (Figure 3B), consistent with Pim-1 protection of Pgp from proteolysis as a mechanism of Pim-1-mediated stabilization of Pgp.

Pim-1 protects Pgp from ubiquitination and proteasomal degradation

We sought to determine whether Pim-1 also protects Pgp from proteasomal degradation. To this end, Pgp stability was studied by measuring its expression by immunoblotting at serial time points in HL60/VCR cells cultured with CHX to inhibit new protein synthesis with and without SGI-1776 in the presence and absence of the proteasome inhibitor MG-132. Similarly to the effect of Pim-1 knockdown in HL60/VCR cells, Pim-1 inhibition by SGI-1776 decreased the half-

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life of cellular 170 kDa Pgp, to 1 versus 9 hours (p=0.03; Wilcoxon rank test) (Figure 4A). Of note, Figure 4 shows Pgp expression in the presence of cycloheximide, and thus the marked decrease or absence of Pgp expression in Figure 4 reflects the effect of Pim-1 inhibition in the absence of new protein synthesis. In contrast, Figure 3 shows decreased but persistent Pgp expression when Pim-1 is inhibited without inhibiting new protein synthesis. Measurement of Pgp stability in the presence of the proteasome inhibitor MG-132 demonstrated that inhibition of proteasomal degradation overcame the effect of SGI-1776 on Pgp stability (Figure 4A). Thus inhibition of Pim-1 by SGI-1776 promotes proteasomal degradation of Pgp, indicating that Pim-1 protects Pgp from proteasomal degradation.

To further test whether Pim-1 protects Pgp from ubquitination, we additionally measured the effects of Pim-1 knockdown on Pgp ubiquitination. Ubiquitinated Pgp was measured by immunoprecipitation with anti-Pgp followed by immunoblotting with anti-ubiquitin. The level of ubiquitinated 150 kDa Pgp was found to be increased in HL60/VCR cells following Pim-1 knockdown (Figure 4B), consistent with ubiquitination and degradation of core-glycosylated Pgp as a mechanism for decreased expression of 170 kDa Pgp protein in cells following Pim-1 knockdown, and thus with Pim-1 protection of core-glycosylated 150 kDa Pgp from ubiquitination and proteasomal degradation.

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Pim-1 stabilization of Pgp enables its glycosylation

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Of note, total cellular Pgp did not decrease in cells incubated with both SGI-1776 and MG-132 (Figure 4A, lower panels), despite inhibition of synthesis of new protein by cycloheximide. This observation suggested that inhibition of proteasomal degradation might allow maturation of previously synthesized immature Pgp. Thus we hypothesized that Pim-1 stabilization of immature Pgp might enable its glycosylation. To test this hypothesis, HL60/VCR cells were treated with the glycosylation inhibitor 2-DG with and without 1 μM SGI-1776 for 24 hours, and expression of Pgp was examined by immunoblotting (Figure 5). BAD phosphorylation at S112 was also measured to demonstrate Pim-1 kinase inhibition, and BAD and GAPDH expression levels were measured as controls. SGI-1776, which inhibited Pim-1 kinase, as evidenced by decreased BAD phosphorylation at S112, was found to decrease expression of the 150 kDa Pgp that accumulates when glycosylation is inhibited by 2-DG, consistent with the hypothesis that Pim-1 stabilizes 150 kDa Pgp and thereby enables its glycosylation and subsequent cell surface translocation.

Pim-1 inhibition sensitizes Pgp-overexpressing cells to doxorubicin

To test whether Pgp phosphorylation by Pim-1 plays a role in Pgp-mediated drug resistance, Pgp-overexpressing multidrug resistant OVCAR-8-Pgp cells were seeded in a 6-well plate at 1 x 10^5 cells per well with and without 10 µM doxorubicin combined with 1 µM SGI-1776 or DMSO control. Colonies visualized by Coomassie Blue staining were quantified by densitometric scanning. Results of triplicate experiments are shown in Figure 6A. While SGI-1776 at 1 µM was

not cytotoxic in relation to DMSO control, culture in the presence of SGI-1776 markedly sensitized OVCAR-8-Pgp cells to doxorubicin (p=0.00008).

To determine the range of concentrations at which SGI-1776 sensitizes Pgp-overexpressing cells to a Pgp substrate chemotherapy drug, we incubated OVCAR-8-Pgp cells as above with and without 10 μM doxorubicin combined with SGI-1776 at 0.01, 0.025, 0.05, 0.075, 0.1, 0.25, 0.5, 0.75, 1, 2.5, 5 and 10 μM, or DMSO control (Figure 6B). SGI-1776 was not cytotoxic to OVCAR-8-Pgp cells in concentrations up to 1 μM, but showed some cytotoxicity at 2.5 μM, and marked cytotoxicity at 5 and 10 μM. Sensitization to doxorubicin increased progressively from 0.1 to 0.25 to 0.5 μM, and was maximal at 0.5, 0.75 and 0.1 μM, in the absence of SGI-1776 cytotoxicty.

DISCUSSION

The serine/threonine protein kinase Pim-1 has been found to be frequently overexpressed in the malignancies in which it has been studied, including acute myeloid and lymphoblastic leukemia and prostate and gastric cancer (Amson et al., 1989; Dhanasekaran et al., 2001; Chen et al., 2005). The multidrug resistance-associated ABC protein Pgp is also frequently overexpressed in diverse malignancies (Mahadevan et al., 2005). Pgp functions as an efflux pump for a number of natural product chemotherapy drugs, including anthracyclines,

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epipodophylloxins, taxanes and vinca alkaloids, and Pgp overexpression and drug efflux mediated by Pgp are strongly associated with clinical drug resistance (Mahadevan et al., 2005). We have demonstrated here that Pim-1 phosphorylates Pgp, protects it from proteolytic degradation and from ubiquitination and proteasomal degradation, and enables its glycosylation, and thus its cell surface expression. The use of Pim-1 knockdown, in addition to Pim-1 kinase inhibition, in our studies served to demonstrate the specific role of Pim-1. Pim-1 is thus a regulator of Pgp-mediated drug resistance, and inhibiting Pim-1 provides a novel approach to abrogating Pgp overexpression and thus drug resistance mediated by Pgp.

Turnover of 170 kDa Pgp reflects both stability of 170 kDa protein and genesis of new 170 kDa protein by glycosylation of 150 kDa protein. We have demonstrated that Pim-1 both protects 170 kDa Pgp from proteolytic and proteasomal degradation and promotes glycosylation of 150 kDa Pgp, likely also by stabilizing it. It is unclear whether Pim-1 protects 170 kDa Pgp from proteolytic and proteasomal degradation by maintaining it in its glycosylated form.

