Propagation of a protease-resistant form of prion protein in long-term cultured human glioblastoma cell line T98G

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INTRODUCTION

Fatal human prion diseases, including sporadic Creutzfeldt–Jakob disease (CJD), inherited prion diseases, iatrogenic CJD, kuru and variant CJD, are transmissible spongiform encephalopathies that are characterized by the formation and accumulation of an abnormal isoform of prion protein (PrP) in the brain (Prusiner, 2001). The PrPres isoform is an insoluble aggregate that is resistant to proteinase K (PK) digestion. The conversion from cellular prion protein (PrPC) into PrPres could be a potential therapeutic target for prion diseases, but the mechanism of the conversion is unclear.

Several animal cell lines, including mouse neuroblastoma cells (Butler et al., 1988; Race et al., 1987), mouse hypothalamic neuronal cells (Nishida et al., 2000; Schätzl et al., 1997), mouse Schwann cells (Follet et al., 2002) and rat pheochromocytoma cells (Rubenstein et al., 1984), have been infected successfully with scrapie agents, and a human neuroblastoma cell line can also be infected with CJD agents (Ladogana et al., 1995). These cells have been used to study the conversion mechanisms (Lehmann & Harris, 1997) and the subcellular localization (Naslavsky et al., 1997; Vey et al., 1996) of PrPres and to evaluate therapeutic agents (Caughley & Raymond, 1993; Doh-Ura et al., 2000). However, the efficiencies of infection and propagation of PrPres are relatively low. The mouse cell line SMB was established from a scrapie-infected mouse brain (Clarke & Haig, 1970) and has been used to study the properties of PrP (Birkett et al., 2001). Recently, stable cell lines were established from mouse peripheral neuroglial cells expressing ovine PrP and simian virus 40 T antigen. These cells were readily infectible by sheep PrPsc, a scrapie isoform of PrP (Archer et al., 2004). However, there are currently no human cell lines that have been used to study the conversion mechanism from PrPC into PrPres.

PrP mRNA is expressed not only in neurons, but also in glia (Moser et al., 1995) and PrPsc accumulates in the cytosol and cell-surface membrane of glial cells (van Keulen et al., 1995). The role of glial cells in prion disease is not clear. Human glioblastoma T98G cells, like normal cells, become arrested in G1 phase under stationary-phase conditions (Stein, 1979). In a previous study, we showed that T98G cells express PrPC mRNA constitutively and produce a high level of endogenous PrPC in G1 phase (Kikuchi et al., 2002). In the present study, we have investigated whether PrPC is...
converted into PrP\textsuperscript{res}, a marker for prion diseases, in cultured T98G cells under various conditions.

**METHODS**

**Materials.** A primer set for the human PrP coding sequence (CDS) (GenBank accession no. AL133396) [5'-CGAGGCCGAGCGATCTACTAGTCCGAGAC-3', starting 18 nt before the ORF, and 5'-AGATGTTGAAACCGAGGAGGAC-3', ending 6 nt after the ORF (expected product size, 806 bp]) and an internal primer set [5'-GGCAGTGACTATGAGACGCCGTTAC-3' and 5'-GTAACGGTCTCATATGACGTGCC-3'], corresponding to nt 424-447 relative to the start site of the ORF] were synthesized chemically. Peptide N-glycosidase F (PNGase F) and BsaAI were purchased from New England Biolabs and RPMI 1640 medium was purchased from Nissui Pharmaceutical. A BCA protein assay kit and SuperSignal West Femto Maximum Sensitivity substrate were from Pierce Biotechnology. Hybond-P PVDF membranes were purchased from Amersham Biosciences. Anti-human PrP mAb 3F4 was purchased from Signet Laboratories and 6H4 from Prionics AG. Fetal calf serum (FCS), horseradish peroxidase 1640 medium was purchased from Nissui Pharmaceutical. A BCA protein assay kit and SuperSignal West Femto Maximum Sensitivity substrate were from Pierce Biotechnology. Hybond-P PVDF membranes were purchased from Amersham Biosciences. Anti-human PrP mAb 3F4 was purchased from Signet Laboratories and 6H4 from Prionics AG. Fetal calf serum (FCS), horseradish peroxidase 1640 medium was purchased from Nissui Pharmaceutical.

