Role of α7 Nicotinic Acetylcholine Receptor in Calcium Signaling Induced by Prion Protein Interaction with Stress-inducible Protein 1*

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Flavio H. Beraldo1, Camila P. Arantes1, Tiago G. Santos1, Nicolle G. T. Queiroz1, Kirk Young*, R. Jane Rylett1, Regina P. Markus**, Marco A. M. Prado1,** and Vilma R. Martins1

From the 1Ludwig Institute for Cancer Research, Hospital Alemão Oswaldo Cruz, São Paulo 01323-903, Brazil, the 6Departamento de Bioquímica, Instituto de Química, Universidade de São Paulo, São Paulo 05508-900, Brazil, the 1Centro de Tratamento e Pesquisa do Hospital AC Camargo, São Paulo 01508-010, Brazil, the 3J. Allyn Taylor Centre for Cell Biology, Molecular Brain Research Group, Robarts Research Institute and Department of Physiology and Pharmacology, University Western Ontario, London, Ontario N6A 5K8, Canada, the 4Departamento de Fisiologia, Instituto de Biociências, Universidade de São Paulo, São Paulo 05508-090, Brazil, and the 58Department of Anatomy and Cell Biology, University Western Ontario, London, Ontario N6A 5K8, Canada

The prion protein (PrPC) is a conserved glycosylphosphatidylinositol-anchored cell surface protein expressed by neurons and other cells. Stress-inducible protein 1 (STI1) binds PrPC extracellularly, and this activated signaling complex promotes neuronal differentiation and neuroprotection via an intracellular signal-independent kinase 1 and 2 (ERK1/2) and PKA pathways. However, the mechanism by which the PrPC-STI1 interaction transduces extracellular signals to the intracellular environment is unknown. We found that in hippocampal neurons, STI1–PrPC engagement induces an increase in intracellular Ca2+ levels. This effect was not detected in PrPnull neurons or wild-type neurons treated with an STI1 mutant unable to bind PrPC. Using a best candidate approach to test for potential channel involvement in Ca2+ influx evoked by STI1–PrPC, we found that α-bungarotoxin, a specific inhibitor for α7 nicotinic acetylcholine receptor (α7nAChR), was able to block PrPC-STI1-mediated signaling, neuroprotection, and neuritogenesis. Importantly, when α7nAChR was transfected into HEK 293 cells, it formed a functional complex with PrP and allowed reconstitution of signaling by PrPC-STI1 interaction. These results indicate that STI1 can interact with the PrPC–α7nAChR complex to promote signaling and provide a novel potential target for modulation of the effects of prion protein in neurodegenerative diseases.

Prions are the infectious components of transmissible spongiform encephalopathies that can self-perpetuate by imprinting an anomalous conformation onto a glycosylphosphatidylinositol-anchored host protein known as the prion protein (PrPC). Conversion of PrPC to the protease-resistant prion is thought to be a major event in prion diseases (1). However, despite the wealth of knowledge on prions, the roles of PrPC on synaptic function and neuronal health are still not completely understood. Studies in yeast, mammalian cells, and mouse models support the hypothesis that PrP plays a major role in neuroprotection and neuronal differentiation (for review, see Refs. 1–3).

In humans, the initial cognitive dysfunction observed in transmissible spongiform encephalopathies is remarkably similar to those observed in Alzheimer disease (AD). Therefore, synaptic failure is likely to play a major role in the cognitive alterations seen in these neurological disorders (4). For instance, in AD, the role for Aβ ligands in synaptic dysfunction has received considerable attention (5, 6). Interestingly, recent work provided evidence that PrPC functions as a receptor for Aβ and that this interaction mediates some of the effects of Aβ oligomers in synaptic plasticity (7) although these results are controversial at the moment (8, 9). Moreover, PrPC seems to regulate the β-secretase cleavage of amyloid precursor protein, thereby regulating the production of Aβ (10). In addition, α-secretase regulates the cleavage of PrPC, generating an N-terminal fragment with neuroprotective activity (11, 12).

PrPC also binds to transmembrane proteins such as the 67-kDa laminin receptor (13–15), neuronal cell adhesion molecule (16, 17), G protein-coupled serotonergic receptors (18), and low density lipoprotein receptor-related protein 1 (19, 20), which are able to promote intracellular signaling-mediated neuronal adhesion and differentiation as well as PrPC internalization. Remarkably, PrPC functions as a receptor or co-receptor for extracellular matrix proteins such as laminin (21, 22) and

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1 To whom correspondence may be addressed: Robarts Research Institute, University Western Ontario, P.O. Box 5015, 100 Perth Dr., London, ON N6A 5K8, Canada. Tel.: 519-663-5777 (ext. 24888); E-mail: mprado@roberts.ca.

