Role of glycosylphosphatidylinositol s in the activation of phospholipase A2 and the neurotoxicity of prions

Clive Bate1 and Alun Williams2

1Department of Veterinary Pathology, Glasgow University Veterinary School, Bearsden Road, Glasgow G61 1QH, UK
2Department of Pathology and Infectious Diseases, Royal Veterinary College, Hawkshead Lane, North Mymms, Herts AL9 7TA, UK

Prion-induced neuronal injury in vivo is associated with prostaglandin E2 production, a process that can be reproduced in tissue-culture models of prion disease. In the present study, neuronal phospholipase A2 was activated by glycosylphosphatidylinositol s (GPIs) isolated from the cellular prion protein (PrPc) or from disease-associated isoforms (PrPSc), resulting in prostaglandin E2 production, but not by GPIs isolated from Thy-1. The ability of GPIs to activate neuronal phospholipase A2 was lost following the removal of acyl chains or cleavage of the phosphatidylinositol–glycan linkage, and was inhibited by a mAb that recognized phosphatidylinositol. In competition assays, pretreatment of neurons with partial GPIs, inositol monophosphate or sialic acid reduced the production of prostaglandin E2 in response to a synthetic miniprion (sPrP106), a synthetic correlate of a PrPSc species found in Gerstmann–Sträussler–Scheinker disease (HuPrP82–146), prion preparations or high concentrations of PrP-GPIs. In addition, neurons treated with inositol monophosphate or sialic acid were resistant to the otherwise toxic effects of sPrP106, HuPrP82–146 or prion preparations. This protective effect was selective, as inositol monophosphate- or sialic acid-treated neurons remained susceptible to the toxicity of arachidonic acid or platelet-activating factor. Addition of PrP-GPIs to cortical neuronal cultures increased caspase-3 activity, a marker of apoptosis that is elevated in prion diseases. In contrast, treatment of such cultures with inositol monophosphate or sialic acid greatly reduced sPrP106-induced caspase-3 activity and, in co-cultures, reduced the killing of sPrP106-treated neurons by microglia. These results implicate phospholipase A2 activation by PrP-GPIs as an early event in prion-induced neurodegeneration.

INTRODUCTION

The transmissible spongiform encephalopathies (TSEs) or prion diseases are fatal, neurodegenerative disorders that include Creutzfeldt–Jakob disease (CJD) in man, bovine spongiform encephalopathy in cattle and scrapie in sheep and goats. They are thought to develop following the conversion of a normal host protein, designated PrPc, into disease-associated isoforms, PrPSc (Prusiner, 1998). This process results in a profound change in the biochemical properties of the PrP protein, such that the α-helical structure of PrPc is converted to the β-sheet-rich forms of PrPSc (Pan et al., 1993). This conformational change also confers partial resistance to digestion with proteinase K, a property that defines disease-associated PrPSc from the normal cellular PrPc isoform (Prusiner, 1982). The subsequent accumulation of insoluble, fibrillar aggregates of PrPSc is thought to lead to neuronal dysfunction, degeneration (Williams et al., 1997a; Jeffrey et al., 2000) and death via caspase-3-associated apoptosis (Giese et al., 1995; Jamieson et al., 2001).

The cellular mechanisms leading to neuronal death can be studied in tissue-culture systems to determine the functional significance of in vivo observations. Thus, neuronal culture systems developed to investigate interactions between prions and neurons have demonstrated that synthetic peptides derived from the prion protein are neurotoxic (Forloni et al., 1993; Salmona et al., 2003), provided that the peptides contain substantial β-sheet content (Hope et al., 1996). One of the important events leading to the degeneration of cultured neurons following the addition of toxic PrP peptides is the activation of phospholipase A2 (PLA2) and the subsequent metabolism of arachidonic acid to prostaglandins (PGs) by the cyclo-oxygenases (COXs) (Bate et al., 2004b). This observation is consistent with observations that levels of PGE2 are raised in brain areas showing neuronal death in murine scrapie (Williams et al.,
1994, 1997b) and that raised levels of PGE2 are detected in the cerebrospinal fluid of patients with CJD (Minghetti et al., 2000, 2002). However, little is known about the processes by which prions or neurotoxic PrP peptides activate PLA2.