**Preparation of whole-cell lysates.** All cell lines were plated at 5 x 10\(^5\) cells per 9 cm dish (55 cm\(^2\)) in 10 ml medium on day 0 (D0). The medium was changed every 4 days. At the indicated times, cells were washed twice with ice-cold PBS and scraped into lysis buffer [1 x 10\(^6\) cells ml\(^{-1}\), 10 mM Tris/HCl (pH 7.5), 150 mM NaCl, 1 % sodium deoxycholate, 0.1 % SDS, 1 % NP-40, 10 mM NaF, 1 mM EDTA, 0.5 mM Na\textsubscript{3}VO\textsubscript{4}, 10 mM tetrasodium pyrophosphate] with protease inhibitor cocktail [0-06 trypsin inhibitor units (TIU) aprotinin ml\(^{-1}\), 20 \mu M leupeptin and 1 mM PMSF]. After sonication, insoluble material was pelleted by centrifugation at 500 g for 15 min at 4 °C to yield whole-cell lysates. Protein concentration was determined by the BCA protein assay.

**Subcellular fractionation.** At the indicated times, cells were washed twice with ice-cold PBS and scraped into PBS/2-5 mM EDTA with the protease inhibitor cocktail. After sonication, insoluble material was pelleted by centrifugation at 500 g for 15 min at 4 °C to yield homogenates. The postnuclear fraction was centrifuged at 100 000 g for 60 min at 4 °C to obtain a cytosolic fraction and a membrane fraction. The membrane fraction was dissolved in PBS/2-5 mM EDTA with the protease inhibitor cocktail. Protein concentration was determined by the BCA protein assay.

**Detergent solubility test.** A detergent solubility test was carried out according to a described method (Capellari et al., 2000) with slight modifications. Cells were washed twice with ice-cold PBS and scraped into PBS/2-5 mM EDTA with the protease inhibitor cocktail. After sonication, insoluble material was pelleted by centrifugation at 500 g for 15 min at 4 °C to yield homogenates. The postnuclear fraction was centrifuged in 4 vols 0.5 % NP-40/0.5 % deoxycholate/PBS with the protease inhibitor cocktail and centrifuged at 100 000 g for 60 min at 4 °C to obtain a detergent-insoluble pellet fraction and a soluble supernatant fraction. The supernatant fraction was precipitated with 4 vols methanol for 16 h at −20 °C. Both fractions were resuspended in the same volume of lysis buffer.

**Protease-resistant PrP assay.** To generate material for the protease-resistant PrP assay, aliquots of the sample (50 \mu g protein) were precipitated with 4 vols methanol for 16 h at −20 °C to remove the protease inhibitor cocktail (Capellari et al., 2000), centrifuged at 14 000 g for 15 min at 4 °C and the pellet was dissolved in 50 mM Tris/HCl (pH 7.2). Samples were treated with PK (at 10 \mu g ml\(^{-1}\) unless stated otherwise) at 37 °C for 30 min, according to a described method (Caughley et al., 1999). After incubation, digestion was stopped by the addition of AEBSF to 4 mM. Samples were prepared with the protease inhibitor cocktail at a concentration that did not inhibit the activity of PK (Fig. 1a, lane 1).

**Enzymic deglycosylation.** For the removal of Asn-linked oligosaccharides, aliquots of whole-cell lysates were treated with PNGase F as follows (Kikuchi et al., 2002): lysates (50 \mu g protein) were denatured by boiling for 10 min in 0.5 % SDS, 1 % 2-mercaptoethanol. After addition of NP-40 to 1 %, the lysates were incubated at 37 °C for 2 h with 0.77 IUB mU PNGase F in 50 mM phosphate buffer (pH 7.5).

**Immunoblotting.** Usually, 50 \mu g total protein (prepared from approximately 1 x 10\(^5\) cells) was subjected to SDS gel electrophoresis. Briefly, aliquots of the samples were mixed with 2x electrophoresis sample buffer. After boiling for 10 min, the samples were electrophoresed on 10 % sodium dodecyl sulfate polyacrylamide gels and transferred to nitrocellulose membranes. Membranes were blocked with 5 % non-fat dry milk in Tris-buffered saline (TBS) containing 0.1 % Tween-20 (TTB). Membranes were incubated with monoclonal or polyclonal antibodies (diluted in TBS containing 0.1 % Tween-20) at room temperature for 1 h, washed, and incubated for 1 h with secondary antibodies (diluted in TBS containing 0.1 % Tween-20 and 5 % non-fat dry milk). After washing, signals were detected using chemiluminescence reagents.
were electrophoresed on 12.5% acrylamide gel and the proteins were transferred onto PVDF membranes. The membranes were blocked with 0.5% casein in PBS (casein/PBS) and incubated with anti-prion antibodies in casein/PBS. Immunoreactive bands were visualized with HRP-conjugated anti-IgG and SuperSignal West Femto Maximum Sensitivity substrate, according to the manufacturer's instructions (Pierce Biotechnology).