2 International Scholar of the Howard Hughes Medical Institute. To whom correspondence may be addressed: Ludwig Institute for Cancer Research, Rua João Julião 245 1A, São Paulo, SP 01323-903, Brazil. Tel.: 55-11-33883239; E-mail: vmartins@ludwig.org.br.

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vitronec (23), as well as the secreted co-chaperone stress-inducible protein 1 (STI1) (24). These data suggest that glycosylphosphatidylinositol-anchored PrPC is a potential scaffold receptor in a multiprotein, cell surface, signaling complex, that may be the basis for the multiple neuronal functions ascribed to PrPC (2, 3, 25).

We demonstrated previously that PrPC amino acids 113–128 constitute the STI1 binding site (24). Furthermore, PrPC–STI1 engagement rescues retinal and hippocampal neurons from staurosporine-induced programmed cell death through activation of protein kinase A (PKA). Additionally, PrPC–STI1 binding also induces the differentiation and protein synthesis in hippocampal neurons via extracellular signal-regulated kinase 1 and 2 (ERK1/2) and phosphoinositide 3-kinase (PI3K)–Akt–mTOR activation (26, 27). Trafficking of both PrPC and STI1 following binding at the membrane regulates the ERK1/2 pathway, but does not alter PrPC regulation of PKA signaling (28).

Although several signaling pathways triggered by PrPC have been identified, little is known regarding how intracellular signaling is activated by PrPC following its interaction with extracellular ligands. In this study we mapped the upstream signaling events triggered by PrPC–STI1 binding to identify the putative transmembrane protein responsible for connecting this extracellular complex to the intracellular milieu. Our data show that a transmembrane protein responsible for connecting this extracellular site to the intracellular milieu can activate ERK1/2 and phosphoinositide 3-kinase (PI3K)–Akt–mTOR. Additionally, PrPC–STI1 binding also induces the differentiation and protein synthesis in hippocampal neurons via extracellular signal-regulated kinase 1 and 2 (ERK1/2) and phosphoinositide 3-kinase (PI3K)–Akt–mTOR activation (26, 27). Trafficking of both PrPC and STI1 following binding at the membrane regulates the ERK1/2 pathway, but does not alter PrPC regulation of PKA signaling (28).

EXPERIMENTAL PROCEDURES

Reagents—Mouse recombinant STI1 (His6-STI1) and an STI1 deletion mutant lacking the PrPC binding site (STI1Δ230–245) were purified as described previously (24). The mitogen-activated protein kinase MAPK/ERK1/2 (p44/p42 MAPK) inhibitor 1,4-diamino-2,3-dicyano-1,4-bis (2-aminophenylthio)butadiene (U0126) was purchased from Promega. The PKA inhibitor KT5720, phosphodiesterase inhibitor isobutylmethylxanthine, and 4′-6-diamino-2-phenylindole (DAPI) were purchased from Calbiochem. The PKA activator (forskolin) was purchased from LC Laboratories (Woburn, MA). The L-type calcium channel blocker (nifedipine), Ca2+-ATPase inhibitor (thapsigargin, THG), FLAG beads, FLAG peptide, and anti-FLAG antibodies were obtained from Sigma-Aldrich. The Q-type Ca2+ channel blocker (ω-conotoxin MVII) was purchased from Calbiochem (San Diego, CA), neurobasal medium, Opti-MEM, Hanks’ buffered saline solution, and Lipofectamine were obtained from Invitrogen. Anti-phospho-ERK1/2 and anti-total ERK1/2 antibodies were purchased from Cell Signaling Technology (Beverly, MA), and peroxidase-coupled goat anti-rabbit secondary antibody and enhanced chemiluminescence (ECL) solution were obtained from GE Healthcare. Complete Protease Inhibitor Mixture was purchased from Roche Applied Science. The PKA assay system kit was purchased from Upstate Biotechnology. Anti-cleaved caspase-3, Alexa Fluor 488 anti-rabbit antibodies, and Alexa Fluor 647 anti-mouse antibodies were purchased from Molecular Probes. Immu-Mount was purchased from Thermo Scientific (Waltham, MA). The monoclonal antibodies 3F4 and 6H4 against PrPC were acquired from Abcam (Cambridge, MA) and Prionics (Schlieren, Switzerland).