Cellular PrPSc is required for the process by which PrP peptides induce apoptosis (Brown et al., 1994), suggesting that there are specific interactions between PrP peptides, PrPSc, PLA2, and apoptotic pathways. Most PrPSc molecules are linked to membranes via a glycosylphosphatidylinositol (GPI) anchor (Stahl et al., 1992); the presence of the GPI anchor affects the properties of PrPSc (Taraboulos et al., 1995). GPI anchors contain a conserved core that consists of ethanolamine phosphate in an amide linkage to the carboxyl terminus of the protein, three mannose residues, glucosamine and phosphatidylinositol (Mayor & Riezman, 2004). However, many variations on this core structure are possible and the GPIs isolated from PrPSc in hamster brains contain high amounts of galactose, mannose and sialic acid (Stahl et al., 1992). We therefore investigated the ability of GPIs extracted from both PrPSc and PrPSc, obtained from uninfected and infected cells of a murine neuroblastoma cell line, and GPIs extracted from Thy-1 to activate PLA2, as measured by the induction of PGE2. We also examined the ability of GPIs from these sources to induce caspase-3 activity in primary cultures of cortical neurons, as this enzyme is known to be involved in apoptotic cell death. To determine which moiety of the GPI molecules was responsible for the effects observed in each case, the inhibitory effect of some GPI-related molecules on the induction of PGE2 and on the neuronal toxicity of PrP peptides was investigated.

METHODS

Cell lines. Murine neuroblastoma NB4-1A3 cells were grown in neurobasal medium supplemented with 2 mM glutamine, 100 U penicillin ml-1, 100 μg streptomycin ml-1 and 1 % B27 components (Invitrogen). Uninfected N2a neuroblastoma cells and prion-infected ScN2a cells were grown in Hams F12 medium containing 2 mM glutamine, 200 nM retinoic acid, 5 % fetal calf serum (FCS), 100 U penicillin ml-1 and 100 μg streptomycin ml-1. NB4-1A3 cells were plated into 96-well plates at 5 x 104 cells per well and allowed to adhere overnight. The following day, cells were pretreated with test compounds for 3 h before addition of PrP peptides or prion preparations for a further 24 h. Cell survival was determined by treating cultures with WST-1 (Roche Diagnostics); percentage cell survival was calculated by reference to untreated cells incubated with WST-1 (100 %). PLA2 activity was determined by measuring PGE2 in NB4-1A3 cells plated in 24-well plates at 5 x 105 cells per well that had adhered overnight. Cells were then treated with test compounds for 3 h before the addition of PrP peptides or prion preparations. After a further 24 h, total PGE2 levels were determined by using a competitive enzyme immunoassay kit (Amersham Biosciences) according to the manufacturer’s instructions. All experiments were performed in triplicate with each of three separate batches of GPI preparations.

Primary neuronal cultures. Primary cortical neurons were prepared from the brains of mouse embryos as described previously (Bate et al., 2002) and plated in 48-well plates at 2 x 104 cells per well. Cultures were pretreated with test compounds for 3 h before the addition of PrP peptides. Caspase-3 activity was measured 24 h later by using a fluorometric immunosensor enzyme assay kit according to the manufacturer’s instructions (Roche Diagnostics). For cell-survival assays, microglia [prepared by dissociating the cerebral cortices of newborn mice, as described previously (Bate et al., 2002)] were added to peptide-treated neurons in the ratio of 1 microglial cell: 10 neurons. After 4 days, microglia were removed by shaking (260 r.p.m for 30 min) and survival of neurons was determined by treating cultures with WST-1.

Prion peptides. The toxic peptide HuPrP(R2–146), containing aa 82–146 of the human prion protein found in Gerstmann–Sträussler–Scheinker disease (Salmona et al., 2003), and the synthetic miniprion sPrP106 derived from the murine PrP sequence were synthesized by solid-phase chemistry and purified by reverse-phase HPLC (Bonetto et al., 2002).

Prion preparations. PrP molecules resistant to limited protease digestion (10 μg proteinase K ml-1 for 1 h at 37 °C) were partially purified by reverse-phase chromatography on a C18 Sep-Pak column (Waters) and quantified by a PrP-specific ELISA, as described previously (Bate et al., 2004a).

Reagents. Phosphatidylinositol, inositol monophosphate, inositol, inositol-1,4-bisphosphate, inositol-1,4,5-trisphosphate, arachidonic acid, platelet-activating factor (PAF), hydrogen peroxide, mannose, glucosamine, galactose, sialic acid (N-acetylsperguraminic acid) and staurosporine were obtained from Sigma.