**Indirect immunofluorescence staining.** T98G cell monolayers grown on a 15 mm glass coverslip (Matsumani) in a 9 cm dish (55 cm²) were maintained in 10 ml medium. At the indicated times, cells were washed twice with ice-cold PBS and then fixed with 3.7% formaldehyde in PBS for 30 min at 4°C. The fixed cells were washed twice with PBS and then treated with 0.2% Triton X-100 in PBS for 15 min at room temperature. The cells were blocked with 10% normal goat serum in PBS (NGS/PBS) for 30 min and incubated with antibody (100 ng ml⁻¹) for 16 h at 4°C. After extensive washing with 0.05% Tween 20/PBS, cells were treated with Alexa 594 goat anti-mouse IgG (H+L) conjugate (5 μg ml⁻¹) (Molecular Probes) in NGS/PBS for 1 h at 4°C, washed with 0.05% Tween 20/PBS and mounted with 2.5% DABCO/90% glycerin/PBS. The stained cells were observed and photographed with the aid of a fluorescence microscope (Olympus).

**Competitive ELISA.** ELISA was carried out according to a method described previously (Kikuchi et al., 1991). For a dilution buffer, casein/PBS was used throughout the present study. Briefly, the wells were coated with 100 ng recombinant bovine PrP (rBoPrP) (Takekida et al., 2002) in PBS and left at 4°C overnight. Appropriately diluted test solutions or samples were added to the antigen-coated wells and incubated at room temperature for 60 min, in a total volume of 50 μl, with 6H4 antibody (460 pg). The wells were washed, incubated with β-galactosidase-conjugated goat anti-mouse IgG for 60 min, washed again and then incubated with 4-MUG as a substrate at 37°C for 60 min. Enzyme activity was determined by fluorescence intensity measurements.

### RESULTS

**Production of protease-resistant isoform of PrP in T98G cells**

We analysed whole-cell lysates of long-term cultured T98G cells by immunoblotting with anti-PrP antibodies. When we cultured the cells for 38 days after 3 passages [passage 3, day 38 (P3D38)], the lysates revealed two bands (35 and 31 kDa) that reacted with mouse anti-human PrP mAb 6H4 (Fig. 1a, lane 2) and were destroyed completely after digestion with PK (Fig. 1a, lane 1). When lysates from cells that were cultured for 39 days after 13 passages [passage 13, day 39 (P13D39)] were digested with PK (10, 20 or 30 μg ml⁻¹), the 35 kDa band, but not the 31 kDa band, was diminished (Fig. 1b), indicating the presence of PrPres.

We then attempted to detect PrPres formation in long-term cultures of another human glial cell line, U373MG, an astrocytoma line that expresses consistently high levels of PrPC mRNA (Satoh et al., 1998). The lysates from P11D38 U373MG cells exhibited the 31 kDa band that reacted with the 6H4 antibody and disappeared after digestion with PK (Fig. 1c). Lysates from P3D150 T98G cells showed a faint 31 kDa band after PK treatment (Fig. 1d). In contrast, P13D39 T98G cells had produced highly PK-resistant PrP. These data indicated that PrPres propagation in T98G cells required not only long-term culture, but also a high passage number.

**Examination of phenotypic variants of PrPres**

We first asked whether an inherited or a sporadic CJD-like form of PrPres was propagated in T98G cells. Inherited prion

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**Fig. 1.** Formation of a protease-resistant form of PrP in T98G cells is increased in a long-term incubation after repeated passages. T98G cells and U373MG cells were incubated under the following conditions with 10% FCS/RPMI 1640 and methanol-precipitated lysates (50 μg protein) were treated with PK (10 μg ml⁻¹ unless stated otherwise) at for 30 min at 37°C. (a) T98G cells were incubated for 38 days after 3 passages (P3D38); lysates were treated with PK (lane 1) or left undigested (lane 2). (b) T98G cells were incubated for 39 days after 13 passages (P13D39); lysates were treated with 10, 20 or 30 μg PK ml⁻¹ (lanes 1–3) or left undigested (lane 4). (c) U373MG cells were incubated for 38 days after 11 passages (P11D38); lysates were treated with PK (lane 1) or left undigested (lane 2). (d) T98G cells were incubated for 150 days after 3 passages; lysates were treated with PK (lane 1) or left undigested (lane 2). PK-treated lysates were subjected to immunoblot with the 6H4 antibody as described in Methods.