Animals and Primary Neuronal Cultures—PrPC–null mice (Prnp0/0), descendants of the Zwchl line, were provided by Dr. Charles Weissmann (Scripps Florida). Wild-type animals were generated by crossing F1 descendants from 129/SV and C57BL/6J matings. All studies were conducted in accordance with National Institutes of Health guidelines for the care and use of animals and with animal protocols approved by the Institutional Animal Care and Use Committee.

Primary cultures of hippocampal neurons from embryonic day 17 (E17) wild-type (Prnp+/+) or PrPC–null mice (Prnp0/0) were obtained as previously described (26) and plated onto poly-L-lysine (5 μg/ml)–coated coverslips (35 mm) for 4 days.

Ca2+ Signaling and Data Analysis—Neurons and HEK 293 cells were loaded with 10 μM intracellular Ca2+ indicator Fluor-3 AM for 30 min at 37 °C in the presence of neurobasal medium or Opti-MEM supplemented with 2 mM CaCl2. Cells were washed three times with Hanks’ buffered saline solution and resuspended in Krebs buffer (124 mM NaCl, 4 mM KCl, 25 mM Hepes, 1 mM MgSO4, 10 mM glucose) supplemented with 2 mM CaCl2. Ca2+-free experiments were performed in Krebs buffer without CaCl2 plus 1 mM EGTA. Cells were preincubated (30 min) in the presence of 25 μM SKF-96365, voltage-gated calcium channel (VGCC) inhibitors (1 μM ω-conotoxin MVII plus 50 μM nifedipine) or 1 μM aBgt. Cells were treated with recombinant STI1 (1 μM for neurons and 2 μM for HEK 293), which mimics the effects of STI1 secreted from astrocytes (28, 29). HEK 293 cells were also pretreated with monoclonal antibodies against PrPC (6H4 and 3F4 both at 10 μg/ml) followed by recombinant STI1 (2 μM). In addition, recombinant STI1 deleted of the PrPC binding site, STI1Δ230–245 (2 μM) (26) was used in control experiments, and treatment with THG (1 μM) was performed to estimate calcium responses. Data acquisition was performed by confocal microscopy using either a Bio-Rad Radiance 2100/Nikon (TE2000U) or a Zeiss LSM 510 (Zeiss, Toronto, ON) with excitation at 488 nm (argon laser) and emission collected with bandpass filter at 522–535 nm. The fluorescence was normalized as F1/F0 (F1, maximal fluorescence after drug addition and F0, basal fluorescence before drug addition). Software-based analysis (WCIF ImageJ (National Institutes of Health)) allowed quantification of fluorescence imaging in selected cells as a function of time. Experiments were carried out with at least three different cell cultures, and 40–50 cells were monitored in each experiment. Traces represent typical single-cell responses.

ERK1/2 Activity—Primary hippocampal neurons (1 × 106 cells) from Prnp+/+ mice were plated on dishes pretreated with poly-L-lysine and stimulated with STI1 (350 nM) for 1 min (26) in the presence or absence of 2 mM CaCl2. Some cells were also preincubated with 1 nM aBgt for 30 min prior to STI1 treatment. Cells were rinsed with ice-cold phosphate-buffered saline (PBS) and lysed in Laemmli buffer. Cell extracts were...
subjected to SDS-PAGE (10%), and proteins were transferred onto nitrocellulose membranes. The membranes were blocked (5% milk, 0.1% Tween 20 in Tris-buffered saline) for 1 h at room temperature, incubated with anti-phospho-ERK1/2 or anti-total ERK1/2 antibodies (1:2,000) overnight at 4 °C, followed by incubation with peroxidase-coupled, goat anti-rabbit secondary antibody (1:2,000) for 1 h at room temperature. Reactions were developed using ECL solution, and the bands obtained after x-ray film exposure to the membranes were analyzed by densitometric scanning and quantified using ImageJ software. Alternatively, in some experiments, a CCD-based system was used (Alpha Innotech). ERK1/2 band densities were quantified as a relative value representing the ratio between phospho-ERK1/2 and total ERK1/2 for each sample. Results represent five independent experiments for neurons and three separate experiments for HEK 293 cells.

**PKA Activity**—Primary hippocampal neurons (1 × 10⁶ cells) were preincubated with 100 μM isobutylmethylxanthine for 1 h at 37 °C, followed by incubation with 1 μM STI1 in the presence or absence of extracellular CaCl₂ (2 mM) or forskolin (10 μM) for 20 min at 37 °C as a positive PKA signaling control. Cells were washed with cold PBS and homogenized in ice-cold extraction buffer (150 mM NaCl, 20 mM MgCl₂, 1% Triton X-100, and 25 mM Tris-HCl, pH 7.4), including Complete Protease Inhibitor mixture. Cellular debris was removed by centrifugation at 6,000 × g for 10 min. PKA activity was determined by [γ-³²P]ATP incorporation to a PKA-specific substrate provided by the PKA assay system kit.

