Diverse Antiapoptotic Signaling Pathways Activated by Vasoactive Intestinal Polypeptide, Epidermal Growth Factor, and Phosphatidylinositol 3-Kinase in Prostate Cancer Cells Converge on BAD*

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It has been demonstrated that vasoactive intestinal polypeptide, epidermal growth factor, and chronic activation of phosphatidylinositol 3-kinase can protect prostate cancer cells from apoptosis; however, the signaling pathways that they use and molecules that they target are unknown. We report that vasoactive intestinal polypeptide, epidermal growth factor, and phosphatidylinositol 3-kinase activate independent signaling pathways that phosphorylate the proapoptotic protein BAD. Vasoactive intestinal polypeptide operated via protein kinase A, epidermal growth factor required Ras activity, and effects of phosphatidylinositol 3-kinase were predominantly mediated by Akt. BAD phosphorylation was critical for the antiapoptotic effects of each signaling pathway. None of these survival signals was able to rescue cells that express BAD with mutations in the BH3 domain, whereas knockdown of BAD expression was able to rescue cells that express BAD with mutations in the phosphorylation sites, whereas knockdown of BAD expression was able to rescue cells that express BAD with mutations in the phosphorylation sites. Therefore, resistance to apoptosis has been connected to prostate cancer progression.

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† The on-line version of this article (available at http://www.jbc.org) contains supplemental Figs. 1 and 2.

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‡ The abbreviations used are: PI3K, phosphatidylinositol 3-kinase; EGF, epidermal growth factor; EGFR, epidermal growth factor receptor; VIP, vasoactive intestinal polypeptide; ERK, extracellular signal-regulated kinase; GPCR, G protein-coupled receptor; MEK, mitogen-activated protein kinase; extracellular signal-regulated kinase kinase; PAK, p21-activated kinase; PTEN, phosphatase and tensin homolog deleted on chromosome 10; PKA, protein kinase A; siRNA, small interfering RNA; shRNA, small hairpin RNA; GFP, green fluorescent protein; HA, hemagglutinin; LY, LY294002; BH3, Bcl homology domain 3.

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(27, 35, 36). However, the molecular mechanism of cell survival mediated by VIP is not completely understood.

A number of reports have provided evidence of interactions between signaling pathways activated by PI3K, EGF, and GPCR agonists. For example, GPCR agonists α-thrombin and lysophosphatic acid were shown to transactivate EGFR (37), PI3K has been implicated in EGFR and HER2 survival signaling (8, 38), and the Ras/MEK pathway was reportedly activated by VIP in prostate cells (31). The goal of this study was to examine antiapoptotic mechanisms activated by PI3K, EGF, and VIP and determine whether they utilize common or separate signaling pathways.

In this paper, we report that VIP protects prostate cancer cells from apoptosis by phosphorylating BAD via a PKA-dependent mechanism. Furthermore, we found that PI3K, EGF, and VIP activate redundant, mutually independent signaling pathways that induce phosphorylation of the proapoptotic protein BAD. Knocking down BAD expression by shRNA substantially decreases sensitivity of prostate cancer cells to apoptosis, whereas expression of BAD with mutations in phosphorylation sites induces apoptosis that cannot be inhibited by antiapoptotic signals. Taken together, these results identify BAD as a convergence point of several antiapoptotic signaling pathways in prostate cancer cells.

EXPERIMENTAL PROCEDURES

Cell Lines—The prostate cancer LNCaP and C4-2 cells were a gift from Dr. Leland Chung (Emory University, Atlanta, GA). C4-2LN7Ras cells were obtained by transfecting C4-2 cells with pGL4 mixed with Tet-on and pTRE2hygN17Ras cDNA. To obtain control C4-2L cells, empty pTRE2hyg vector was used instead of pTRE2hygN17Ras. Cells were selected in G418 with pGL4 mixed with Tet-on and pTRE2hygN17Ras cDNA.

Antibodies and Other Reagents—Antibodies were from the following sources. BAD, phospho-specific BAD (Ser112, Ser136, and Ser155), phospho-ERK (Thr202/Tyr204), Akt, phospho-Akt (Ser27), and phospho-GSK3α (Ser9) were from Cell Signaling Technology (Beverly, MA); phospho-MEK1 (Ser298) antibodies were a gift from Andrew Catling (Louisiana State University, New Orleans, LA); anti-FLAG M2 monoclonal antibodies were from Sigma; secondary horseradish peroxidase-conjugated antibodies used for Western blots were from Amersham Biosciences. Protein G-agarose beads, DEVD-7-amino-4-methylcoumarin, VIP, and rapamycin were from Calbiochem. Recombinant EGF was from Upstate Biotechnology, Inc. (Lake Placid, NY). Scramble and Akt-siRNA were from Cell Signaling Technology (catalog numbers 6201 and 6211). All other chemicals and reagents (unless specified) were purchased from Sigma. Tissue culture reagents were purchased from Gibco.