Pim-1 has been shown to regulate stability of a number of important cellular proteins, including p21 (Zhang et al., 2007), SOCS-1 (Chen et al., 2002), RUNX3 (Kim et al., 2008) and c-myc (Zhang et al., 2008). Our data further support the role of Pim-1 in regulating protein expression by increasing protein stability. We have demonstrated a role for Pim-1 in stabilizing and preventing proteolytic and

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proteasomal degradation of a substrate core-glycosylated protein, thus enabling its glycosylation. Thus Pim-1-mediated increased protein half-life may be due to stabilization and, thereby, enhanced maturation of immature protein as well as to stabilization of mature protein.

We previously demonstrated that Pim-1 promotes cell surface expression of BCRP, another multidrug resistance-associated ABC protein (Xie et al., 2008). Pim-1 thus promotes cell surface expression of two ABC proteins that confer multidrug resistance, Pgp and BCRP, in cells in which these proteins are expressed. However, Pim-1 appears to have different effects on Pgp and BCRP. BCRP is a half-transporter that requires multimerization for function, and Pim-1 phosphorylates BCRP at Thr-362, promoting BCRP multimerization and consequent plasma membrane trafficking and function (Xie et al., 2008). In contrast, Pgp is a full transporter that does not require multimerization, and the effect of Pim-1 on Pgp is to inhibit its proteolytic and proteasomal degradation and enable its glycosylation. Pim-1 does not appear to directly regulate the drug efflux function of either protein.

Pgp phosphorylation by PKC was previously demonstrated not to affect Pgp ubiquitination and proteasomal degradation based on study of NIH3T3 cells transfected with PKC phosphorylation site Pgp mutants, as substituting Pgp PKC phosphorylation sites by nonphosphorylatable residues did not affect Pgp ubiquitination (Gribar et al., 2000). Our demonstration that Pim-1 phosphorylation

of Pgp affects Pgp ubiquitination may therefore *a priori* be unexpected, since studies of Pgp phosphorylation mutants did not implicate phosphorylation in regulation of ubiquitination. However transfecting Pgp phosphorylation site mutants into cells that do not otherwise overexpress Pgp may yield different results from our approach of studying cells that overexpress Pgp. It is also possible that selection of the transfectants with drug substrate (vincristine) resulted in stabilization of the mutant Pgps, as demonstrated in *in vitro* studies of Clarke's group (Loo and Clarke, 1997; Loo and Clarke, 1998b).

Inhibition of Pgp maturation has been previously proposed as a novel approach to inhibiting Pgp-mediated multidrug resistance (Loo and Clarke, 1999). Most clinical strategies for inhibiting Pgp-mediated multidrug resistance to date have focused on administering competitive inhibitors of Pgp function, or Pgp modulators, in conjunction with chemotherapy (Mahadevan et al., 2005). Although Pgp functions as an efflux pump for many clinically used chemotherapy drugs and Pgp overexpression and function in patients' tumor cells are associated with inferior treatment outcome, clinical results of incorporation of Pgp modulators into treatment have generally been disappointing (Mahadevan et al., 2005). PSC-833, a structural analog of cyclosporin A (CsA) that is a potent inhibitor of Pgp-mediated drug resistance *in vitro* and can be administered at doses yielding concentrations that inhibit drug efflux *in vivo*, has not improved treatment outcome (Baer et al., 2002; van der Holt et al., 2005). Toxicity due to interactions with chemotherapy drugs has compromised outcome in some trials

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(Baer et al., 2002), but benefit has also not been seen in other trials in which outcome was not compromised by toxicity (van der Holt et al., 2005). Pgp overexpression and function remain strong adverse prognostic factors in AML (van der Holt et al., 2005) and other malignancies (Mahadevan et al., 2005), and it is possible that inhibiting Pgp maturation as a novel approach to inhibiting Pgp-mediated multidrug resistance might show clinical benefit as a strategy for inhibiting resistance to chemotherapy. Based on our data presented here, inhibiting Pim-1 may represent a viable strategy for inhibiting Pgp maturation. Inhibiting Pim-1 also has the potential advantage of inhibiting drug resistance mediated by both Pgp and BCRP. Of note, our data on SGI-1776 resensitization of Pgp-overexpressing cells to a Pgp substrate drug are consistent with recently published data demonstrating SGI-1776 resensitization of 22Rv1 prostate cancer cells to paclitaxel (Mumenthaler et al., 2009). Both that study and our study focused on cancer cells, and it is not yet known whether Pim-1 inhibition also affects Pgp levels in non-malignant cells, such as CD56+ lymphocytes.

Efforts are ongoing to identify inhibitors of Pim-1 kinase (Holder et al., 2007; Cheney et al., 2007; Pogacic et al., 2007), and SGI-1776 (Chen et al. 2009) has entered clinical trials. Our data suggest that clinically applicable Pim-1 inhibitors may have promise as a novel approach to reversing clinical multidrug resistance.

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REFERENCES

Aho TL, Sandholm J, Peltola KJ, Mankonen HP, Lilly M, and Koskinen PJ (2004) Pim-1 kinase promotes inactivation of the pro-apoptotic Bad protein by phosphorylating it on the Ser112 gatekeeper site. *FEBS Lett* **571:** 43-49.

Amson R, Sigaux F, Przedborski S, Flandrin G, Givol D, and Telerman A (1989) The human protooncogene product p33pim is expressed during fetal hematopoiesis and in diverse leukemias. *Proc Natl Acad Sci U S A* **86:** 8857-8861.

Bachmann M, Kosan C, Xing PX, Montenarh M, Hoffmann I, and Möröy T (2006) The oncogenic serine/threonine kinase Pim-1 directly phosphorylates and activates the G2/M specific phosphatase Cdc25C. *Int J Biochem Cell Biol* **38:** 430-443.

Baer MR, George SL, Dodge RK, O'Loughlin KO, Minderman H, Caligiuri MA, Anastasi J, Powell BL, Kolitz JE, Schiffer CA, Bloomfield CD, and Larson RA (2002) Phase 3 study of the multidrug resistance modulator PSC-833 in previously untreated patients 60 years of age and older with acute myeloid leukemia: Cancer and Leukemia Group B Study 9720. *Blood* **100:** 1224-1232.

Bullock AN, Amos AL, Knapp S, and Turk BE (2005) Structure and substrate

specificity of the Pim-1 kinase. *J Biol Chem* **280:** 41675-41682.

Chambers TC, Pohl J, Glass DB, and Kuo JF (1994) Phosphorylation by protein kinase C and cyclic AMP-dependent protein kinase of synthetic peptides derived from the linker region of human P-glycoprotein. *Biochem J* **299:** 309-315.

Chen CN, Lin JJ, Chen JJ, Lee PH, Yang CY, Kuo ML, Chang KJ, and Hsieh FJ (2005) Gene expression profile predicts patient survival of gastric cancer after surgical resection. *J Clin Oncol* **23:** 7286-7295.