**Neuritogenesis Assays**—Primary hippocampal neurons (4 × 10⁴) from wild-type (Prnp+/+) mice were treated with STI1 (350 nM) and incubated for 24 h at 37 °C. Neuritogenesis mediated by STI1 was evaluated after preincubation with 10 nM Bgt for 30 min. The cells were fixed with 4% paraformaldehyde and 0.12 M sucrose in PBS, pH 7.4, for 20 min at room temperature, washed three times with PBS, and stained with hematoxylin.

Morphometric analyses were performed using ImageJ software and the Neuron J plug in. The parameters analyzed were percentage of cells with neurites and percentage of neurons with neurites longer than 30 μm, which represents three or more times the average cell body. Approximately 200 cells were analyzed per sample.

**Cell Death Assay**—Primary hippocampal cultures (7 × 10⁴ cells) were treated with STI1 (1.2 μM) for 1 h, followed by staurosporine (50 nM) treatment for 16 h as described previously (26). Alternatively, Bgt (10 nM) was added to the cultures 30 min prior to incubation with STI1. Cells were then fixed with 4% paraformaldehyde and 0.12 M sucrose in PBS, pH 7.4, for 20 min, and immunofluorescence reactions were performed to detect cleaved caspase-3. Briefly, cells were permeabilized and blocked with PBS/0.2% Triton X-100 plus 5% BSA for 1 h and subsequently incubated with anti-cleaved caspase-3 primary antibody (1:200) diluted in PBS/0.2% Triton X-100 plus 1% BSA for 2 h. After rinsing with PBS, cells were incubated with Alexa Fluor 488 anti-rabbit antibody and DAPI for 1 h. Immunolabeled cells were imaged with a BX61 Olympus Fluorescence microscope. Cell death induced by staurosporine was addressed by counting the percentage of cleaved caspase-3-positive cells. Results represent three independent experiments; at least 300 cells total were counted per condition.

**DNA Constructs**—The cDNA encoding the human α7nAChR subunit was cloned from a human universal QUICK-Clone cDNA library (Clontech) using the forward primer, 5’-CGAAGGCGAGACTGGCTGA-3’ and reverse primer, 5’-TGATGCAGTACTGGAGTAT-3’. 100 μl of FLAG beads for 1 h at 4 °C. Beads were washed three times with wash buffer (50 mM Tris-HCl, pH 7.5, 150 mM NaCl, and 1% Triton X-100, plus protease inhibitors for 15 min on ice, followed by two sonication pulses. Protein extracts (800 μg) were incubated with 20 μl of FLAG beads for 16 h at 4 °C. Beads were washed three times with wash buffer (50 mM Tris-HCl, pH 7.5, 150 mM NaCl, pH 7.4, and proteins were eluted by incubating the beads with 15 μg of FLAG peptide (in 100 μl of 50 mM Tris-HCl, pH 7.4, and 150 mM NaCl) for 10 min at room temperature. One quarter of the eluate was resolved by 4–12% SDS-PAGE, followed by immunoblotting.
PrP<sup>C</sup>-STI1 interaction promotes intracellular Ca<sup>2+</sup> influx. A and B, Prnp<sup>+/+</sup> (A) or Prnp<sup>0/0</sup> (B) hippocampal neurons loaded with Fluo-3 AM were treated with STI1 (1 μM) in medium supplemented with (solid lines) or without (dashed line) Ca<sup>2+</sup>. THG-treated Prnp<sup>0/0</sup> neurons show normal levels of intracellular Ca<sup>2+</sup> stores. C, Prnp<sup>+/+</sup> neurons were treated with an STI1 deletion mutant, STI1Δ230–245, lacking the PrP<sup>C</sup> binding site. D, relative intracellular Ca<sup>2+</sup> levels in Prnp<sup>0/0</sup> (white bars) and Prnp<sup>+/+</sup> (black bars) neurons treated with STI1 or STI1Δ230–245 in the presence or absence of CaCl<sub>2</sub> are indicated. The results represent the mean ± S.E. (error bars) of four independent experiments, and statistical significance was determined by one-way ANOVA and Newman-Keuls post test, *p < 0.05 compared with controls.