Plasmid and DNA Constructs—pcDNA3-HA-BAD, pcDNA3-HA-BADS112A, and pcDNA3-HA-BADS112/136A constructs were from Michael Greenberg (Harvard Medical School, Boston, MA); pRK5-Mye-PAK1(K299R) and pCMV-HA-MEK1 were from Andrew Catling. EGFP was from Clontech. PKI-GFP was from Dr. Raymond Penn (Wake Forest University, Winston-Salem, NC). Dominant negative Akt (AAA-Akt) and constitutively active Akt (Myr-Akt) were from Dr. Dario Alessi (University of Dundee, Scotland). The UBC-GFPLuc construct that expresses luciferase fused to green fluorescent protein under the ubiquitin promoter was a gift from Dr. Purnima Dubey (Wake Forest University, Winston-Salem, NC).

Cell Culture and Transfection—LNCaP and C4-2 cells were plated in 10-cm plates and maintained in T-medium supplemented with 5% fetal bovine serum and RPMI 1640 with 10% fetal bovine serum, respectively. All cells were kept in 5% CO₂ at 37 °C. Transient transfection was performed at 60–70% confluence using Lipofectamine (Invitrogen) according to the manufacturer’s recommendations. The following amounts of DNA were used per 10-cm plate: 0.6 μg of EGF, 0.5 μg of BAD, 1 μg of Bcl-X₅, and 4 μg of DN-N17Ras, PKI-GFP, DN-PAK1, AAA-Akt, or Myr-Akt expression constructs.

siRNA Experiments—For Akt-siRNA experiments, cells were cotransfected with 0.2 μg of HA-BAD, 0.4 μg of Bcl-X₅, and 50 nM Akt-siRNA or scramble siRNA using Metafectene transfection reagent (Biontex, Germany). For the first 24 h after transfection, cells were maintained in serum-supplemented medium and under serum-starved conditions for the following 48 h. Then cells were lysed and probed for Akt and BAD phosphorylation. For shRNA BAD knockdown experiments, a lentiviral vector (pLL3.7) was used with an shRNA insert of annealed oligonucleotides. The Bad DNA target sequences used were 5′-TGAAGGGACTTCTCGCCCTG-3′ and 5′-GGCTTG-GTCCCATCGGAAG-3′. HEK 293 cells were transfected with pLL3.7 vector containing either of these sequences or a scrambled sequence 5′-GTTACGGTCAGCGTCAGTCT-3′ in combination with packaging vectors (VSVG, RSV-REV, and pMDL g/p RE). After 48 h, supernatants were collected from these cells and used to infect LNCaP or C4-2 cells. Forty-eight hours after infection, cells were plated for subsequent experiments.

Immunoprecipitation—Twenty hours after transfection with BAD expression constructs, cells were deprived of serum for 3 h, and different treatments were given at this point as described in the figure legends. Cells were harvested in a cell lysis buffer (20 mM Tris, pH 7.4, 40 mM NaF, 2 mM EDTA, 1 mM EGTA, 1% Triton X-100, 1 μg each of leupeptin, pepstatin, and aprotinin, 1 mM phenylmethylsulfonyl fluoride, 1 mM NaVO₄, 50 mM β-glycerophosphate, 40 mM p-nitrophenyl phosphate, and 1 mM dithiothreitol). The lysates were cleared of insoluble material by centrifugation at 14,000 × g for 10 min at 4 °C. Cell extracts were incubated with 6–8 μg of anti-HA antibodies (12CA5) overnight at 4 °C and protein G-agarose beads for another 3 h. Beads were washed three times with cell lysis buffer, and proteins were eluted with an SDS sample buffer for Western blot analysis.

Apoptosis Assays—Apoptosis was induced as follows. Cells were serum-starved overnight (16 h) and treated with 50 μM LY294002 and 1 μM thapsigargin, an inhibitor of the sarcoplasmic/endoplasmic reticulum calcium ATPase. Thapsigargin alone does not induce apoptosis in prostate cancer cells within 24 h (39, 40), but in the experimental conditions that we used it synchronized caspase activation in cells treated with LY294002. This protocol shortened the time and increased the reproducibility of caspase assays and also permitted analysis of apoptosis by time lapse video recording. Apoptosis in whole cell popul-
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A, LNCaP cells were treated with 50 μM LY and 1 μM thapsigargin followed by either 5 nM EGF or 100 nM VIP as indicated. After 6 h, cells were collected, lysed, and caspase activity was measured with the fluorogenic substrate Ac-DEVD-7-amido-4-trifluoromethylcoumarin (Bachem) as specified by the manufacturer. For these experiments, attached and floating cells were collected and lysed in caspase lysis buffer (1% Nonidet P-40, 150 mM NaCl, 20 mM HEPES, 1 mM EDTA, 1 mM dithiothreitol, and 5 μg/ml aprotinin, leupeptin, and pepstatin). Fluorescence was recorded each 15 min for 1 h, and caspase activity was expressed in arbitrary units. Apoptosis in a population of transfected proteins by growth factors. Ten minutes later, cells were washed with PBS three times and lysed, and luciferase activity was measured on a microplate luminometer according to the manufacturer’s instructions using a kit from Promega (catalog number E1500).