Chen LS, Redkar S, Bearss D, Wierda WG, and Gandhi V (2009) Pim kinase inhibitor, SGI-1776, induces apoptosis in CLL lymphocytes. *Blood* **114:** 4150-4157.

Chen XP, Losman JA, Cowan S, Donahue E, Fay S, Vuong BQ, Nawijn MC, Capece D, Cohan VL, and Rothman P (2002) Pim serine/threonine kinases regulate the stability of Socs-1 protein. *Proc Natl Acad Sci U S A* **99:** 2175-2180.

Cheney IW, Yan S, Appleby T, Walker H, Vo T, Yao N, Hamatake R, Hong Z, and Wu JZ (2007) Identification and structure-activity relationships of substituted pyridones as inhibitors of Pim-1 kinase. *Bioorg Med Chem Lett* **17:** 1679-1683.

Dhanasekaran SM, Barrette TR, Ghosh D, Shah R, Varambally S, Kurachi K,

Pienta KJ, Rubin MA, and Chinnaiyan AM (2001) Delineation of prognostic biomarkers in prostate cancer. *Nature* **412:** 822–826.

Germann UA, Chambers TC, Ambudkar SV, Pastan I, and Gottesman MM (1995) Effects of phosphorylation of P-glycoprotein on multidrug resistance. *J Bioenerg Biomembr* **27:** 53-61.

Germann UA, Chambers TC, Ambudkar SV, Licht T, Cardarelli CO, Pastan I, and Gottesman MM (1996) Characterization of phosphorylation-defective mutants of human P-glycoprotein expressed in mammalian cells. *J Biol Chem* **271:** 1708-1716.

Goodfellow HR, Sardini A, Ruetz S, Callaghan R, Gros P, McNaughton PA, and Higgins CF (1996) Protein kinase C-mediated phosphorylation does not regulate drug transport by the human multidrug resistance P-glycoprotein. *J Biol Chem* **271:** 13668-13674.

Gribar JJ, Ramachandra M, Hrycyna CA, Dey S, and Ambudkar SV (2000) Functional characterization of glycosylation-deficient human P-glycoprotein using a vaccinia virus expression system. *J Membr Biol* **173:** 203-214.

Hazlehurst LA, Foley NE, Gleason-Guzman MC, Hacker MP, Cress AE, Greenberger LW, De Jong MC, and Dalton WS (1999) Multiple mechanisms

confer drug resistance to mitoxantrone in the human 8226 myeloma cell line. *Cancer Res* **59:** 1021-1028.

Holder S, Zemskova M, Zhang C, Tabrizizad M, Bremer R, Neidigh JW, and Lilly MB (2007) Characterization of a potent and selective small-molecule inhibitor of the PIM1 kinase. *Mol Cancer Ther* **6:** 163-172.

Kerr KM, Sauna ZE, and Ambudkar SV (2001) Correlation between steady-state ATP hydrolysis and vanadate-induced ADP trapping in Human P-glycoprotein. Evidence for ADP release as the rate-limiting step in the catalytic cycle and its modulation by substrates. *J Biol Chem* **276:** 8657-8664.

Kim HR, Oh BC, Choi JK, and Bae SC (2008) Pim-1 kinase phosphorylates and stabilizes RUNX3 and alters its subcellular localization. *J Cell Biochem* **105:** 1048-1058.

Kim KT, Levis M, and Small D (2006) Constitutively activated FLT3 phosphorylates BAD partially through pim-1. *Br J Haematol* **134:** 500-509.

Kim O, Jiang T, Xie Y, Guo Z, Chen H, and Qiu Y (2004) Synergism of cytoplasmic kinases in IL6-induced ligand-independent activation of androgen receptor in prostate cancer cells. *Oncogene* **23:** 1838-1844.

Liscovitch M and Ravid D (2007) A case study in misidentification of cancer cell lines: MCF-7/AdrR cells (re-designated NCI/ADR-RES) are derived from OVCAR-8 human ovarian carcinoma cells. *Cancer Lett* **245:** 350-352.

Loo TW and Clarke DM (1997) Correction of defective protein kinesis of human P-glycoprotein mutants by substrates and modulators. *J Biol Chem* **272:** 709-712.

Loo TW and Clarke DM (1998a) Quality control by proteases in the endoplasmic reticulum. Removal of a protease-sensitive site enhances expression of human P-glycoprotein. *J Biol Chem* **273:** 32373-32376.

Loo TW and Clarke DM (1998b) Superfolding of the partially unfolded core-glycosylated intermediate of human P-glycoprotein into the mature enzyme is promoted by substrate-induced transmembrane domain interactions. *J Biol Chem* **273:**14671-14674.

Loo TW and Clarke DM (1999) The human multidrug resistance P-glycoprotein is inactive when its maturation is inhibited: potential for a role in cancer chemotherapy. *FASEB J* **13:** 1724-1732.

Mahadevan D and Shirahatti N (2005) Strategies for targeting the multidrug resistance-1 (MDR1)/P-gp transporter in human malignancies. *Curr Cancer Drug*

Targets **5:** 445-455.

Minderman H, O'Loughlin KL, Pendyala L, and Baer MR (2004) VX-710 (biricodar) increases drug retention and enhances chemosensitivity in resistant cells overexpressing P-glycoprotein, multidrug resistance protein, and breast cancer resistance protein. *Clin Cancer Res* **10:** 1826-1834.

Mochizuki T, Kitanaka C, Noguchi K, Muramatsu T, Asai A, and Kuchino Y (1999) Physical and functional interactions between Pim-1 kinase and Cdc25A phosphatase. Implications for the Pim-1-mediated activation of the c-Myc signaling pathway. *J Biol Chem* **274:** 18659-18666.

Morishita D, Katayama R, Sekimizu K, Tsuruo T, and Fujita N (2008) Pim kinases promote cell cycle progression by phosphorylating and down-regulating p27Kip1 at the transcriptional and posttranscriptional levels. *Cancer Res* **68:** 5076-5085.

Mumenthaler SM, Ng PYB, Hodge A, Bearss D, Berk G, Kanekal S, Redkar S, Taverna P, Agus DB, and Jain A (2009) Pharmacologic inhibition of Pim kinases alters prostate cancer cell growth and resensitizes chemoresistant cells to taxanes. *Mol Cancer Ther* **8:** 2882-2893.

Ogretmen B and Safa AR (2000) Identification and characterization of the MDR1

promoter-enhancing factor 1 (MEF1) in the multidrug resistant HL60/VCR human acute myeloid leukemia cell line. *Biochemistry* **39:** 194-204.