PrP<sup>C</sup>-STI1 Interaction Increases Intracellular Ca<sup>2+</sup>—We demonstrated previously that PrP<sup>C</sup>-STI1 engagement resulted in ERK1/2 phosphorylation and PKA activation, which in turn promoted neuritogenesis and neuroprotection, respectively (26). Ca<sup>2+</sup> signaling is an early event upstream of both PKA and ERK1/2 activation (32, 33). In addition, PrP<sup>C</sup> has consistently been shown to modulate Ca<sup>2+</sup> signaling (34–36). Therefore, to determine whether STI1 interaction with PrP<sup>C</sup> affects intracellular Ca<sup>2+</sup> levels, we performed Ca<sup>2+</sup> imaging experiments on cultured hippocampal neurons using Fluo-3 AM. STI1 treatment promoted intracellular Ca<sup>2+</sup> increases in neurons derived from Prnp<sup>+/+</sup> mice (Fig. 1, A and D), but no effect was observed in neurons from Prnp<sup>0/0</sup> mice (Fig. 1, B and D). However, treatment with THG, a blocker of the endoplasmic reticulum Ca<sup>2+</sup>-ATPase, mobilized the release of intracellular Ca<sup>2+</sup> stores (Fig. 1B), suggesting that these stores were available in Prnp<sup>0/0</sup> neurons. Consistent with these observations, intracellular Ca<sup>2+</sup> levels remained unchanged in hippocampal neurons treated with anti-FLAG antibodies. The remaining eluate was resolved with a second 4–12% SDS-PAGE, followed by immunoblotting with anti-PrP<sup>C</sup> (3F4). These experiments were repeated four times.

Statistical Analysis—The statistical analyses were performed using GraphPad Prism 4. Results are represented as means ± S.E., and the total number of experiments is specified in each figure legend. Data were compared by one-way ANOVA and Newman-Keuls post test.

RESULTS

PrP<sup>C</sup>-STI1 Interaction Increases Intracellular Ca<sup>2+</sup>—We demonstrated previously that PrP<sup>C</sup>-STI1 engagement resulted in ERK1/2 phosphorylation and PKA activation, which in turn promoted neuritogenesis and neuroprotection, respectively (26). Ca<sup>2+</sup> signaling is an early event upstream of both PKA and ERK1/2 activation (32, 33). In addition, PrP<sup>C</sup> has consistently been shown to modulate Ca<sup>2+</sup> signaling (34–36). Therefore, to determine whether STI1 interaction with PrP<sup>C</sup> affects intracellular Ca<sup>2+</sup> levels, we performed Ca<sup>2+</sup> imaging experiments on cultured hippocampal neurons using Fluo-3 AM. STI1 treatment promoted intracellular Ca<sup>2+</sup> increases in neurons derived from Prnp<sup>+/+</sup> mice (Fig. 1, A and D), but no effect was observed in neurons from Prnp<sup>0/0</sup> mice (Fig. 1, B and D). However, treatment with THG, a blocker of the endoplasmic reticulum Ca<sup>2+</sup>-ATPase, mobilized the release of intracellular Ca<sup>2+</sup> stores (Fig. 1B), suggesting that these stores were available in Prnp<sup>0/0</sup> neurons. Consistent with these observations, intracellular Ca<sup>2+</sup> levels remained unchanged in hippocampal neurons treated with a mutant STI1 missing the PrP<sup>C</sup> binding site (STI1Δ230–245) (Fig. 1, C and D). Interestingly, when Ca<sup>2+</sup> was removed from the extracellular medium, STI1 had no effect on intracellular Ca<sup>2+</sup> levels (Fig. 1, A and D). These results suggest that PrP<sup>C</sup>-STI1 engagement can activate Ca<sup>2+</sup> influx.

Ca<sup>2+</sup> Influx Induced by PrP<sup>C</sup>-STI1 Interaction Promotes ERK1/2 and PKA Activation—The effect of PrP<sup>C</sup>-STI1-mediated Ca<sup>2+</sup> influx on ERK1/2 and PKA activation was tested in wild-type neuronal cultures. In the presence of extracellular Ca<sup>2+</sup>, STI1 treatment increased both PKA and ERK1/2 activation (Fig. 2). Forskolin, which activates adenyl cyclase and increases intracellular levels of cAMP, was used as a positive control for PKA activation (Fig. 2A). Conversely, no effect was observed when cells were treated with STI1 in the absence of cAMP.
extracellular Ca\(^{2+}\) (Fig. 2). Thus, upstream Ca\(^{2+}\) signaling is required for PrP\(^C\)-STI1-mediated ERK1/2 and PKA activation.