BAD Phosphorylation in Mouse Prostate—C57BL/6 male mice were anesthetized with ketamine/xylazine mixture, the abdomen was opened, and both lobes of anterior prostates were injected in three locations with 10 μl of saline alone or with 10 nM EGF or with 100 nM VIP. The abdomen was then closed with a metal clip. Twenty minutes later, the anesthetized mice were euthanized by cervical dislocation, and the anterior prostates were removed and frozen in liquid nitrogen. Prostates were lysed, and phosphorylation of endogenous BAD was analyzed by immunoblotting.

RESULTS

PI3K, EGF, and VIP Protect Cells from Apoptosis and Induce BAD Phosphorylation—PI3K signaling is constitutively up-regulated in LNCaP prostate cancer cells due to a frameshift mutation of the lipid phosphatase PTEN (41). As a result, these cells can survive in serum-free medium in the absence of trophic caspase 3. For these experiments, cells were plated in 6-well plates and transfected by Lipofectamine with a mixture of cDNA that included GFP in a 1:9 ratio. At least four randomly chosen fields (containing on average 200–300 cells for each treatment) were recorded. Video recording was performed on an Axiovert100 microscope (Carl Zeiss, Germany) equipped with a moving stage and climate control chamber (37 °C, 5% CO2) and controlled by Openlab software (Improvement Inc., Lexington, MA). The results reported herein were confirmed by at least two independent experiments.

Luciferase Assays—Cells were co-transfected with 0.5 μg/ml HA-BADwt or HA-BADS112A or HA-BAD S112/136A (BAD2SA) and 0.1 μg/ml of luciferase expressing vector UBC-GFPluc. Twenty-four hours after transfection, cells were serum-starved for 3 h and treated with 20 μM LY294002 and 3 μg/ml cycloheximide to prevent changes in expression of transfected proteins by growth factors. Ten minutes later, cells were treated with either 5 nM EGF or 100 nM VIP. Six hours later, cells were washed with PBS three times and lysed, and luciferase activity was measured on a microplate luminometer according to the manufacturer’s instructions using a kit from Promega (catalog number E1500).

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... factors. Recently, we have shown that inhibition of PI3K with LY294002 in LNCaP cells induces apoptosis, characterized by release of cytochrome c from mitochondria, activation of caspases 3 and 7, and fragmentation of the nucleus and cytoplasm. We also have demonstrated that treatment with EGF can protect LNCaP cells by inhibiting proapoptotic signaling upstream of mitochondria independent of PI3K activity and new protein synthesis (20). To test whether PI3K-independent survival can be induced by other extracellular ligands, we examined the effects of VIP on apoptosis in prostate cancer cells. Analysis of caspase activity showed that in the presence of LY294002, VIP provided protection from apoptosis comparable with that obtained with EGF (Fig. 1A). Similar results were obtained when apoptosis was measured by time lapse video recording that permits dynamic documentation of apoptosis in individual cells (Fig. 1B).

Previously, BAD, a BH3-only member of the Bcl-2 family, has been identified as a target of the PI3K/Akt antiapoptotic signaling pathway (42, 43). BAD phosphorylation at Ser112 and Ser136 facilitates BAD association with 14-3-3 proteins and inhibits apoptosis (44). We examined the status of BAD phosphorylation in prostate cancer cells treated with LY294002 alone and in combination with EGF and VIP. In LNCaP cells maintained in serum-free medium, phosphorylation of endogenous BAD was recognized with phospho-Ser112-specific antibodies. Upon treatment with LY294002, BAD became dephosphorylated; however, treatment with either EGF or VIP restored BAD phosphorylation in the absence of Akt activation (Fig. 1C). Similar effects of EGF and VIP on BAD phosphorylation and protection from apoptosis were observed in C4-2 prostate cancer cells, which exhibit more aggressive tumor growth in vivo (not shown). Furthermore, BAD phosphorylation at Ser112 was observed in mouse prostate glands injected with EGF and VIP (Fig. 1D). The latter result demonstrates that the ability of EGF and VIP to induce phosphorylation of BAD was not limited to prostate cancer cell lines maintained in tissue culture but also occurred in the context of the intact prostate gland.