Palaty CK, Clark-Lewis I, Leung D, and Pelech SL (1997) Phosphorylation site substrate specificity determinants for the Pim-1 protooncogene-encoded protein kinase. *Biochem Cell Biol* **75:** 153-162.

Pétriz J, Gottesman MM, and Aranc JM (2004) An MDR-EGFP gene fusion allows for direct cellular localization, function and stability assessment of P-glycoprotein. *Curr Drug Deliv* **1:** 43-56.

Pogacic V, Bullock AN, Fedorov O, Filippakopoulos P, Gasser C, Biondi A, Meyer-Monard S, Knapp S, and Schwaller J (2007) Structural analysis identifies imidazo[1,2-b]pyridazines as PIM kinase inhibitors with in vitro antileukemic activity. *Cancer Res* **67:** 6916-6924.

Qadir M, O'Loughlin KL, Fricke SM, Williamson NA, Greco WR, Minderman H, and Baer MR (2005) Cyclosporin A is a broad-spectrum multidrug resistance modulator. *Clin Cancer Res* **11:** 2320-2326.

Saris CJ, Domen J, and Berns A (1991) The pim-1 oncogene encodes two related protein-serine/threonine kinases by alternative initiation at AUG and CUG. *EMBO J* **10:** 655-664.

van der Holt B, Löwenberg B, Burnett AK, Knauf WU, Shepherd J, Piccaluga PP, Ossenkoppele GJ, Verhoef GE, Ferrant A, Crump M, Selleslag D, Theobald M, Fey MF, Vellenga E, Dugan M, and Sonneveld P (2005) The value of the MDR1 reversal agent PSC-833 in addition to daunorubicin and cytarabine in the treatment of elderly patients with previously untreated acute myeloid leukemia (AML), in relation to MDR1 status at diagnosis. *Blood* **106:** 2646-2654.

Xie Y, Xu K, Dai B, Guo Z, Jiang T, Chen H, and Qiu Y (2006) The 44 kDa Pim-1 kinase directly interacts with tyrosine kinase Etk/BMX and protects human prostate cancer cells from apoptosis induced by chemotherapeutic drugs. *Oncogene* **25:** 70-78.

Xie Y, Xu K, Linn DE, Yang X, Guo Z, Shimelis H, Nakanishi T, Ross DD, Chen H, Fazli L, Gleave ME, and Qiu Y (2008) The 44-kDa Pim-1 kinase phosphorylates BCRP/ABCG2 and thereby promotes its multimerization and drug resistant activity in human prostate cancer cells. *J Biol Chem* **283:** 3349-3356.

Zhang Y, Wang Z, and Magnuson NS (2007) Pim-1 kinase-dependent phosphorylation of p21Cip1/WAF1 regulates its stability and cellular localization in H1299 cells. *Mol Cancer Res* **5:** 909-922.

Zhang Y, Wang Z, Li X, and Magnuson NS (2008) Pim kinase-dependent inhibition of c-Myc degradation. *Oncogene* **27:** 4809-4819.

Zhang Z, Wu JY, Hait WN, and Yang JM (2004) Regulation of the stability of P-glycoprotein by ubiquitination. *Mol Pharmacol* **66:** 395-403.

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FOOTNOTES

Yingqiu Xie and Mehmet Burcu are co-first authors.

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FIGURE LEGENDS

Figure 1 Pim-1 knockdown decreases both cellular and cell surface Pgp expression and decreases Pgp stability. HL60/VCR cells were infected with lentivirus containing Pim-1 shRNA or non-target shRNA control (**A**), or Pim-1 siRNA or Pim-1 scrambled siRNA control (**B**). Three days after infection, expression of Pim-1, measured by immunoblotting (IB), decreased in cells treated with Pim-1 shRNA or siRNA, in relation to controls, as expected, and expression of 170 kDa mature Pgp also decreased, with GAPDH expression shown as a control. A decrease in serine-phosphorylated Pgp, measured by immunoprecipitation and immunoblotting, was also seen, and was commensurate with the decrease in Pgp. **C.** Cell surface expression of Pgp, studied by flow cytometry with the MRK16 antibody, was decreased six days after infection in cells treated with shRNA, in relation to non-target shRNA control. Labeling with IgG2a isotype control is also shown. **D.** HL60/VCR cells were infected with lentivirus containing Pim-1 shRNA or non-target shRNA control for 72 hours, and expression of Pgp and of GAPDH, as a loading control, was measured by immunoblotting after cycloheximide (C) treatment for the times indicated, demonstrating decreased stability of 170 kDa Pgp in cells following Pim-1 knockdown, in relation to control. The results of densitometric scanning are also shown graphically, with Pgp signal normalized to GAPDH signal. Pgp half-lives were 5 versus 9 hours (p=0.04; Wilcoxon rank test).

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Figure 2 Pim-1 interacts with and phosphorylates Pgp. A. To test for Pim-1 interaction with Pgp, lysates of drug-resistant HL60/VCR, 8226/Dox6 and OVCAR-8-Pgp cells overexpressing Pgp were immunoprecipitated with anti-Pim-1 antibody, then immunoblotted with anti-Pgp antibody (Row 1) or immunoprecipitated with anti-Pgp antibody, then immunoblotted with anti-Pim-1 antibody (Row 3). Levels of Pgp and Pim-1 expression were measured both in total cell lysates (Rows 1 and 3) and by immunoblotting of immunoprecipitates (Rows 2 and 4) as controls. Pim-1 interaction with Pgp was demonstrated in all three cell lines. Of note, Pim-1 interacted predominantly with 150 kDa Pgp in 8226/Dox6 cells and OVCAR-8-Pgp cells, but interacted primarily with 170 kDa Pgp in HL60/VCR cells, possibly reflecting the fact that Pgp expression requires ongoing drug exposure in 8226/DOX6 and OVCAR-8-Pgp, while 170 kDa Pgp is expressed in the absence of ongoing drug exposure in HL60/VCR cells. **B.** To test for direct interaction between Pim-1 and Pgp, purified GST-tagged recombinant Pim-1 (GST-Pim-1) protein or GST control pulled down by glutathione beads was incubated with lysates of HL60/VCR cells, which overexpress Pgp, and immunoblotting demonstrated specific and direct interaction of Pim-1 and Pgp (Row 1, left). Pgp expression was measured in total cell lysates (TCL) as a control (Row 1, right). Additionally, GST-Pim-1 and GST in the reaction mixture were also measured by immunoblotting with anti-GST, as controls (Row 2). Direct interaction of Pim-1 with Pgp was demonstrated in the GST pull-down assay. **C.** To test whether Pim-1 directly phosphorylates Pgp, Pgp immunoprecipitated from High Five insect cell membranes (100 µg)

expressing Pgp was incubated with GST-tagged recombinant Pim-1 (GST-Pim-1) protein in an *in vitro* kinase assay and Pgp phosphorylation was measured by immunoblotting with anti-phosphoserine (pSer) (Row 1). Pgp, GST-Pim-1 and GST in the reaction mixtures were measured by immunoblotting with anti-Pgp and anti-GST as controls (Rows 2 and 3). Direct phosphorylation of Pgp by Pim-1 was demonstrated *in vitro*.