<table>
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<th>PK (μg ml⁻¹)</th>
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</tr>
<tr>
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<td>0</td>
<td>P3D150</td>
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diseases are determined by mutations in the 762 bp CDS of the prion protein gene \((PRNP)\) (Kovács et al., 2002). We performed PCR direct sequencing of the \(PRNP\) mRNA that was expressed in short- and long-term cultured T98G cells and found no mutations other than the presence of both adenine and guanine at the first position of codon 129 (the basis of the common M129V polymorphism) (data not shown). When digested by \(Bsa\)AI, the 806 bp PCR product from the M129V haplotype (Fig. 2a, lane 1) yielded products of 402 and 404 bp and also undigested wild-type product (Fig. 2a, lane 2), which we confirmed by RFLP analysis. These results indicated that T98G cells were heterozygotes, having both methionine and valine at codon 129 of \(PRNP\) with no coding-region mutation.

Next, to estimate the size of the deglycosylated PrP\(^{\text{res}}\), we treated the lysates from P40D40 T98G cells with PK and/or PNGase F. PNGase F yields a full-length (25 kDa) and an N-terminally truncated (18 kDa) form of PrP\(^C\) (Kikuchi et al., 2002). As shown in Fig. 2b, PNGase F treatment reduced the glycosylated 35 and 31 kDa bands (lane 4) to 25 and 18 kDa (lane 3), representing the deglycosylated full-length and N-terminally truncated forms. An additional PNGase F treatment changed fully glycosylated (31 kDa) and partially glycosylated (23 kDa) forms of PrP\(^{\text{res}}\), detectable after digestion with PK (lane 2), to an unglycosylated form of 18 kDa (lane 1). These results established that the size of the deglycosylated PK-resistant fragment in T98G cells was approximately 18 kDa.

**Confirming heterogeneity of PrP\(^{\text{res}}\) by immunoblotting with sets of anti-PrP antibodies**

To further investigate the heterogeneity of PrP\(^{\text{res}}\) from long-term cultured T98G cells, we determined the antigenicity of PrP\(^{\text{res}}\). By immunoblotting with sets of antibodies to PrP (Kikuchi et al., 2002), we detected a full-length PrP (35 kDa) in lysates from P40D40 T98G cells that reacted with the anti-N terminus PrP antibody HUC2-13 (Fig. 3a, lane 2), as well as with the 6H4 antibody (Fig. 3c, lane 2). Following PK treatment of the lysates, the 31 kDa band was still detected by 6H4 antibody (Fig. 3c, lane 1), but not by HUC2-13 antibody (Fig. 3a, lane 1), indicating that PK treatment had cleaved the N terminus of PrP\(^{\text{res}}\). The 31 kDa band was also detected by the anti-C terminus PrP antibody HPC2 (Fig. 3d, lane 1). HPC2 antibody, which reacts strongly with the deglycosylated form of PrP\(^C\), but weakly with the glycosylated form (Kikuchi et al., 2002), also recognized the N-terminally truncated form of PrP\(^{\text{res}}\). Surprisingly, the 3F4 antibody, which recognizes residues 109–111, failed to detect the N-terminally truncated form of PrP\(^{\text{res}}\) (Fig. 3b), such as is seen with the HUC2-13 antibody (Fig. 3a). These experiments showed that the N-terminally truncated form of PrP\(^{\text{res}}\) in T98G cells lacks the epitope that is recognized by the 3F4 antibody.

**Subcellular localization and detergent solubility of PrP\(^{\text{res}}\) in T98G cells**

To determine the subcellular localization of PrP\(^{\text{res}}\), we studied the distribution of PrP in P40D40 T98G cells.