In addition to Ser112, BAD can be phosphorylated at Ser136 and Ser155. Because phosphospecific antibodies against Ser136 and Ser155 are not sensitive enough to detect phosphorylation of endogenous BAD, analysis of BAD phosphorylation at these sites was performed on immunoprecipitates of HA-BAD ectopically expressed in LNCaP cells. In cells growing in serum-free conditions, HA-BAD was constitutively phosphorylated at Ser112 and also at Ser136 and Ser155. Treatment with LY294002 resulted in dephosphorylation of Ser112 and Ser136 within 2 h but did not reduce Ser155 phosphorylation (supplemental Fig. 1). VIP induced only Ser112 phosphorylation, whereas EGF restored BAD phosphorylation at both Ser112 and Ser136 (Fig. 1E). Thus, the antiapoptotic effects of PI3K, EGF, and VIP correlate with BAD phosphorylation status.

**BAD Phosphorylation Is Necessary for Cell Survival Mediated by PI3K, VIP, and EGF**—To examine the role of BAD in apoptosis of prostate cancer cells, we engineered lentiviral vectors that express BAD-specific shRNA or scrambled shRNA. Infection with lentivirus that expresses BAD shRNA dramatically reduced expression of endogenous BAD (Fig. 2A). Time lapse video recording demonstrated reduced apoptosis in LNCaP and C4-2 cells where BAD expression is knocked down (Fig. 2B). Thus, BAD expression is required for apoptosis induction in prostate cancer cells.

To address the role of BAD phosphorylation in antiapoptotic signaling, we tested the survival effects of EGF and VIP in cells that express BAD with mutated phosphorylation sites (Fig. 3A). LNCaP cells were transfected with either wild type BAD (BADwt), BADS112A (where serine 112 is replaced with alanine), or BAD2SA (where both Ser112 and Ser136 are mutated). Cell survival was judged by measuring luciferase activity in cells co-transfected with luciferase expression vector and BAD constructs. A similar method utilizing a ß-galactosidase reporter construct has been previously used to examine survival in cells that transiently express BAD with mutations in phosphorylation sites (45). Both EGF and VIP were able to restore survival in LY294002-treated cells that express BADwt. However, in cells that express BADS112A, the survival effect of VIP was diminished, whereas EGF still showed a strong survival effect. In cells transfected with BAD2SA, survival was lower even without LY294002 treatment than in LY294002-treated cells transfected with the other BAD constructs. Neither VIP nor EGF increased survival in cells transfected with BAD2SA. However, co-transfection of the antiapoptotic protein Bcl-XL with BAD2SA restored survival, which is consistent with the idea that BAD2SA induces apoptosis (Fig. 3A). These results suggest that BAD phosphorylation at Ser112 is necessary for VIP-mediated survival, whereas both Ser112 and Ser136 have to be mutated to inhibit the survival effects of PI3K and EGF.

To further corroborate the results of this experiment, we measured apoptosis in cells co-transfected with BAD constructs and GFP by time lapse video microscopy. Expression of BADwt and BADS112A was achieved at similar levels and was well tolerated by LNCaP cells (Fig. 3B). Inhibition of PI3K with LY294002 induced apoptosis in cells that expressed BAD constructs. Consistent with the results shown in Fig. 3A, VIP reduced apoptosis in cells that express BADwt but not in cells that express BADS112A, whereas EGF was able to decrease apoptosis in both BADwt and BADS112A-expressing cells (Fig. 3C and supplemental Fig. 2). Thus, phosphorylation of BAD at
Ser\textsuperscript{112} is important for the antiapoptotic effects of VIP, whereas it is less so for EGF- or PI3K-induced survival. Apparently, phosphorylation at Ser\textsuperscript{136} in cells with active PI3K signaling and Ser\textsuperscript{136} induced by constitutive PI3K signaling (compare lanes 1 and 4 in Fig. 4A) or in BAD phosphorylation at Ser\textsuperscript{112} induced by VIP in the presence of LY294002 (Fig. 4B).

In contrast to BAD\textsubscript{wt} and BAD\textsubscript{S112A} constructs, we were unable to express the BAD\textsubscript{SA} construct even in cells treated with EGF or VIP. Apparently, even a small amount of BAD\textsubscript{SA} expression was sufficient to trigger apoptosis in LNCap cells that cannot be inhibited by PI3K, EGF, or VIP. In agreement with this idea, BAD\textsubscript{SA} expression can be detected in cells co-transfected with antiapoptotic protein Bcl-X\textsubscript{L} (Fig. 3E).