Figure 3 Pim-1 protects Pgp from proteolytic degradation. A. To determine whether Pim-1 binding stabilizes Pgp in part by inhibiting its proteolytic degradation, the effect of Pim-1 knockdown on the 130 kDa Pgp proteolytic species was measured by immunoblotting with anti-Pgp following Pim-1 knockdown, with prolonged exposure to detect 130 kDa Pgp. HL60/VCR cells were infected with lentivirus containing Pim-1 shRNA or non-target control, and Pim-1 expression was measured six days after infection. Infection with Pim-1 shRNA, in relation to control, resulted in an increase in 130 kDa proteolytic Pgp product, in conjunction with decreased expression of 170 kDa Pgp. **B.** To investigate the dynamic effects of Pim-1 inhibition on 130 kDa and 170 kDa Pgp, OVCAR-8-Pgp cells were treated with the Pim-1-selective inhibitor SGI-1776 (1 μM) for the times indicated and expression of Pgp was measured by immunoblotting. A long exposure was used to visualize the 130 kDa Pgp proteolytic product, while changes in expression of 170 kDa Pgp were more sensitively demonstrated with a shorter exposure. BAD phosphorylation at S112 was also measured to demonstrate Pim-1 kinase inhibition, and GAPDH

expression levels were measured as controls. The results are also shown graphically. Pim-1 inhibition, demonstrated by decreased BAD phosphorylation at S112, resulted in a transient increase in the 130 kDa proteolytic Pgp product, with subsequent decreased expression of 170 kDa mature Pgp.

Figure 4 Pim-1 protects Pgp from proteasomal degradation. A. To determine whether Pim-1 also protects Pgp from proteasomal degradation, Pgp turnover was studied by measuring expression by immunoblotting at serial time points in HL60/VCR cells cultured with cycloheximide (CHX) to inhibit new protein synthesis with and without the selective inhibitor SGI-1776 (1 μM) in the presence and absence of the proteasome inhibitor MG-132. Expression of Pgp and of GAPDH, as a loading control, was measured by immunoblotting, demonstrating decreased stability of 170 kDa Pgp in following Pim-1 inhibition by SGI-1776 compared to control, also shown graphically, demonstrating Pgp half-lives of 9 and 1 hours ($p=0.03$). Additionally, the effect of SGI-1776 was inhibited in the presence of the proteasome inhibitor MG-132. Thus Pim-1 inhibition decreases Pgp stability, and proteasome inhibition overcomes this effect, consistent with Pim-1 protecting Pgp from proteasomal degradation. **B.** To further test whether Pim-1 protects Pgp from ubquitination, the effects of Pim-1 knockdown on Pgp ubiquitination were measured. Pgp ubiquitination, demonstrated by immunoprecipitation followed by immunoblotting with anti-ubiquitin (αUbi), was increased in cells treated with shRNA, in relation to non-target shRNA control, for 3 days, and ubiquitination of 150 kDa immature Pgp

was seen predominantly, consistent with ubiquitination and degradation of core-glycosylated Pgp as a mechanism for decreased expression of 170 kDa Pgp protein in cells following Pim-1 knockdown.

Figure 5 Pim-1 stabilization of 150 kDa Pgp enables its glycosylation. To test whether Pim-1 stabilization of immature Pgp enables its glycosylation, HL60/VCR cells were treated with the glycosylation inhibitor 2-deoxy-D-glucose (2-DG) at 50 mM with and without the Pim-1-selective inhibitor SGI-1776 (1 μM) for 24 hours, and expression of Pgp was examined by immunoblotting. BAD phosphorylation at S112 was also measured to demonstrate Pim-1 kinase inhibition, and BAD and GAPDH expression levels were measured as controls. SGI-1776, which inhibited Pim-1 kinase, as evidenced by decreased BAD phosphorylation at S112, was found to decrease expression of the 150 kDa Pgp that accumulates when glycosylation is inhibited by 2-DG, consistent with the hypothesis that Pim-1 stabilizes 150 kDa Pgp and thereby enables its glycosylation and subsequent cell surface translocation.

Figure 6 Pim-1 inhibition sensitizes Pgp-overexpressing cells to doxorubicin. A. To test whether Pgp phosphorylation by Pim-1 plays a role in Pgp-mediated drug resistance, Pgp-overexpressing multidrug resistant OVCAR-8-Pgp cells were seeded in a 6-well plate at 1 x 10^5 cells per well with and without 10 μM doxorubicin in the presence of 1 μM SGI-1776 or DMSO control. After 48 hours, cells were gently washed 3 times and then cultured again in fresh

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medium with or without drug(s). Colonies visualized by Coomassie Blue staining after 120 hours were quantified by densitometric scanning. The results of densitometric scanning of triplicate experiments are shown graphically, normalized to DMSO control signal. While SGI-1776 at 1 μM was not cytotoxic in relation to DMSO control, culture in the presence of SGI-1776 markedly sensitized OVCAR-8-Pgp cells to doxorubicin ($p=0.00008$). **B.** To determine the range of concentrations at which SGI-1776 sensitizes Pgp-overexpressing cells to a Pgp substrate chemotherapy drug, we incubated OVCAR-8-Pgp cells as above with and without 10 μM doxorubicin combined with SGI-1776 at 0.01, 0.025, 0.05, 0.075, 0.1, 0.25, 0.5, 0.75, 1, 2.5, 5 and 10 μM, or DMSO control. SGI-1776 was not cytotoxic to OVCAR-8-Pgp cells in concentrations up to 1 μM. Sensitization to doxorubicin increased progressively from 0.1 to 0.25 to 0.5 μM, and was maximal at 0.5, 0.75 and 0.1 μM, in the absence of SGI-1776 cytotoxicty. A representative experiment among triplicate experiments is shown.