Isolation of GPI anchors. GPIs were isolated from uninfected N2a cells that were lysed in water, passed through a 26-gauge needle to solubilize cellular debris and centrifuged (10 min at 14 000 g). Insoluble material was suspended in a buffer containing 10 mM Tris/HCl, 100 mM NaCl, 10 mM EDTA, 0-5 % Nonidet P-40, 0-5 % sodium deoxycholate and 2 mM PMSF, pH 7-2. PrPSc was immunoprecipitated following the addition of mAb SAF53 (a gift from Professor J. Grassi, CEA, Saclay, France) and protein G–agarose (Sigma). A sample of immunoprecipitated PrPSc was retained for analysis by Western blot. The depleted lysate was subsequently incubated with an anti-Thy-1 mAb (Serotech) and protein G–agarose and immunoprecipitated. Precipitates were washed five times with PBS containing 0-02 % Tween 20, suspended in PBS containing 100 μg proteinase K ml-1 and digested at 37 °C for 24 h to release GPIs. Insoluble material was collected by centrifugation at 14 000 g and the pellet was washed five times with water. The released GPIs were extracted with water-saturated butan-1-ol, washed with water, split into two and lyophilized. One sample was dissolved in ethanol at 2 μg ml-1 and applied to silica gel 60 high-performance TLC (HPTLC) plates (Whatman) for analysis; the other sample was dissolved in tissue-culture medium for bioassays. Controls were prepared by incubating mAb SAF53 in buffer (in the absence of cellular lysates) and protein G–agarose. Control preparations were treated as above.

Isolation of PrPSc-GPI. GPIs were also isolated from prion-infected ScN2a cells that were lysed in water and treated as described above before solubilization in extraction buffer that did not contain PMSF. As ScN2a cells contain both PrPSc and PrPsc, cell lysates were digested with 10 μg proteinase K ml-1 for 1 h at 37 °C to remove PrPsc. Digestion was stopped with 5 mM PMSF and prionase-resistant PrPSc was immunoprecipitated with mAb SAF53 and protein G–agarose. After extensive washing, immunoprecipitated PrPSc was split into two samples. One sample was retained for Western blot analysis, whilst the other was further digested with 100 μg proteinase K ml-1 at 37 °C for 24 h to release the GPIs. GPIs were subsequently extracted with water-saturated butan-1-ol, as described above.

Western blotting. Samples were dissolved in 50 μl Laemmli buffer (Bio-Rad), boiled and subjected to electrophoresis on a 15 % polyacrylamide gel. Proteins were transferred onto a Hybond-P PVDF membrane and blocked with 5 % BSA before incubation with mAb SAF53. Blots were washed and probed with a secondary antibody labeled with horseradish peroxidase and developed with ECL. A standard curve was always included to allow quantification.

Reagents. Phosphatidylinositol, inositol monophosphate, inositol, inositol-1,4-bisphosphate, inositol-1,4,5-trisphosphate, arachidonic acid, platelet-activating factor (PAF), hydrogen peroxide, mannose, glucosamine, galactose, sialic acid (N-acetylsperguraminic acid) and staurosporine were obtained from Sigma.
membrane (Amersham Biosciences) by semi-dry blotting. Membranes were blocked by using 10% milk powder in Tris-buffered saline, pH 7.2, containing 0.2% Tween 20. PrP was detected by incubation with mAb SAF53, followed by a secondary anti-mouse IgG conjugated to peroxidase. Bound antibody was visualized by using an enhanced chemiluminescence kit (Amersham Biosciences).

**TLC immunoblotting.** Extracted GPIs were examined by HPTLC on silica gel 60 HPTLC plates by using a mixture of chloroform/methanol/water (10:10:2 by volume). Plates were soaked in 0.1% poly(isobutylmethacrylate) in hexane, dried and blocked with PBS containing 5% milk powder. They were probed with 1 µg mAb 5AB3-11 [which binds to phosphatidylinositol (Rate & Kwiatkowski, 1994)], washed with PBS/Tween and incubated with goat anti-mouse IgG conjugated to peroxidase (Sigma) for 1 h. Bound antibody was washed and visualized by using an enhanced chemiluminescence kit (Amersham Biosciences).

**Chemical manipulation of GPIs.** To remove acyl chains from GPIs (deacylation), extracted GPIs (2 µg ml⁻¹) were treated with 0.05 M NaOH at 60 °C for 2 h and the reaction mixture was then neutralized. Extracted GPIs (2 µg ml⁻¹) were also deaminated by treatment with a mixture containing 0.1 M sodium acetate, pH 3.8, and 0.5 M sodium nitrite (NaNO₂) at room temperature for 24 h, after which time the reaction mixture was neutralized.

**Statistical analysis.** Results were compared by using one- and two-way analysis of variance techniques as appropriate. Statistical significance was set at the 1% level.