Taken together, our experiments with BAD knock-out by shRNA and ectopic expression of phosphorylation-deficient BAD mutants indicate that BAD phosphorylation is critical for the antiapoptotic effects of EGF, VIP, and PI3K.

**Dominant Negative N17Ras Specifically Blocks EGF-induced Survival and BAD Phosphorylation**—Our subsequent efforts were focused on the analysis of signaling pathways induced by PI3K, EGF, and VIP that lead to BAD phosphorylation and protection of cells from apoptosis.

Ras plays an important role in signaling by receptor tyrosine kinases, GPCRs, and PI3K (46, 47). Therefore, Ras activation can potentially contribute to the antiapoptotic effects of PI3K, EGF, and VIP. The role of Ras in BAD phosphorylation was assessed by co-transfecting dominant negative N17Ras mutant and HA-BAD in LNCap cells. N17Ras inhibited EGF-induced BAD phosphorylation at both Ser\textsuperscript{112} and Ser\textsuperscript{136} (Fig. 4A) as well as MEK activation (Fig. 4C). However, there was no change in the status of BAD phosphorylation at Ser\textsuperscript{112} and
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Since phosphorylation of BAD at Ser\textsuperscript{112} and Ser\textsuperscript{136} results in its association with 14-3-3, we examined how inhibition of Ras signaling affects this protein complex. In untreated cells, phosphorylated BADwt was co-precipitated with 14-3-3. This interaction and BAD phosphorylation was markedly reduced by puromycin treatment. Twelve hours after transfection, cells were serum-starved for 3 h and treated with 30 ng/ml EGF for 15 min. HA-ERK was immunoprecipitated with 12CA5 antibodies, and phosphorylation of ERK was detected using phospho-ERK (Thr202/Tyr204) antibodies. Equal loading was verified by anti-HA antibodies. Expression of DN-Ras was confirmed by anti-HA antibodies. Expression of N17Ras was verified by probing cell lysates with anti-FLAG antibodies. C, dominant negative N17Ras inhibits MAPK activity in LNCaP cells. LNCaP cells were transfected with HA-ERK and either empty vector or N17Ras. Twenty hours after transfection, cells were serum-starved for 3 h and treated with 30 ng/ml EGF for 15 min. HA-ERK was immunoprecipitated with 12CA5 antibodies, and phosphorylation of ERK was detected using phospho-ERK (Thr202/Tyr204) antibodies. Equal loading was verified by anti-FLAG antibodies. Expression of DN-Ras was confirmed by anti-HA antibodies. D, dominant negative N17Ras specifically inhibits EGF-induced cell survival. LNCaP cells were co-transfected with EGFP and either empty pcDNA3 vector or N17Ras (1:9 ratio). After 20 h, cells were serum-starved and treated as in Fig. 1A to induce apoptosis. Six hours later, the percentage of apoptosis was determined by counting cells with fragmented cytoplasm among GFP-positive cells. Solid bars, pcDNA3 vector; striped bars, N17Ras. At least 300 cells were counted for each treatment. The error bars show deviation of individual fields from the average. E, C4-2L cells (solid bars) and C4-2LN17Ras cells (striped bars) that stably express N17Ras were serum-starved for 20 h and apoptosis was induced as in Fig. 1A. Six hours later, cells were collected and lysed, and caspase activity was measured with the fluorogenic substrate Ac-DEVD-7-amido-4-trifluoromethylcoumarin.

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Next, we studied the effect of N17Ras on cell survival. Transient transfection of N17Ras into LNCaP cells completely inhibited the cytoprotective effect of EGF in LY294002-treated cells; however, it did not interfere with antiapoptotic effects of VIP, nor did it induce apoptosis in cells with active PI3K signaling (Fig. 4D). Inhibition of EGF-dependent survival was also observed in experiments with C4-2LN17Ras cells that stably express N17Ras, where caspase activity was used to measure apoptosis (Fig. 4E). Together, these results indicate that Ras activity is necessary for EGF-induced BAD phosphorylation and protection from apoptosis. In contrast, VIP and PI3K use Ras-independent mechanisms to regulate BAD phosphorylation and cell survival.

Protein Kinase A Mediates VIP-induced BAD Phosphorylation and Survival—In prostate cells, VIP exerts its biological effects through the VPAC1 receptor, a member of the GPCR superfamily. Upon binding to VPAC1, VIP activates adenylyl cyclase and increases cAMP levels (33). In turn, cAMP activates PKA, which has been shown to phosphorylate BAD and thereby protect cells from apoptosis (48).

To address the role of PKA in BAD phosphorylation and cell survival induced by PI3K, VIP, and EGF, we used an inhibitory molecule, PKI (49), expressed as a chimera with GFP (PKI-GFP) (50). Co-transfection of LNCaP cells with PKI-GFP and BADwt significantly inhibited VIP-induced phosphorylation of BAD at Ser\textsuperscript{112}. However, PKI-GFP expression had no effect on the PI3K-dependent steady state level of BAD phosphorylation or BAD phosphorylation induced by EGF (Fig. 5A).