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Figure 1

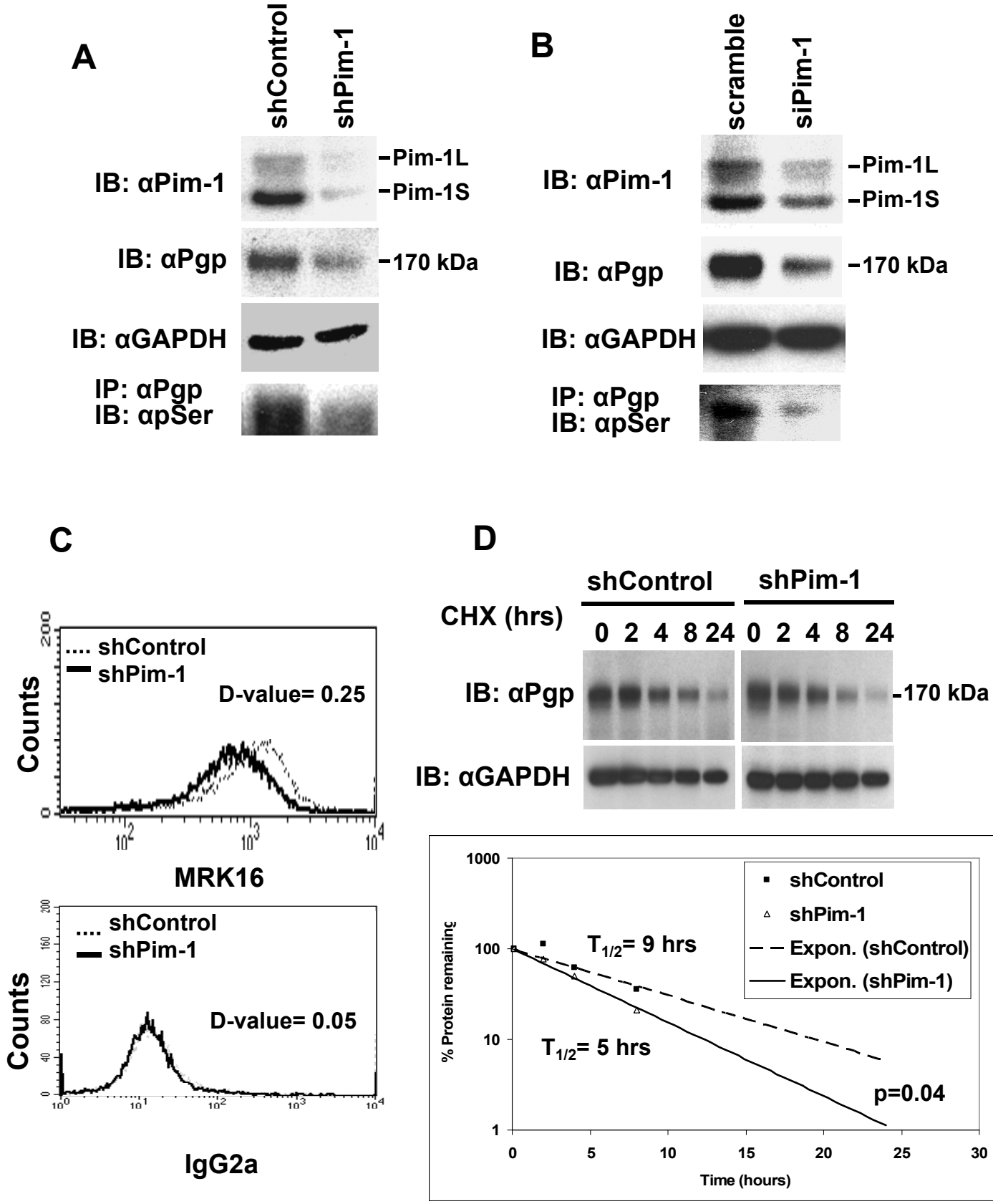

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Figure 2

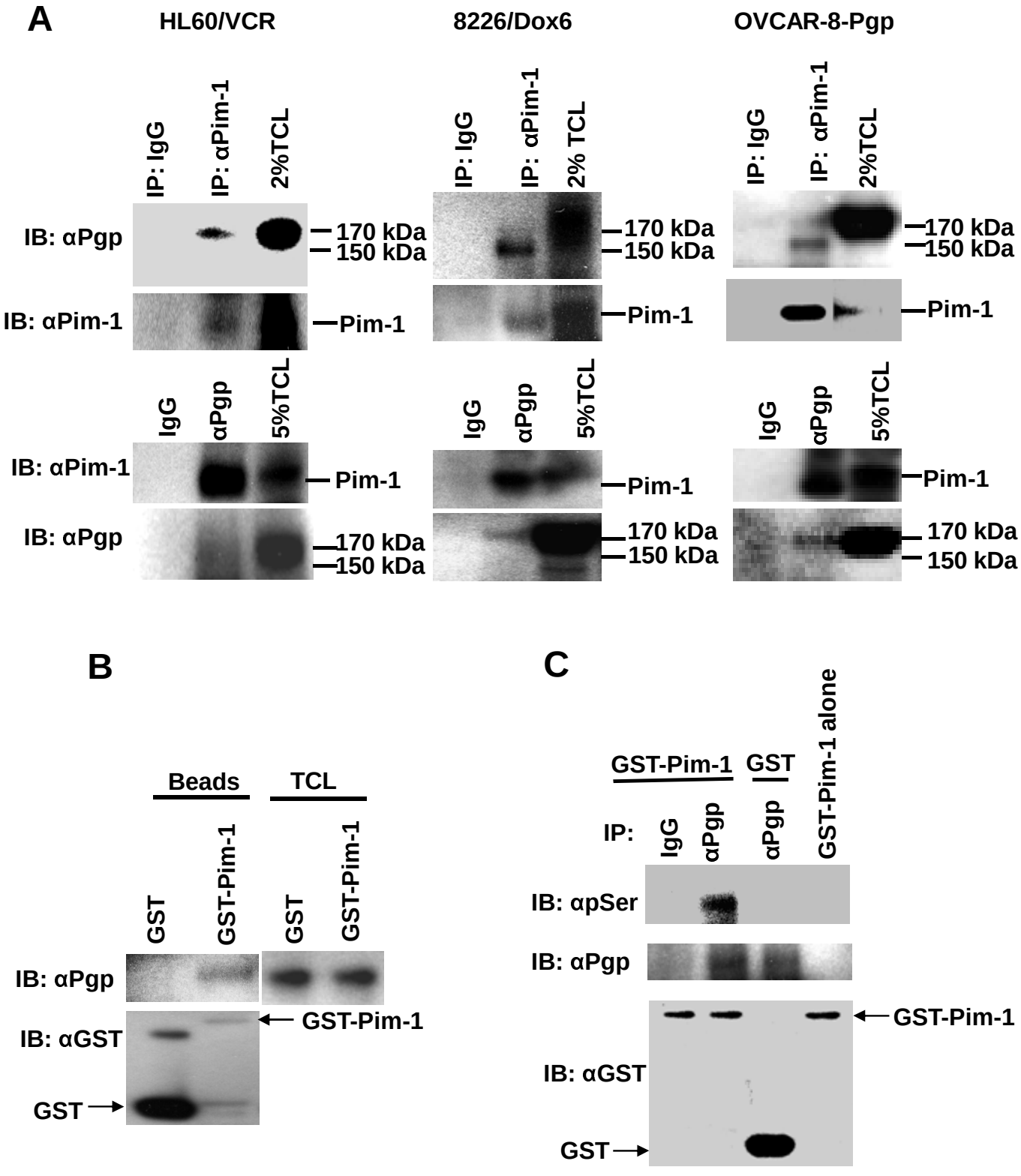