**RESULTS**

**Induction of PGE2 by GPIs associated with PrP<sup>c</sup> and PrP<sup>Sc</sup>**

Neuronal death induced by prions or PrP peptides is accompanied by increased PGE₂ production, a marker of the activity of the PLA₂/COX pathway (Bate et al., 2004b). Similarly, overnight incubation of NB4-1A3 neuroblastoma cells with GPIs extracted from N2a cells (PrP<sup>c</sup>-GPI) or from ScN2a cells containing the PrP<sup>Sc</sup> isofrom (PrP<sup>Sc</sup>-GPI) caused a significant increase in the production of PGE₂, compared with untreated cells or cells incubated with GPIs isolated from Thy-1 (Table 1). No significant differences were observed in the amounts of PGE₂ produced in response to PrP<sup>c</sup>-GPI from uninfected N2a cells or to PrP<sup>Sc</sup>-GPI from ScN2a cells (both at 20 ng ml⁻¹); in each case, the amounts were comparable to those induced by 10 µM arachidonic acid. HPTLC analysis was unable to detect any significant differences between PrP<sup>c</sup>-GPI and PrP<sup>Sc</sup>-GPI (Fig. 1). Pretreatment with 1 µg mAb 5AB3-11 ml⁻¹ (which recognizes phosphatidylinositol; Bate & Kwiatkowski 1994) blocked induction of PGE₂ by both PrP<sup>c</sup>-GPI and PrP<sup>Sc</sup>-GPI preparations, but had no effect on the production of PGE₂ in cells incubated with arachidonic acid, indicating that the phosphatidylinositol part of the GPIs was involved specifically in the stimulation of the PLA₂ pathway by GPIs.

**GPI structures required to activate neuronal PGE₂ production**

To determine the structural characteristics of GPIs that are required to activate neuronal PGE₂ production, NB4-1A3 cells were incubated with 20 ng PrP-GPI, deaminated PrP-GPI or deacylated PrP-GPI ml⁻¹. Treatment with nitrous acid (deamination) releases the phosphatidylinositol component of the GPI from the glycan core by breaking the linkage between phosphatidylinositol and glucosamine; HPTLC analysis showed that the resultant product migrated with similar properties to a control phosphatidylinositol (Fig. 1). In biological assays, PGE₂ levels in cells incubated with 20 ng deaminated PrP-GPI ml⁻¹ were significantly lower than in cells incubated with 20 ng untreated PrP-GPI ml⁻¹ (Fig. 2). Treatment with mild NaOH (deacylation) was also effective in inhibiting the production of PGE₂ by GPIs. No significant differences were observed in the amounts of PGE₂ produced in response to PrP<sup>c</sup>-GPI from uninfected N2a cells or to PrP<sup>Sc</sup>-GPI from ScN2a cells (both at 20 ng ml⁻¹); in each case, the amounts were comparable to those induced by 10 µM arachidonic acid. HPTLC analysis was unable to detect any significant differences between PrP<sup>c</sup>-GPI and PrP<sup>Sc</sup>-GPI (Fig. 1). Pretreatment with 1 µg mAb 5AB3-11 ml⁻¹ (which recognizes phosphatidylinositol; Bate & Kwiatkowski 1994) blocked induction of PGE₂ by both PrP<sup>c</sup>-GPI and PrP<sup>Sc</sup>-GPI preparations, but had no effect on the production of PGE₂ in cells incubated with arachidonic acid, indicating that the phosphatidylinositol part of the GPIs was involved specifically in the stimulation of the PLA₂ pathway by GPIs.

**Table 1.** Production of PGE₂ by NB4-1A3 cells incubated with GPIs extracted from normal (PrP<sup>c</sup>-GPI) or prion-infected (PrP<sup>Sc</sup>-GPI) neuroblastoma cells

<table>
<thead>
<tr>
<th>Treatment</th>
<th>PGE₂ (pg ml⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PrP&lt;sup&gt;c&lt;/sup&gt;-GPI (20 ng ml⁻¹)</td>
<td>178 ± 64*</td>
</tr>
<tr>
<td>PrP&lt;sup&gt;c&lt;/sup&gt;-GPI (20 ng ml⁻¹) + mAb 5AB3-11</td>
<td>&lt;20</td>
</tr>
<tr>
<td>PrP&lt;sup&gt;Sc&lt;/sup&gt;-GPI (20 ng ml⁻¹)</td>
<td>162 ± 51*</td>
</tr>
<tr>
<td>PrP&lt;sup&gt;Sc&lt;/sup&gt;-GPI (20 ng ml⁻¹) + mAb 5AB3-11</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Arachidonic acid (10 µM)</td>
<td>205 ± 20*</td>
</tr>
<tr>
<td>Arachidonic acid (10 µM) + mAb 5AB3-11</td>
<td>212 ± 44*</td>
</tr>
<tr>
<td>Thy-1-GPI (20 ng ml⁻¹)</td>
<td>&lt;20</td>
</tr>
<tr>
<td>None</td>
<td>&lt;20</td>
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</tbody>
</table>

*P<0.01 compared with untreated cells.