Since PKI-GFP inhibited VIP-induced BAD phosphorylation at Ser\textsuperscript{112}, we examined its effect on the association of 14-3-3 with BAD. VIP restored the binding of BAD to 14-3-3 protein in cells transfected with GFP but failed to do so in cells transfected with PKI-GFP. However, expression of PKI-GFP did not decrease the interaction between 14-3-3 and BAD in cells treated with EGF or in cells with active PI3K signaling (Fig. 5A). Thus, our experiments with PKI-GFP show that BAD phosphorylation and interaction with 14-3-3 induced by VIP depends on PKA activity, whereas PI3K and EGF induced BAD phosphorylation via PKA-independent mechanisms.
Next, we studied the effect of PKI-GFP on cell survival mediated by VIP, EGF, and PI3K. Apoptosis in cells that express GFP or PKI-GFP was determined by time lapse video recording of GFP-positive cells followed by counting the percentage of cells with apoptotic morphology. As shown in Fig. 5A, PKI-GFP did not significantly decrease survival effects of PI3K or EGF. In contrast, the antiapoptotic effect of VIP was completely abolished in cells where PKA activity was inhibited by PKI-GFP. Thus, the PKA inhibitor PKI-GFP suppressed VIP-induced BAD phosphorylation and cell survival without altering the effects of PI3K or EGF on these parameters.

**Akt Is a Principal BAD Kinase Downstream of PI3K in LNCaP and C4-2 Cells**—Since PI3K-dependent BAD phosphorylation and cell survival are observed despite inhibition of Ras or PKA, we decided to address the role of PI3K effectors in further detail. The biological effects of PI3K activation are mediated by a wide array of downstream kinases. Akt, p70S6 kinase, and the PAK family of kinases are all known to be activated downstream of PI3K and phosphorylate BAD (42, 51, 52). Akt and p70S6 kinases have been shown to phosphorylate BAD at Ser136, whereas PAK1 phosphorylates both Ser112 and Ser136. To test whether Akt, p70S6, and PAK kinases are regulated by PI3K in LNCaP cells, the effect of LY294002 on their activation was followed.
Activation of Akt and p70S6 kinases were assessed using antibodies that recognize their active forms, whereas PAK activation status was judged by measuring phosphorylation of Ser298 on MEK1, which is widely used to monitor PAK activity (53). Fig. 6A shows that Akt, p70S6, and PAK kinases are active in LNCaP cells maintained in serum-free medium, and their activity is reduced upon treatment with LY294002. To determine which of these kinases are responsible for phosphorylation of BAD, we inhibited p70S6 kinase with rapamycin and blocked PAK1 activity with DN-PAK1 (PAK1-K299R). As shown in Fig. 6B, rapamycin suppressed phosphorylation of p70S6 kinase without diminishing phosphorylation of BAD at Ser112 and Ser136. Likewise, expression of DN-PAK1 did not affect BAD phosphorylation, although it suppressed MEK1 phosphorylation at Ser298 and, hence, endogenous PAK activity (Fig. 6C). To determine the role of Akt kinase in BAD phosphorylation, LNCaP cells were transfected with a dominant negative mutant Akt-3A (where Ser73, Thr308, and Lys379 are mutated to alanines). Expression of Akt-3A in LNCaP cells with active PI3K signaling reduced both Ser112 and Ser136 phosphorylation, with stronger inhibition of Ser136 phosphorylation (Fig. 7A, lane 3). The role of Akt in BAD phosphorylation was further tested by expression of a constitutively active myristoylated Akt construct. In cells that express Myr-Akt, BAD phosphorylation was maintained at both Ser112 and Ser136 despite inhibition of PI3K by LY294002 (Fig. 7A, lane 6). In agreement with the preferential inhibition of Ser136 by the dominant negative Akt mutant, the effect of constitutively active M-Akt on Ser136 markedly surpassed the increase in Ser112 phosphorylation.