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Figure 3

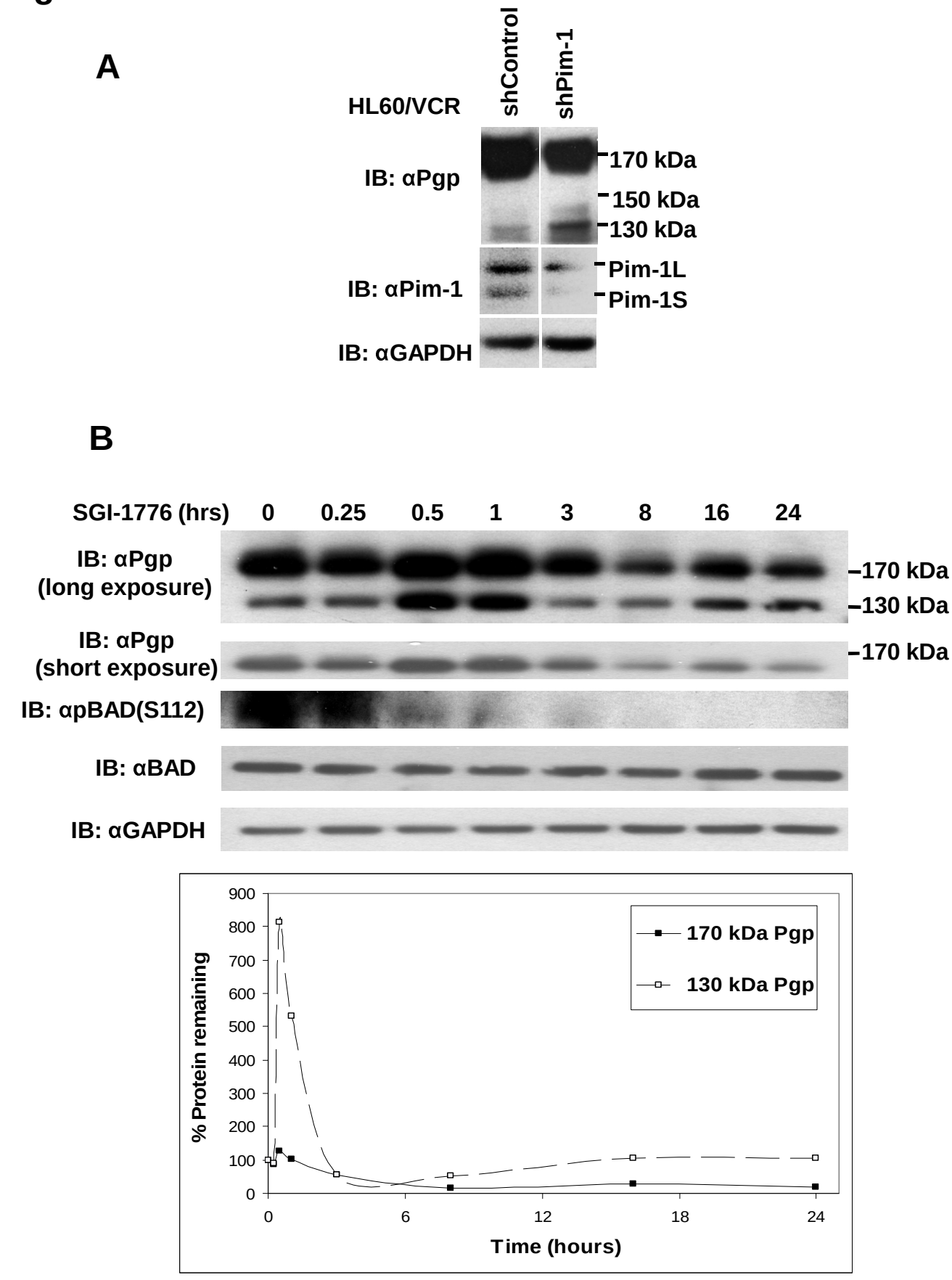

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Figure 4

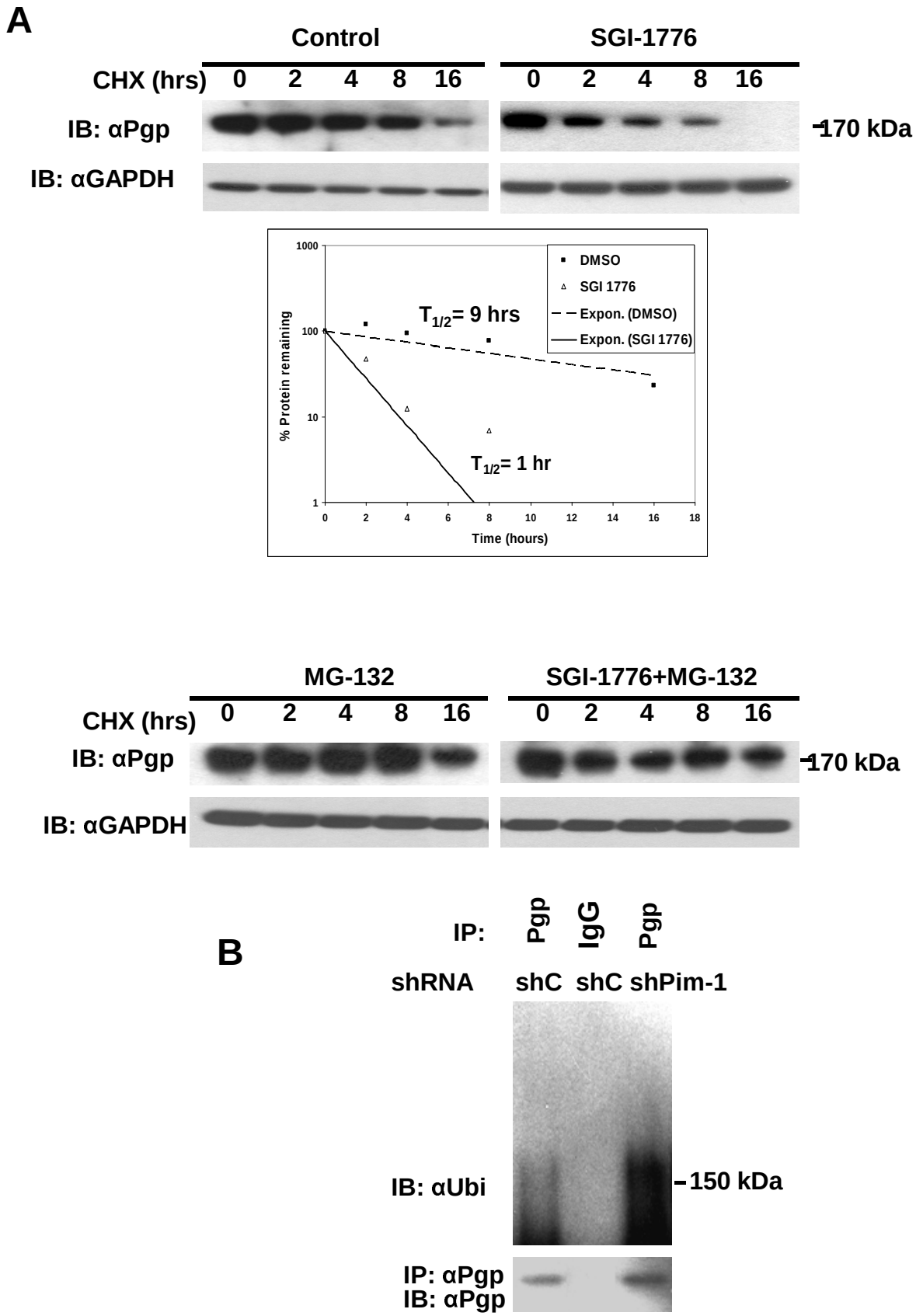