**Fig. 1.** (a) Immunoblot of HPTLC plate containing GPIs from PrP<sup>c</sup>, PrP<sup>Sc</sup> or Thy-1. Analysis of GPIs isolated from PrP<sup>c</sup>, PrP<sup>Sc</sup> or Thy-1 was determined by using silica gel HPTLC plates and immunoblotting with 1 µg mAb 5AB3-11 ml⁻¹. Lane 1, PrP<sup>c</sup>-GPI; lane 2, PrP<sup>Sc</sup>-GPI; lane 3, Thy-1-GPI; lane 4, phosphatidylinositol; lane 5, PrP<sup>c</sup>-GPI after deamination by treatment with nitrous acid; lane 6, PrP<sup>c</sup>-GPI after deacylation by treatment with NaOH. (b) Western blot showing immunoprecipitated PrP<sup>c</sup> and PrP<sup>Sc</sup>. Lane 1, PrP<sup>c</sup>; lane 2: protease-resistant PrP (PrP<sup>Sc</sup>). PrP<sup>c</sup> was demonstrated by immunoblot with mAb SAF53.
removes ester-linked acyl chains, resulting in a water-
soluble product. The production of PGE2 by cells incu-
bated with 20 ng deacylated PrP-GPI ml⁻¹ was significantly
lower than that of cells incubated with 20 ng untreated
PrP-GPI ml⁻¹ (Fig. 2).

**Partial GPIs inhibit PGE₂ production induced by
PrP peptides**

Competition studies were used to further identify com-
ponents of GPIs that are required for activation of the
PLA₂/PG pathways. Levels of PGE₂ in cells incubated with
100 µM GPI-related molecules (partial GPIs), such as
inositol monophosphate, glucosamine, mannose or sialic
acid, were not raised above those of untreated cells. How-
ever, production of PGE₂ by NB4-1A3 cells incubated
with 10 µM HuPrP82–146, 10 µM sPrP106, 10 ng prion
preparation ml⁻¹ or 20 ng PrP-GPI ml⁻¹ was reduced
significantly in cells that had been pretreated with inositol
monophosphate or sialic acid, but not in cells pretreated
with glucosamine, inositol or mannose (Table 2). As the
production of PGE₂ is a two-stage process that requires
the release of arachidonic acid by PLA₂ and the conversion
of arachidonic acid to PGs by the COX enzymes, we
examined whether inositol monophosphate or sialic acid
had an effect on PGE₂ production in cells exposed to 10 µM
arachidonic acid. Pretreatment with inositol monophos-
phate or sialic acid did not reduce PGE₂ production in
response to arachidonic acid, showing that they had no
effect on the COX enzymes (Table 2). Treatment with these
partial GPIs did not compromise cell survival and neurons
could be grown in 100 µM inositol monophosphate or
100 µM sialic acid for weeks without any adverse effects
on cell survival or growth rates (unpublished results).

**Table 2. Inositol monophosphate and sialic acid reduce PGE₂ production**

Levels of PGE₂ (pg ml⁻¹) produced by NB4-1A3 cells pretreated with 100 µM partial GPIs as shown and incubated thereafter with 10 ng prion preparation ml⁻¹, 10 µM HuPrP82–146, 10 µM sPrP106, 20 ng PrP-GPI ml⁻¹ or 10 µM arachidonic acid. Each value is the mean ± SD level of PGE₂ produced from triplicate experiments repeated three times (nine observations).

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>PGE₂ produced (pg ml⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Galactose</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Glucosamine</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Inositol monophosphate</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Inositol</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Mannose</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Sialic acid</td>
<td>&lt;20</td>
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</table>

*P < 0.01 compared to cells incubated with peptides or PrP-GPI alone.

**Inhibition of the toxic effect of PrP peptides on
NB4-1A3 cells by partial GPIs**

To determine the effect of partial GPIs on the toxicity of
PrP peptides, NB4-1A3 cells were pretreated with selected
partial GPIs at 100 µM before the addition of 10 µM
HuPrP82–146, 10 µM sPrP106 or 10 ng prion preparation
ml⁻¹. Incubation of NB4-1A3 neuroblastoma cells over-
night with HuPrP82–146, sPrP106 or prion preparation
reduced cell survival by approximately 50 % (Table 3).
Pretreatment of the cultures with inositol monophosphate
or sialic acid protected cells in each case, whereas pre-
treatment with galactose, glucosamine or mannose had no
effect. The efficacy of these compounds was examined by
pretreating cells with different concentrations of the partial