To further clarify the role of Akt in BAD phosphorylation, we inhibited Akt expression with siRNA. As shown in Fig. 7B, co-transfection of BAD and Akt siRNA inhibited BAD phosphorylation at Ser136 in both LNCaP and C4-2 cells by ~80%, which is comparable with inhibition by dominant negative Akt-3A. Still, Ser112 phosphorylation was decreased only by 30%, which suggests that kinase(s) other than Akt contribute to BAD phosphorylation at this site. To confirm Akt inhibition, we examined the effect of siRNA-Akt on the phosphorylation of endogenous GSK3 (an established Akt substrate (54)). For this purpose, cells were co-transfected with siRNA-Akt and GFP, and GFP-positive and GFP-negative cells were separated by fluorescence-activated cell sorter. As shown in Fig. 7C, GSK3 phosphorylation in GFP-positive cells is decreased to the level observed in cells treated with LY294002.
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To address the role of Akt in apoptosis regulation in prostate cells, we examined survival in cells co-transfected with a luciferase construct (UBC-GFP+Luc) and either siRNA-Akt or scrambled siRNA or PTEN cDNA. Transfection with siRNA-Akt decreased luciferase activity compared with cells transfected with scrambled siRNA. Because the difference in luciferase activity between siRNA-Akt and scramble siRNA transfected cells was reduced dramatically when Bcl-XL was included in the transfection mix, we reasoned that reduction of luciferase reflects decreased survival in cells transfected with siRNA-Akt (Fig. 7D). To reinforce this point, we examined apoptosis in cells co-transfected with siRNA-Akt and GFP by time lapse video recording (Fig. 7E). Transfection with siRNA-Akt increased apoptosis within 72 h although to a lesser degree than that observed with re-expression of PTEN that has been shown to reduce BAD dephosphorylation at both Ser\textsuperscript{112} and Ser\textsuperscript{136} (55).

Taken together, our results support the role of Akt as a principal kinase that phosphorylates BAD at Ser\textsuperscript{136} downstream of PI3K in LNCaP and C4-2 prostate cancer cells. Phosphorylation of BAD at Ser\textsuperscript{112} downstream of PI3K is partially regulated by Akt and another, yet to be identified, kinase.

**DISCUSSION**

Results presented in this paper show that antiapoptotic signals activated by PI3K, EGF, and VIP converge on BAD, a member of the BH3-only family of proapoptotic proteins. BAD was the first proapoptotic protein shown to be inhibited by phosphorylation. In its dephosphorylated form, BAD interacts with Bcl-X\textsubscript{L} in the outer mitochondrial membrane and increases apoptosis. Phosphorylation at Ser\textsuperscript{112}, Ser\textsuperscript{136}, or both sites facilitates interaction with 14-3-3 proteins, whereas phosphorylation of Ser\textsuperscript{155} (positioned within the BH3 domain) directly inhibits binding to Bcl-X\textsubscript{L}. In the phosphorylated states, BAD is retained in the cytoplasm by 14-3-3 and, thus, cannot bind Bcl-X\textsubscript{L} and increase apoptosis (44).

After it was identified as a target of antiapoptotic signaling by the PI3K/Akt pathway (42, 43), BAD was shown to be phosphorylated by numerous protein kinases, including PKA, p90RSK, p70S6K, and PAK kinases (51, 52, 56, 57). Most reports describing BAD phosphorylation emphasized the dominant role of a single signaling pathway that regulates BAD phosphorylation in a given cell type. In HEK293 and MDA-MB-468 cell lines, EGF and PI3K send nonoverlapping signals that stimulate BAD phosphorylation at Ser\textsuperscript{112} and Ser\textsuperscript{136}, respectively (58, 59).

According to our data, regulation of BAD phosphorylation in prostate cells appears to be more complex. PI3K and EGF activate independent signaling mechanisms that induce phosphorylation of both Ser\textsuperscript{112} and Ser\textsuperscript{136} sites. Analysis of PI3K-dependent BAD phosphorylation shows that Ser\textsuperscript{136} is the primary target of Akt, whereas Ser\textsuperscript{112} phosphorylation is only partially Akt-dependent. This is in agreement with earlier publications that demonstrated that Ser\textsuperscript{136} is the main Akt site (42). Partial dependence of Ser\textsuperscript{112} phosphorylation on Akt was previously shown in a kinase reaction in vitro (60). Further experiments are needed to identify the PI3K-dependent Ser\textsuperscript{112} kinase and its role in apoptosis regulation.

Our results on EGF-induced BAD phosphorylation reveal the mechanism of EGF-mediated survival in prostate cells. Extending other reports that connected the survival effect of EGF with BAD phosphorylation at Ser\textsuperscript{112} (58, 59, 61), we show that both Ser\textsuperscript{112} and Ser\textsuperscript{136} are phosphorylated in a Ras-dependent but PI3K-independent fashion. The evidence from xenograft studies that supports the role of Ras in prostate cancer warrants detailed analysis of this signaling mechanism (62). Our recent experiments have shown that BAD phosphorylation induced by EGF is controlled by two parallel pathways. One pathway is mediated via Raf/MEK and another by Rac/PAK signaling.\textsuperscript{3}

In addition to EGF and PI3K signaling, BAD phosphorylation at Ser\textsuperscript{112} is induced by VIP. BAD phosphorylation at Ser\textsuperscript{112} is sufficient for binding to 14-3-3 protein and inhibition of the proapoptotic function of BAD. Furthermore, BAD phosphorylation at Ser\textsuperscript{112} is necessary for the antiapoptotic effect of VIP (Fig. 6). This effect of VIP is mediated by PKA, which is not activated by either PI3K or EGF in prostate cells (63).