PrP\(^C\)-STI1 Interaction Induces Ca\(^{2+}\) Influx through \(\alpha7nAChR\) —The PrP\(^C\)-STI1 interaction likely induces Ca\(^{2+}\) influx via modulation of an unidentified Ca\(^{2+}\) channel at the plasma membrane. Transmembrane Ca\(^{2+}\) channels include VGCCs and several ligand-gated channels. To determine the Ca\(^{2+}\) channel responsible for PrP\(^C\)-STI1-mediated Ca\(^{2+}\) influx, we used a best candidate approach. To ascertain the role of VGCCs in this response, we used a VGCC inhibitor mixture (ω-conotoxin MCVIIC and nifedipine) targeting the majority of neuronal Ca\(^{2+}\) channels, including Ca\(_{2.1}\), Ca\(_{2.2}\), Ca\(_{1.1}\), Ca\(_{1.2}\), and Ca\(_{1.3}\). Hippocampal neurons still exhibited Ca\(^{2+}\) influx upon STI1 treatment in the presence of VGCC inhibitors (Fig. 3A), although Ca\(^{2+}\) influx due to KCl depolarization was blunted (data not shown).

To determine which ligand-gated channel might transduce PrP\(^C\)-STI1-mediated Ca\(^{2+}\) influx, modulators of transient receptor potential channels and several neurotransmitter receptors (data not shown) were utilized. One candidate, the \(\alpha7nAChR\), has been shown to activate PKA and ERK1/2 (37) and to promote neuronal differentiation and survival (38–40). In the presence of the \(\alpha7nAChR\)-specific inhibitor αBgt, the PrP\(^C\)-STI1-mediated intracellular Ca\(^{2+}\) influx was abolished (Fig. 3B). Moreover, PKA activation (Fig. 3C) and ERK1/2 phosphorylation (Fig. 3D) were completely blocked in the presence of αBgt. These data show that STI1 binding to PrP\(^C\) induces intracellular Ca\(^{2+}\) influx via modulation of \(\alpha7nAChR\), leading to ERK1/2 and PKA activation.

To verify whether \(\alpha7nAChR\) can be modulated by PrP\(^C\)-STI1, we used HEK 293 cells, which do not express endogenous \(\alpha7nAChR\), to reconstitute the expression of these receptors. HEK 293 cells were transfected with plasmid vectors encoding PrP\(^C\), \(\alpha7nAChR\), or \(\alpha7nAChR\) and RIC3 a chaperone that is required for correct assembly of this receptor at the cell surface (41). The functional expression of \(\alpha7nAChR\) at the cell surface was confirmed by binding of fluorescent αBgt only upon its co-expression with RIC3 (Fig. 4A).

Co-immunoprecipitation experiments using anti-FLAG antibodies against FLAG-tagged \(\alpha7nAChR\), followed by immunoblotting using anti-3F4 antibodies toward 3F4-tagged mouse PrP\(^C\) (28) or anti-FLAG antibodies, demonstrated that PrP\(^C\) physically interacts with \(\alpha7nAChR\) in these cells (Fig. 4B). To further test whether heterologous expression of \(\alpha7nAChR\) was able to reconstitute PrP\(^C\)-STI1-mediated Ca\(^{2+}\) signaling, we performed signaling experiments in HEK 293 cells. When these cells were transfected with empty vector (Fig. 5A), or with the vector encoding PrP\(^C\) alone (Fig. 5B), STI1 treatment did not induce an increase in the level of intracellular Ca\(^{2+}\). Similar results were observed in cells transfected only with \(\alpha7nAChR\) (Fig. 5C), likely due to the absence of RIC3. However, when HEK 293 cells were co-transfected with vectors encoding \(\alpha7nAChR\), RIC3, and PrP\(^C\), STI1 was able to increase intracellular Ca\(^{2+}\) (Fig. 5E). Interestingly, even in cells transfected only with \(\alpha7nAChR/RIC3\), STI1 was able to evoke a Ca\(^{2+}\) signal although this effect could be blocked by antibodies against PrP\(^C\) (3F4 and 6H4) (Fig. 5D). In addition, STI1 deleted of the PrP\(^C\) binding site (STI1Δ230–245) was unable to induce Ca\(^{2+}\) signaling (Fig. 5F). These results indicate that endogenous levels of PrP\(^C\) expression in HEK 293 cells are sufficient to promote Ca\(^{2+}\) signaling when \(\alpha7nAChR\) is present. These data are quantified in Fig. 5G.

PrP\(^C\)-STI1 Interaction Induces PKA and ERK1/2 Activation through \(\alpha7nAChR\) —We also found that STI1 induced both PKA activation (Fig. 6A) and ERK1/2 phosphorylation (Fig. 6B) in HEK 293 cells transfected with both \(\alpha7nAChR\) and RIC3. Conversely, activation of PKA or ERK1/2 was not observed upon STI1 treatment when these cells were trans-
fected with empty vector or α7nAChR alone (Fig. 6 and data not shown).