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**Fig. 2.** Molecular analysis of PrP\(^{\text{res}}\) in T98G cells. (a) Detection of polymorphism at codon 129 on PrP mRNA in T98G cells. T98G cells were incubated with 10% FCS/RPMI 1640 for 5 days after 43 passages (P43D5) and total RNA was prepared, reverse-transcribed and PCR-amplified as described in Methods and digested with \(Bsa\)AI (lane 2) or left undigested (lane 1). A DNA size marker (100 bp ladder) is shown on the left. (b) Analysis of deglycosylated forms of PrP in T98G cells. T98G cells were incubated with 10% FCS/RPMI 1640 for 40 days after 40 passages (P40D40); whole-cell, methanol-precipitated lysates were treated with PK (lanes 1 and 2) or left undigested (lanes 3 and 4). All lysates were incubated with (lanes 1 and 3) or without (lanes 2 and 4) PNGase F for 120 min. PK-treated lysates were subjected to immunoblot with the 6H4 antibody as described in Methods.
Propagation of a protease-resistant form of PrP

by indirect immunofluorescence staining. Immunoreactive PrP with 6H4 antibody was observed on the cell surface as a bright fluorescent signal (Fig. 4a), whereas little signal was observed with mouse IgG, a control antibody purified from normal mouse serum (data not shown). We next prepared membrane and cytosolic fractions from homogenates of P40D40 T98G cells and measured the amount of PrP by competitive ELISA using the 6H4 antibody. PrP was recovered predominantly in the membrane fraction (Table 1). As shown in Fig. 4b, the distribution of PrPres in P40D40 T98G cells (left panel) was similar to that of PrPres in P3D36 T98G cells (right panel); PrPres was detected in the membrane fraction (left panel, lane 3), as well as in homogenates (left panel, lane 1), but no PrP was detected in the cytosolic fraction (left panel, lanes 5 and 6). These data indicated that most PrPres was in the membrane fraction, probably on the plasma membrane. To test the detergent solubility of PrP, the homogenates of P40D40 T98G cells were centrifuged in non-ionic detergents. A large proportion of immunoreactive PrP was found in the supernatant fraction (Fig. 4c, lane 3), but no PrP was detected in the pellet fraction (Fig. 4c, lane 2). These data suggest that PrPres is predominantly membrane-bound.

Fig. 3. Immunoblot analysis using anti-PrP antibodies for the protease-resistant form of PrP in T98G cells. T98G cells were incubated with 10% FCS/RPMI 1640 for 40 days after 40 passages (P40D40); whole-cell, methanol-precipitated lysates were treated with PK (lane 1) or left undigested (lane 2). PK-treated lysates were subjected to immunoblot with the HUC2-13 (a), 3F4 (b), 6H4 (c) or HPC2 (d) antibodies as described in Methods. Epitope recognition sites located within PrP are shown as amino acid numbers.

Fig. 4. Subcellular localization and detergent solubility of PrPres in long-term cultured T98G cells. T98G cells were incubated with 10% FCS/RPMI 1640 in the long-term incubation after repeated passages. (a) T98G cells for 40 days after 40 passages (P40D40) on a 15 mm glass coverslip were subjected to indirect immunofluorescence staining with the 6H4 antibody as described in Methods. Bar, 10 μm. (b) T98G cells for 40 days after 40 passages (P40D40, left panel) and for 36 days after 3 passages (P3D36, right panel) were scraped into PBS/2.5 mM EDTA and sonicated. Homogenates (homo) were separated into a membrane fraction (mem) and a cytosolic fraction (cyto). Methanol-precipitated lysates were treated with PK (lanes 1, 3 and 5) or left undigested (lanes 2, 4 and 6). PK-treated samples were subjected to immunoblotting with the 6H4 antibody as described in Methods. (c) T98G cells for 40 days after 40 passages (P40D40) were scraped into PBS/2.5 mM EDTA and sonicated. Homogenates (H) of 50 μg protein were centrifuged as described in Methods to obtain a non-ionic detergent-insoluble pellet (P) and a soluble supernatant fraction (S). Homogenates, pellet and supernatant fractions (50 μg protein each) were subjected to immunoblot with the 6H4 antibody as described in Methods.
Table 1. Subcellular localization of PrP in long-term cultured T98G cells

<table>
<thead>
<tr>
<th>Sample</th>
<th>PrP content pmol</th>
<th>%</th>
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<tr>
<td>Homogenate</td>
<td>263.4 ± 20.9</td>
<td>100.0</td>
</tr>
<tr>
<td>Membrane fraction</td>
<td>228.9 ± 17.5</td>
<td>86.9</td>
</tr>
<tr>
<td>Cytosolic fraction</td>
<td>9.9 ± 0.5</td>
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The amount of PrP is expressed as recombinant bovine PrP equivalents per 10^6 cells. Values are means ± SEM (n = 4).