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Fig. 2. PGE₂ production in response to GPIs. Neuroblastoma
cells were treated with 20 ng PrP⁵⁻⁴⁻GPI ml⁻¹ (filled bars) or
20 ng PrP⁰⁻⁴⁻GPI ml⁻¹ (empty bars). Control, untreated PrP-
GPI; deacylated, PrP-GPI treated with NaOH; deaminated, PrP-
GPI treated with NaNO₂. Each value is the mean ± SD level of
PGE₂ (pg ml⁻¹) from triplicate experiments repeated three
times (nine observations).
GPIs before the addition of 10 μM sPrP106. Pretreatment with phosphatidylinositol, inositol monophosphate or sialic acid resulted in a dose-dependent increase in cell survival (Fig. 3); however, pretreatment with inositol did not inhibit the toxicity of sPrP106, indicating that the presence of a phosphate group on the inositol ring was necessary for the protective effect. In addition, the survival of cells incubated with 10 μM sPrP106 (52 ± 5% cell survival; n=9) was not affected by pretreatment with 10 μM inositol-1,4-bisphosphate (50 ± 7%) or 10 μM inositol-1,4,5-triphosphate (54 ± 4%).

We have shown previously that the toxicity of PrP peptides requires activation of PLA2 and the subsequent release of neurotoxins, such as arachidonic acid and PAF (Bate et al., 2004b). To determine whether the partial GPIs inhibited the activity of such neurotoxins, NB4-1A3 cells were treated with 10 μM arachidonic acid or 10 μM PAF in the presence or absence of partial GPI anchors. The survival of cells incubated with arachidonic acid alone (54 ± 6%; n=9) was not significantly different from that of cells incubated with arachidonic acid and 10 μM inositol monophosphate (53 ± 6%) or arachidonic acid and 50 μM sialic acid (55 ± 5%). Similarly, the survival of cells incubated with PAF (60 ± 6%) was not significantly different from that of cells incubated with PAF and 10 μM inositol monophosphate (62 ± 5%) or PAF and 50 μM sialic acid (59 ± 5%). Partial GPIs had no effect on the survival of NB4-1A3 cells incubated with 20 ng staurosporine ml⁻¹ (40 ± 3%) or 5 μM hydrogen peroxide (46 ± 5%). Such observations suggest that inositol monophosphate and sialic acid inhibit PrP-induced activation of PLA2 specifically, rather than by blocking neurotoxins directly or by altering apoptotic pathways in general.

**Inhibition of caspase-3 production in neurons**

Caspase-3 activity was measured in primary cortical neurons as an indication of apoptosis. Caspase-3 activity was increased significantly above that of untreated cells following 24 h incubation with 10 μM sPrP106, 10 μM HuPrP82–146 or 20 ng PrP-GPI ml⁻¹, but not in cells incubated with 20 ng Thy-1-GPI ml⁻¹ or 100 μM partial GPIs. Pretreating PrP-GPI with 1 μg mAb 5AB3-11 ml⁻¹ reduced the caspase-3 activity response to GPIs, but caspase-3 activity in neurons pretreated with sPrP106 or HuPrP82–146 was not affected (Table 4). Competition experiments showed that caspase-3 activity in response to sPrP106, HuPrP82–146 or PrP-GPI was reduced significantly in neurons that had been pretreated with inositol monophosphate or sialic acid, but was not affected by pretreatment with galactose, glucosamine, inositol or mannose.

**Killing of sPrP106-damaged neurons by microglia is blocked by partial GPIs**

Previous studies showed that microglia kill neurons that have been affected sublethally by PrP peptides (Brown et al., 1996). In the present study, primary cortical neurons were pretreated with partial GPIs for 3 h before the addition of 10 μM sPrP106. A further 3 h later, microglia were added and the survival of neurons was measured after 4 days. The survival of neurons in co-cultures containing sPrP106 and 10 μM inositol monophosphate or 100 μM sialic acid was significantly higher than that of untreated neurons or of neurons pretreated with 100 μM glucosamine or 100 μM

**Table 3. Partial GPIs protect neurons against PrP peptides/prion preparations**

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>Cell survival compared to control (%)</th>
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<tbody>
<tr>
<td></td>
<td>HuPrP82–146</td>
</tr>
<tr>
<td>Control medium</td>
<td>64 ± 4</td>
</tr>
<tr>
<td>Galactose</td>
<td>65 ± 4</td>
</tr>
<tr>
<td>Glucosamine</td>
<td>63 ± 5</td>
</tr>
<tr>
<td>Inositol monophosphate</td>
<td>99 ± 4*</td>
</tr>
<tr>
<td>Mannose</td>
<td>68 ± 4</td>
</tr>
<tr>
<td>Sialic acid</td>
<td>94 ± 5*</td>
</tr>
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</table>

*Cell survival is significantly greater (P<0.01) than in cells incubated with peptides/prion preparation alone.