In conclusion, PI3K, EGF, and VIP protect prostate cancer cells from apoptosis by independent signaling pathways that operate via Akt, Ras, and PKA and converge on BAD (Fig. 8). Thus, BAD plays the role of a signaling node that integrates diverse antiapoptotic signals in prostate cancer cells.

These results and the previous report on inactivation of BAD by serum-induced increase of Bcl-X\textsubscript{L} expression (64) uncover a remarkable redundancy of BAD regulation in prostate cancer cells.

Why are several pathways needed to control BAD activity when a single pathway is sufficient to inactivate it (particularly

\textsuperscript{3} K. S. R. Sastry, Y. Karpova, and G. Kulik, submitted for publication.
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in cells with inactive PTEN where PI3K signaling is constitutively “on”? One possible explanation is that cells maintain a delicate balance between dephosphorylated BAD and its antiapoptotic counterparts Bcl-XL and Bcl-2. Even a small excess of dephosphorylated BAD is sufficient to tilt this balance toward apoptosis. This idea is supported by experiments in Fig. 3E, which show that LNCaP cells can express BAD2SA with mutated phosphorylation sites only when expression of Bcl-XL is increased as well. The high proapoptotic potential makes BAD phosphorylation a critical determinant for the survival of prostate cancer cells. Thus, “backup” signaling mechanisms may become necessary when the dominant signal from PI3K is reduced.

A possible explanation for the high proapoptotic potential of BAD in LNCaP cells is that constitutive BAD phosphorylation in cells with increased PI3K activity removes the selection pressure from other antiapoptotic mechanisms that can neutralize dephosphorylated BAD. This makes PTEN-negative prostate cancer cells especially sensitive to apoptosis induced by phosphorylation-deficient BAD. In contrast, cells with normal PI3K signaling may better tolerate expression of dephosphorylated BAD.

Further research is needed to test whether BAD phosphorylation is as important for prostate tumor development in vivo as it is for the survival of prostate cancer cells in tissue culture. Analysis of BAD expression and phosphorylation in tumor samples from prostate cancer patients may be a first step in that direction.

There is ample evidence that supports the involvement of signaling pathways that control BAD phosphorylation in prostate tumorigenesis. In a significant proportion of prostate tumors, PI3K/Akt signaling is constitutively elevated due to mutations or inactivating mutations of the lipid phosphatase PTEN (10). Co-expression of EGFR and its ligand, transforming growth factor-α, has been observed in tissue sections of prostate cancer biopsies (23). Consistently, prostate-specific deletion of PTEN induces prostate cancer in mice and tyrosine kinase inhibitors of HER family suppress the growth of prostate xenografts (65, 66).

In addition to PI3K and EGFR signaling that were shown to control BAD phosphorylation in other tissues, we made a novel observation that VIP induces BAD phosphorylation in prostate cells. VIP is produced by neuroendocrine cells present in normal prostate and prostate tumors (30, 32). Normal prostate epithelial cells and prostate tumors express VPAC1 receptors that belong to the GPCR receptor superfamily and activate PKA (34). It is noteworthy that in advanced prostate tumors, the number of neuroendocrine cells is increased (67). Therefore, VIP/PKA signaling may play a role in maintaining BAD in a phosphorylated state in prostate cancer cells adjacent to neuroendocrine cells by a paracrine mechanism. In this manner, neuroendocrine cells may activate an alternative antiapoptotic mechanism that can support tumor growth in the presence of PI3K and EGFR inhibitors. Reports on synergism between inhibitors of PKA and EGFR kinases in prostate cells and colon tumor xenografts provide circumstantial evidence that support the significance of interaction between EGFR and PKA signaling (68, 69). It remains to be seen if BAD phosphorylation forms the basis for this synergism, as it was recently demonstrated for inducible expression of PTEN and EGFR inhibitor in breast cancer xenografts (59).

In summary, we have identified BAD as a convergence point of diverse antiapoptotic signaling pathways and demonstrated the key role of BAD in the regulation of apoptosis in prostate cancer cells in tissue culture. Future experiments are needed to determine whether a similar complexity of BAD regulation exists in prostate tumors in vivo. In this case, information about the signaling network that controls BAD phosphorylation will help to select an optimal combination of kinase inhibitors, whereas analysis of BAD phosphorylation status in tumors may be used to predict treatment outcome.

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