Direct sequencing of amplified PRNP mRNA and RFLP analysis indicated that the T98G cells were heterozygotes at codon 129 (129M/V) and that no new coding mutations were present in cells that had been subjected to long-term cultures. The deglycosylated form of PK-treated PrPres in T98G cells migrated at approximately 18 kDa. In human prion diseases, two major types of PrPres can be identified, based on electrophoretic migration; the relative molecular mass of the unglycosylated form is approximately 21 kDa (described as type 1) or 19 kDa (described as type 2) (Parchi et al., 1997). Accordingly, PrPres in T98G cells is similar to the previously described MV2 phenotypic variant (Parchi et al., 1999a). However, the size of the deglycosylated PK-resistant fragment in T98G cells was smaller than that of the corresponding fragments observed in type 2 PrPres. Most importantly, the 3F4 antibody, which is a well-characterized antibody known to target residues 109–112 as its epitope (Kascak et al., 1987; Matsunaga et al., 2001), did not react with PK-digested PrPres in T98G cells, suggesting that the N-terminal PrP region up to residue 109 might be absent in PK-treated PrPres in T98G cells. Human PrPres peptide is divided into three regions that are defined by their PK-cleavage patterns: an N-terminal region (residues 23–73) that is invariably PK-sensitive, a C-terminal region (residues 103–231) that is invariably PK-resistant and a variably digested region (residues 74–102), where the major cleavage sites are at G82 in type 1 and at S97 in type 2 (Parchi et al., 2000). The 3F4 antibody was used to type PrPres (Parchi et al., 2000). Therefore, there are striking differences in the antigenicity, which reflect the PK-cleavage patterns, between type 2 PrPres in sporadic CJD brain and in T98G cells. It is unlikely, but not impossible, that PK treatment generated conformational changes in the mid-region of PrPres that interfered with epitope recognition by the 3F4 antibody. Further studies are needed to classify the type of PrPres in lysates from long-term cultured T98G cells.

So far, human PrPSc has been analysed on immunoblots with the 3F4 antibody. Our finding may explain why previous studies have failed to detect PrPres in cultured cells. Interestingly, an N-terminally truncated 18 kDa fragment of PrP (designated C1) in normal and sporadic CJD brains has similar properties except that it is PK-sensitive; it is recognized by the anti-C terminus antibody, but not by the 3F4 antibody, is cleaved around residue 111 and is associated with cell membranes (Chen et al., 1995). PrPSc from human brain homogenates (n = 6) originally displayed a partial PK resistance (20 μg ml⁻¹ for 10 min) and has been detected by the antibody that recognizes residues 145–163, but not by the 3F4 antibody (Buschmann et al., 1998). Taking the data from the various studies of PrP immunoreactivity into consideration, we believe that it would be better to incorporate an additional antibody that recognizes the C terminus of PrP into the standardly used protease resistance-dependent PrPSc assay.

Among the sets of antibodies used in this study, the anti-N-terminal portion antibodies (HUC2-13 and 3F4) reacted strongly with the fully glycosylated form and moderately with the partially glycosylated form. In contrast, the antibodies against the C-terminal portion of PrP (6H4 and HPC) reacted moderately with the fully glycosylated form and strongly with the partially glycosylated form. It is possible that PK digestion induces a conformational change of digested PrP and enhances its immunoreactivity to the anti-C-terminal antibodies. Recently, it has been reported that the amino acid motif Tyr-Tyr-Arg (YYR), located in a β-sheet, is exposed in PrPSc, whilst it is cryptic in PrPSc, and that antibodies recognize YYR in PrPSc, but not in PrPSc (Paramithiotis et al., 2003). Another paper has reported that PK digestion enhances immunoreactivity to the anti-PrP antibody that recognizes the epitope YYR, located in a β-sheet (Brun et al., 2004). These reports suggest that conformation of the C-terminal portion of PrPSc is essential for immunoreactivity of anti-YYR antibodies. The 6H4 antibody also recognizes residues 144–152 of PrP, including a YYR motif that is located in an α-helix, not in a β-sheet (Korth et al., 1997). Further study is needed to clarify the immunoreactivity of anti-C-terminal PrP antibodies.