**PrPC-STI1 Interaction Induces Neuroprotection and Neuritogenesis through α7nAChR**—To determine whether STI1-PrPC-mediated neuroprotection and neuritogenesis were also dependent on α7nAChR, we analyzed activated caspase-3 levels and neurite outgrowth in hippocampal neurons. In primary neuronal cultures, staurosporine-induced cell death was blocked by STI1 treatment, and this was reversed by preincubation with αBgt (Fig. 7A). In addition, the treatment of hippocampal neurons with αBgt blocked PrPC-STI1-mediated neuritogenesis, as measured by the percentage of cells with neurites (Fig. 7B) or the percentage of cells with neurite length >30 μm (Fig. 7C). Taken together, these data indicate that the PrPC-STI1 interaction modulates α7nAChR activity, thereby inducing Ca^{2+} influx and PKA and ERK1/2 activation and ultimately promoting neuronal protection and differentiation.

**DISCUSSION**

In this study, we demonstrate that PrPC binding to STI1 increases Ca^{2+} influx in neurons through α7nAChR. These results provide new insight into the physiological role of PrPC as well as a novel mechanism by which PrPC transduces extracellular signals.

The PrPC-STI1 interaction has been shown to modulate neuronal differentiation and survival. Furthermore, these activities are dependent on activation of PKA, ERK1/2, and PI3K–mTOR via PrPC (26, 27). STI1 is secreted from astrocytes (29), and its
activity is 100 times higher than recombinant STI1, probably due to a better folding or posttranslational modifications (28). The mechanisms associated with STI1 secretion are presently under investigation, but the protein is likely to use a nonconventional type of secretion due to the absence of a signal peptide (42). However, it is clear that secreted STI1 binds to PrPC, potentially acting as a neurotrophic-like factor (25). Interestingly, hippocampal infusion of STI1 or an STI1-derived peptide (STI1pep230–245), which mimics the PrPC binding site, increases PrP<sup>C</sup>-dependent memory consolidation. On the other hand, antibodies against either STI1 or its peptide 230–245 were able to impair memory formation (43). These results indicate that the STI1-PrP<sup>C</sup> interaction has physiological consequences in vivo.

PrP<sup>C</sup> appears to act as a receptor or co-receptor for a number of ligands, including transmembrane, aggregated and soluble proteins. Therefore, it is important to dissect the mechanisms by which glycosylphosphatidylinositol-anchored PrP<sup>C</sup> is able to transduce extracellular signals to the intracellular milieu. Previously, PrP<sup>C</sup> has been shown to interact with neuronal cell adhesion molecule to stimulate Fyn-kinase (17). Furthermore, PrP<sup>C</sup> has also been shown to associate with G protein-coupled serotonergic receptors, interfering with the intensities and/or dynamics of G protein activation by agonist-bound 5-HT receptors (18, 44). PrP<sup>C</sup> also acts as a receptor for Aβ<sub>1–42</sub> oligomers to inhibit synaptic plasticity in the form of long term potentiation (7). In addition, PrP<sup>B</sup> interacts with the γ2 subunit of the extracellular matrix protein laminin (21). Our recent data demonstrate that laminin γ1 chain interaction with PrP<sup>C</sup> triggers neuronal signaling via group I metabotropic glutamate receptors, and regulates intracellular Ca<sup>2+</sup> levels and neuritogenesis (62).

**STI1 Activates α7nAChR and Ca<sup>2+</sup>-dependent Signaling Pathways**—Our data strongly indicate that STI1 activation of Ca<sup>2+</sup> influx is dependent on its engagement with PrP<sup>C</sup>, as neurons from PrP<sup>C</sup>-null mice do not respond to STI1. Moreover, in

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**FIGURE 6.** Expression of α7nAChR in HEK 293 cells rescues PrP<sup>C</sup>-STI1-induced PKA activity and ERK1/2 phosphorylation. PKA activity (A) and ERK1/2 phosphorylation (B) in HEK 293 cells transfected with empty vector or co-transfected with expression vectors for α7nAChR and RIC3. Cells were treated with forskolin, STI1, or choline chloride as indicated. Relative levels of ERK1/2 activity represent the ratio between phosphorylated ERK1/2 and total ERK1/2 (upper panel) in cells treated with STI1 and normalized to cells transfected with empty vector. The results represent the mean ± S.E. (error bars) of three independent experiments compared by one-way ANOVA and Newman-Keuls post test. *, p < 0.01 compared with controls.