![Fig. 3](http://vir.sgmjournals.org)

**Fig. 3.** Protection of NB4-1A3 cells against the toxic effect of sPrP106. Survival of NB4-1A3 neuroblastoma cells pretreated with different concentrations of phosphatidylinositol (●), inositol monophosphate (○), inositol (■) or sialic acid (□) before incubation with 10 μM sPrP106. Each value represents the mean ± SD cell survival (%) from triplicate experiments repeated four times (12 observations).
Caspase-3 activity in primary cortical neurons incubated for 24 h with 10 μM sPrP106, 10 μM HuPrP82–146, 20 ng PrP-GPI ml⁻¹ or 20 ng Thy-1-GPI ml⁻¹, in the presence or absence of 1 μg mAb SAB3-11 ml⁻¹ or 100 μM partial GPIs, as shown. Each value is the mean ± SD level of caspase-3 activity in cells from triplicate experiments repeated twice (six observations).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Caspase-3 activity (fluorescence units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>1.2 ± 0.5</td>
</tr>
<tr>
<td>+ mAb SAB3-11</td>
<td>0.9 ± 0.5</td>
</tr>
<tr>
<td>+ Isotype control</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>Galactose</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>Glucosamine</td>
<td>0.7 ± 0.5</td>
</tr>
<tr>
<td>Inositol monophosphate</td>
<td>1.2 ± 0.5</td>
</tr>
<tr>
<td>Inositol</td>
<td>1.4 ± 0.7</td>
</tr>
<tr>
<td>Mannose</td>
<td>0.8 ± 0.4</td>
</tr>
<tr>
<td>Sialic acid</td>
<td>0.9 ± 0.4</td>
</tr>
</tbody>
</table>

*Casparse-3 activity is significantly lower (P<0.01) than in untreated cells incubated with peptide or PrP-GPI.

**DISCUSSION**

The major neuropathological features of TSEs or prion disease include the accumulation of PrPSc, glial cell activation and the degeneration and apoptotic death of neurons (Giese et al., 1995; Jeffrey et al., 2000; Jamieson et al., 2001). Factors that are increased in affected areas of the brain include PGE₂ (Williams et al., 1994, 1997b) and raised levels of PGE₂ are detectable in the cerebrospinal fluid of patients with CJD (Minghetti et al., 2000, 2002). The present data show that the GPI anchors attached to PrPc and PrPSc stimulate PGE₂ production and induce caspase-3 activity in neurons in a similar manner to PrP peptides, the miniprion sPrP106 and prion preparations (Bate et al., 2001). These results are consistent with reports that concentrated GPI anchors can activate some cell types; for example, GPIs activate lipogenesis in adipocytes (Frick et al., 1998) or induce cytokine production from macrophages (Vijaykumar et al., 2001). The GPIs isolated from PrPc and PrPSc migrate with similar R₁ values in HPTLC and we were unable to detect any significant differences in their biological activity. These observations suggest that conversion from PrPc to PrPSc does not entail significant changes to the GPI anchor, results that are consistent with previous data (Stahl et al., 1992). However, as the exact structure of these GPIs was not determined, it remains possible that subtle differences between GPI-PrPc and GPI-PrPSc exist. It is worth noting that the GPI anchor attached to Thy-1 is modified differently from that of PrPc (Rudd et al., 2001) and that GPI anchors isolated from Thy-1 failed to stimulate PGE₂ production or to activate apoptotic pathways. Thus, although it is not known whether PGE₂ production and the initiation of apoptotic pathways in neurons is a unique property of GPIs attached to PrPc, this activity is not shared by all GPIs.
The studies reported here provide indications of the structures required of the GPI for biological activity. Thus, the compounds generated following deamination, which releases phosphatidylinositol from the glycan component of GPI, did not stimulate PGE₂ production. Decayed GPIs failed to run on HPTLC, indicating a hydrophilic compound consistent with the removal of acyl chains. Decayed GPIs also failed to stimulate PGE₂ production, demonstrating that the ester-linked acyl chains on the phosphatidylinositol are required for biological activity. In addition, mAb studies demonstrated that a phosphatidylinositol moiety of GPIs is essential for biological activity. The effects of mAb 5AB3-11 were specific in that it did not affect PGE₂ produced by cells treated with arachidonic acid, indicating that mAb 5AB3-11 did not affect COX. Such observations suggest that the biological activity of GPI anchors requires both phosphatidylinositol and another, unspecified glycan component.