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Figure 5

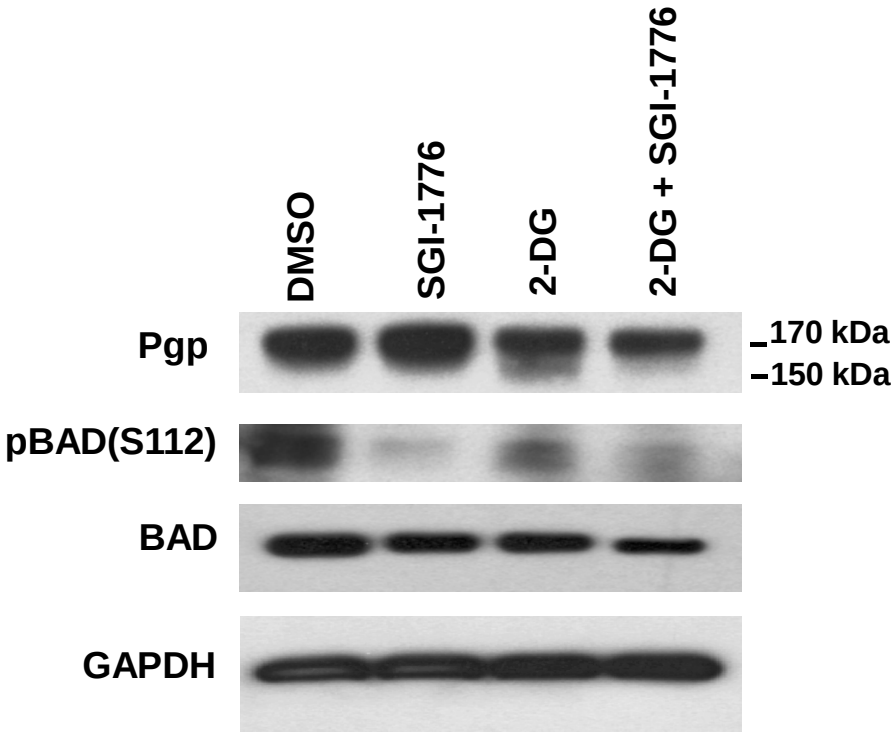

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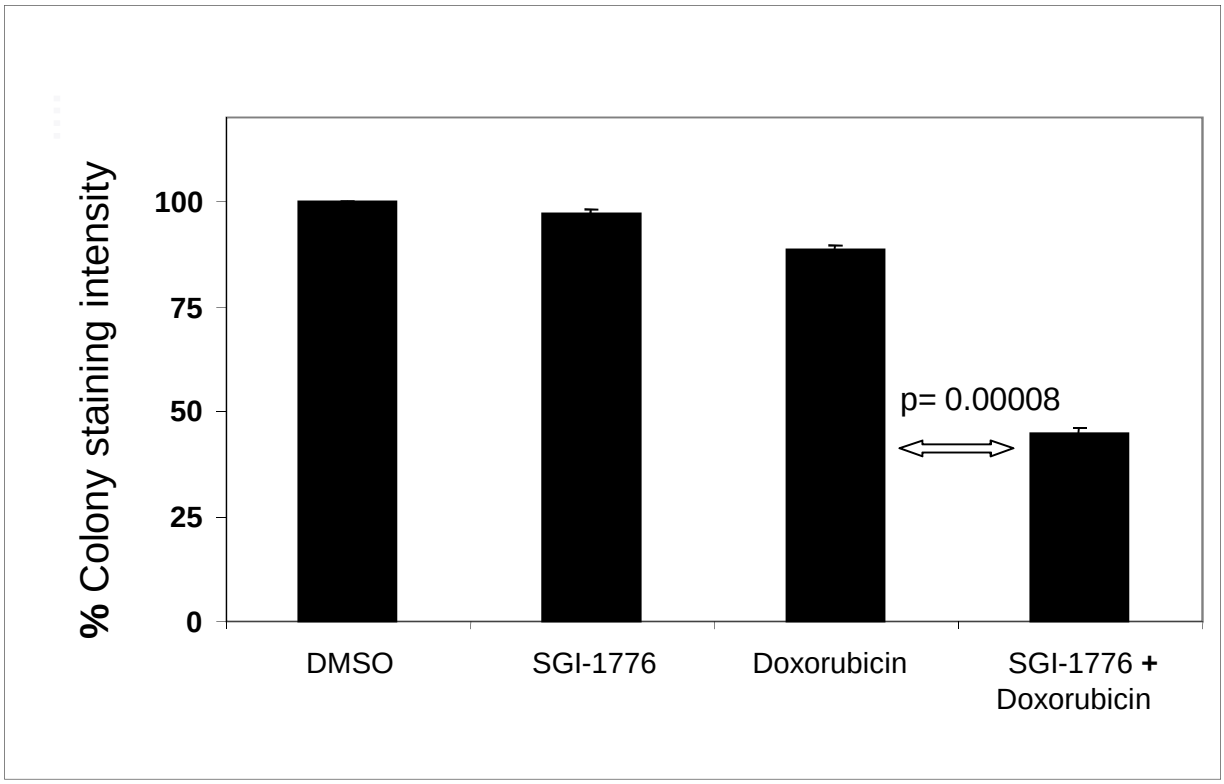
Figure 6

A



B