**FIGURE 7.** PrP<sup>C</sup>-STI1 interaction promotes neuroprotection and neuritogenesis through α7nAChR. A, Prnp<sup>−/−</sup> hippocampal neurons were treated with STI1 (30 min) or STI1 and αBgt, followed by staurosporine, as indicated. Cells were immunolabeled with anti-activated caspase-3, which labels apoptotic cells. Data are represented as the percentage of activated caspase-3-positive cells. B and C, Prnp<sup>−/−</sup> hippocampal neurons were treated with STI1 alone, or STI1 plus αBgt, as indicated, and neuritogenesis was measured as the percentage of cells with neurites or with neurites >30 μm, respectively. The results represent the mean ± S.E. (error bars) of three independent experiments, compared by one-way ANOVA and Newman-Keuls post test. *, p < 0.01 compared with controls.
wild-type cultured hippocampal neurons, Ca\(^{2+}\) influx fails in the presence of STI1 lacking the PrP\(^C\) binding site.

The inhibition of STI1-evoked Ca\(^{2+}\) influx, ERK1/2 phosphorylation, and PKA activation in A\(\beta\)t-treated neurons is consistent with the fact that STI1 can modulate \(\alpha7\)nAChR via PrP\(^C\). Moreover, the fact that STI1-mediated signaling is reconstituted in transfected HEK 293 cells supports the idea of a functional interaction between PrP\(^C\) and \(\alpha7\)nAChR. Indeed, we detected a physical interaction between PrP\(^C\) and \(\alpha7\)nAChR.

The mechanisms by which STI1 modulates \(\alpha7\)nAChR activity through its interaction with PrP\(^C\) are unknown. For instance, it is unclear whether STI1 and PrP\(^C\) act together to activate \(\alpha7\)nAChR, or whether they modulate \(\alpha7\)nAChR sensitivity to agonists. It should be noted that choline, a proposed \(\alpha7\)nAChR agonist (45), is normally found in the extracellular milieu, albeit at a concentration too low to activate \(\alpha7\)nAChR (45). Hence, it is possible that STI1-PrP\(^C\) engagement modulates the response of \(\alpha7\)nAChR to extracellular choline. Further experiments using electrophysiology techniques will be necessary to refine possible mechanisms.

Remarkably, the effects of STI1 on neuritogenesis and protection against stauroporine-induced neuronal cell death were also completely blocked by A\(\beta\)t. Extensive studies have shown that \(\alpha7\)nAChR regulates many brain functions (45). These receptors are formed by homomeric assembly of five subunits and are preferentially permeable to Ca\(^{2+}\) (45). Furthermore, \(\alpha7\)nAChR activation has been shown to be neuroprotective (46–48) and to regulate learning and memory (for review, see Ref. 49) in an ERK1/2- and PKA-dependent manner (50).

The \(\alpha7\)nAChR has also been implicated in AD (51–54), as expression of these receptors is either decreased or increased in AD brains (55, 56) and animal models of AD (57). Furthermore, there is evidence that \(\alpha7\)nAChR interacts with A\(\beta\)\(_{1-42}\) oligomers (58, 59). Moreover, recent experiments involving \(\alpha7\)nAChR knock-out mice crossed with transgenic mice expressing mutated amyloid precursor protein suggest that the synaptic toxicity observed in the latter may be due in part to \(\alpha7\)nAChR (60). On the other hand, experiments using a separate transgenic mouse model for AD indicate that these receptors may be protective at early ages. Interestingly, drugs that prevent binding of A\(\beta\)\(_{1-42}\) to \(\alpha7\)nAChR seem to be beneficial in a model of AD (58). Hence, it seems that STI1 binding to PrP\(^C\) can hijack one of the key signaling pathways related to AD and learning and memory. Therefore, it is possible that STI1 modulation of a complex containing PrP\(^C\) and \(\alpha7\)nAChR may play an important role in AD.

Little is known regarding the role of nAChRs in prion diseases. Recent data demonstrated that PrP\(^C\) is co-localized with the \(\beta4\) subunit of nAChR in the brain and gastrointestinal tract. However, infection experiments using the Rocky Mountain Laboratory prion strain in \(\beta4\)nAChR knock-out mice demonstrated that these animals presented with the same disease incubation period when compared with controls (61).

In summary, we show that STI1 interaction with PrP\(^C\) can modulate Ca\(^{2+}\) influx via \(\alpha7\)nAChR, thereby promoting neuronal survival and differentiation (Fig. 8). Future experiments will need to define the mechanisms involved in PrP\(^C\) modulation of \(\alpha7\)nAChR as well as the pathophysiological roles of this new signaling complex in prion diseases and AD.

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