Little is known about the process by which prions or PrP peptides activate neuronal PLA₂. One possibility is that high concentrations of GPI anchors bind directly to PLA₂. In these assays, high concentrations of GPI anchors were required to activate PLA₂, perhaps mimicking the high concentration of GPI anchors that occurs following the aggregation of PrPSc molecules or the cross-linkage of PrPSc by specific mAbs (Solforosi et al., 2004) or by PrP peptides. The clustering of GPI-anchored proteins is thought to occur in specific membrane microdomains that are known as lipid rafts (Mayor & Riezman, 2004), which are essential for the activation of PLA₂ and the toxicity of prions (Bate et al., 2004a). The results presented here are consistent with exogenous GPI anchors inserting into membranes and trafficking to lipid rafts, where high concentrations activate PLA₂. It is of interest to note that, although the addition of exogenous GPI anchors activated PLA₂ and increased caspase-3 activity in neurons, it did not cause neuronal death. It remains to be seen whether prion-induced neuronal death requires additional, non-GPI signals that are inherent in the prion protein structure or whether the lack of neuronal death in response to GPI anchors is simply a concentration effect.

The neurotoxicity of PrP peptides or prion preparations was reduced by pretreatment with some compounds that are common to all GPI anchors. Initial studies showed that whilst phosphatidylinositol, inositol monophosphate and sialic acid reduced the neurotoxicity of sPrP106 and prion preparations, other components of GPI anchors, namely galactose, glucosamine and mannose, had no effect. The presence of a single phosphate on the inositol ring was essential, as inositol alone and inositols containing more than one phosphate did not affect neurotoxicity. Whilst the protective effects of phosphatidylinositol and inositol monophosphate on sPrP106-induced neurotoxicity were evident at micromolar concentrations, the protective effect of sialic acid was only observed at higher concentrations.

The toxicity of prions or PrP peptides involves the activation of neuronal PLA₂ and the production of bioactive second messengers, including arachidonic acid and PAF (Bate et al., 2004b). Treatment of neurons with inositol monophosphate or sialic acid did not affect the toxicity of arachidonic acid or PAF, indicating that these compounds prevent the formation, rather than the action, of such neurotoxins. The production of PGE₂ that is associated closely with PrP-induced neurotoxicity is a two-stage process that requires the release of arachidonic acid by PLA₂ and the conversion of arachidonic acid to PGs by the COX enzymes. The addition of inositol monophosphate or sialic acid reduced PGE₂ production in response to HuPrP82–146, sPrP106 and PrP-GPIs, but did not affect PGE₂ production in response to arachidonic acid, showing that these compounds had no direct effect on COX. In regard to prion-induced toxicity, these observations identify PLA₂ as the target of inositol monophosphate and sialic acid, a result that is compatible with previous reports that sialic acid inhibits PLA₂ (Yang et al., 1994).

The presence of inositol monophosphate or sialic acid greatly reduced microglial killing of neurons damaged by sPrP106. Microglia respond to changes in neurons that are induced by PrP peptides (Bate et al., 2002) and our data are consistent with the concept that the presence of inositol monophosphate or sialic acid prevents the PrP-induced neuronal changes that activate microglia. An alternative explanation, i.e. that inositol monophosphate and sialic acid have a direct effect on microglia, was discounted, as these compounds did not affect the production of interleukin 6 from microglia incubated with lipopolysaccharide (unpublished data).

To our knowledge, this is the first report to demonstrate that high concentrations of PrP-GPIs result in activation of PLA₂ and neuronal apoptotic pathways (caspase-3). The activity of GPIs was dependent on a phosphatidylinositol moiety, on ester-linked acyl chains and on an unspecified glycan component. There were no obvious physical differences between GPIs isolated from PrPSc or PrPSc®, nor any significant differences in their biological activity. We propose that the high concentrations of GPIs added here mimic the locally high concentrations of GPIs that occur when PrPSc molecules cluster following the addition of PrP peptides, or when the GPI anchors are concentrated following the aggregation of PrPSc molecules. Pretreatment with some partial GPIs, including inositol monophosphate or sialic acid, protected neurons against the toxicity of PrP peptides, sPrP106 and prion preparations. These partial GPIs prevented the activation of PLA₂, rather than inhibiting neurotoxins generated following PLA₂ activation. Inositol monophosphate and sialic acid also reduced the HuPrP82–146- or sPrP106-induced activation of apoptotic pathways in cortical neurons and prevented HuPrP82–146- or sPrP106-treated neurons from activating microglia, resulting in increased neuronal survival. The present results are compatible with the hypothesis that inositol monophosphate and sialic acid compete with the complete GPI.
anchors of PrPc or PrPSc for cellular receptors and prevent PLA2 activation. Whilst neuronal death in response to prions in vitro is undoubtedly a complex process that may include other mechanisms, these observations provide insight into the signalling processes that result in prion-induced neuronal loss.

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