It has been proposed that PrPSc is converted into PrPres either on the cell surface or in endocytic cellular compartments. PrPSc is a surface protein that contains a glycosylphosphatidylinositol anchor (Stahl et al., 1987). A portion of PrPSc is also localized on the cell surface of scrapie-infected mouse neuroblastoma Scn2a cells (Naslavsky et al., 1997; Vey et al., 1996), although it is also found in lysosomes (Taraboulos et al., 1990). Subcellular localization of PrPres in long-term cultured T98G cells was similar to that of PrPSc-infected cells, being present on the cell surface.

DISCUSSION

The mechanism of the conversion of PrP has not been studied in human cell cultures, due to the lack of a model system. In the present study, we developed such a system by culturing human glioblastoma T98G cells, which express endogenous PrPSc constitutively. After reaching a high passage number, long-term cultured T98G cells converted PrPSc into PrPres.
PrPSc in ScN2a cells is sedimented by centrifugation in non-ionic detergents (Caughey et al., 1991). Mutant PrP in stably transfected Chinese hamster ovary cells, which express murine homologues associated with human inherited prion diseases, is also non-ionic detergent-insoluble (Lehmann & Harris, 1996). However, the PrPres in T98G cells is detergent-soluble. PrPres in the human neuroblastoma cell line M-17 BE(2)C carrying the familial subtype CJD, the glutamic acid to lysine substitution at codon 200 (E200K), is also partially non-ionic detergent-insoluble (Capellari et al., 2000). The present study indicates that not all PrPres is non-ionic detergent-insoluble.

Many cultured cells that express PrPres mutants carrying substitutions of inherited prion disease show considerably less protease resistance (up to 3-3 µg ml⁻¹ for 10 min), compared with PrPSc mutants isolated from the human brain (Capellari et al., 2000; Harris, 2001). In contrast, the PrPres in T98G cells displayed a high resistance to digestion with PK (10 µg ml⁻¹ for 30 min), but was less resistant than PrPres in brain homogenates of sporadic CJD (up to 100 µg ml⁻¹ for 24 h). Sporadic CJD is typically characterized by widespread spongiform degeneration with loss of neurons, gliosis and formation of amyloid plaques (Parchi et al., 1999a). It has recently been reported that six cases of sporadic familial insomnia, a prion disease mimicking fatal familial insomina, had no coding-region mutation of PRNP with the 129 M/M genotype and an approximately 19 kDa deglycosylated PrPres, the same as that of type 2 (Mastrianni et al., 1999; Parchi et al., 1999b). Familial progressive subcortical gliosis may also be a prion disease, characterized by astrogliosis at the cortex–white matter junction (Petersen et al., 1995). All patients from two families with that disease showed no coding-region mutation of PRNP, the 129 M/M genotype and the 18–19.3 kDa form of deglycosylated PrPres (Petersen et al., 1995). T98G cells were grown out of human glioblastoma multiforme tumour tissue of a 61-year-old Caucasian man (Stein, 1979). We consider it possible that he also had a sporadic form of prion disease.

Conversion from PrPC into PrPres is an important process, because most prion diseases are characterized by presence of PrPres. Some knowledge of the conversion mechanism is based on studies of scrapie-infected cells. Recently, it has been reported that several conditions can induce the formation of PrPres in cultured cells. Proteasome inhibitors cause accumulation of the unglycosylated form of PrPres in treated cells (Lehmann & Harris, 1997; Ma & Lindquist, 1999; Yedidia et al., 2001). PrP that misfolds during maturation in the endoplasmic reticulum is delivered to the cytosol for degradation by proteasomes (Béranger et al., 2002; Ma & Lindquist, 2001; Yedidia et al., 2001). It has been hypothesized the conversion into PrPres might occur when the number of PrP molecules exceeds the capacity of the cell to degrade them (Ma & Lindquist, 2002). Another study showed that manganese-treated mouse astrocytes express the glycosylated form of PrPres (Brown et al., 2000).

Here, we report for the first time the conversion of PrPC into PrPres in the widely used human glioblastoma cell line T98G; a large number of passages and prolonged incubation under routine cell-culture conditions are required. In vitro-generated PrPres is reportedly not sufficient for the production of infectivity (Caughey et al., 2001; Hill et al., 1999) and further study is needed to clarify the infectivity of PrPres in T98G cells (indeed, caution should be taken with T98G cells in the laboratory). Infectivity assays of PrPres in T98G cells are now in progress in transgenic mice.

In conclusion, T98G cells should be a useful model for studying the mechanisms of PrPC conversion into PrPres.

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