Absence of spontaneous disease and comparative prion susceptibility of transgenic mice expressing mutant human prion proteins

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INTRODUCTION

Inherited prion diseases (IPDs) are fatal neurodegenerative disorders caused by autosomal-dominant mutations in the human PrP gene (PRNP), and constitute about 15% of all human prion disease (Collinge, 2001, 2005; Kovacs et al., 2002; Wadsworth et al., 2003; Mead, 2006). Over 30 mutations have been identified, but the precise biochemical mechanisms that lead to disease remain unknown.

According to the ‘protein-only’ hypothesis (Griffith, 1967), an abnormal isoform of host-encoded cellular prion protein (PrPC) is the principal, and possibly the sole, constituent of the transmissible agent or prion (Prusiner, 1982; Collinge & Clarke, 2007). This hypothesis proposes that the central pathogenic process is the conversion of PrPC to a disease-related isoform, PrPSc, through a conformational change occurring either spontaneously or during interaction with exogenous PrPSc. PrPSc consists of aggregated misfolded PrP and distinct prion strains are thought to be composed of different polymeric forms of PrP (for recent review see Collinge & Clarke, 2007). Importantly, IPDs may also be experimentally transmissible and it is thought that pathogenic mutations in PRNP predispose mutant PrPC to convert spontaneously to a pathogenic isoform (Collinge & Palmer, 1992; Collinge, 2005; Collinge & Clarke, 2007). While patients with IPD have traditionally been classified by the clinicopathological syndromes of Gerstmann–Sträussler–Scheinker disease (GSS), Creutzfeldt–Jakob disease (CJD) or fatal familial insomnia (FFI), the advent of molecular genetic diagnosis led to the recognition of considerable phenotypic hetero-

Approximately 15% of human prion disease is associated with autosomal-dominant pathogenic mutations in the prion protein (PrP) gene. Previous attempts to model these diseases in mice have expressed human PrP mutations in murine PrP, but this may have different structural consequences. Here, we describe transgenic mice expressing human PrP with P102L or E200K mutations and methionine (M) at the polymorphic residue 129. Although no spontaneous disease developed in aged animals, these mice were readily susceptible to prion infection from patients with the homotypic pathogenic mutation. However, while variant Creutzfeldt–Jakob disease (CJD) prions transmitted infection efficiently to both lines of mice, markedly different susceptibilities to classical (sporadic and iatrogenic) CJD prions were observed. Prions from E200K and classical CJD M129 homozygous patients, transmitted disease with equivalent efficiencies and short incubation periods in human PrP 200K, 129M transgenic mice. However, mismatch at residue 129 between inoculum and host dramatically increased the incubation period. In human PrP 102L, 129M transgenic mice, short disease incubation periods were only observed with transmissions of prions from P102L patients, whereas classical CJD prions showed prolonged and variable incubation periods irrespective of the codon 129 genotype. Analysis of disease-related PrP (PrPSc) showed marked alteration in the PrPSc glycoform ratio propagated after transmission of classical CJD prions, consistent with the PrP point mutations directly influencing PrPSc assembly. These data indicate that P102L or E200K mutations of human PrP have differing effects on prion propagation that depend upon prion strain type and can be significantly influenced by mismatch at the polymorphic residue 129.
genity even within families with the same PRNP mutation (Collinge et al., 1989, 1990, 1992; Mallucci et al., 1999; Kovacs et al., 2002; Wadsworth et al., 2006) and subclassification of IPD by pathogenic mutation was proposed (Collinge et al., 1992; Collinge & Prusiner, 1992).

The mutation at codon 200 of PRNP, which results in a glutamic acid substitution by lysine (E200K) in PrP, is one of the most prevalent, being responsible for the high incidence of CJD amongst Libyan Jews and in areas of Slovakia and Chile, and is recognized in many other countries (Goldfarb et al., 1990, 1991; Hsiao et al., 1991; Brown et al., 1992; Collinge et al., 1993; Kovacs et al., 2002). Families with the E200K mutation demonstrate varied clinical symptoms including uncommon features such as fatal insomnia, pruritus and demyelinating peripheral neuropathy or protracted dementia without other distinguishing characteristics (Chapman et al., 1993). Indeed, this form of IPD can present clinically and pathologically like classic sporadic CJD (Chapman et al., 1993), and although PRNP E200K homozygotes do not seem to differ in clinical features from heterozygotes, a statistically significant younger age at disease onset was found for homozygotes (Simon et al., 2000). Penetrance for the E200K mutation is age dependent and approaches 100% by 85 years of age (Chapman et al., 1993).

A proline to leucine substitution at codon 102 (P102L) of human PrP is the most common mutation associated with the GSS phenotype and was first reported in 1989 (Hsiao et al., 1989). Many other families have now been documented worldwide (Kovacs et al., 2002), including the original Austrian family reported by Gerstmann, Strässler and Scheinker in 1936 (Kretzschmar et al., 1991; Hainfellner et al., 1995). Progressive ataxia is the dominant clinical feature, with dementia and pyramidal features occurring later in a disease course typically much longer than that of classical CJD. However, marked variability at both the clinical and neuropathological levels is apparent, with some patients developing a classical CJD-like phenotype with early and rapidly progressive dementia (Hainfellner et al., 1995; Barbanti et al., 1996; Majtenyi et al., 2000; Wadsworth et al., 2006; Kretzschmar et al., 1992; Webb et al., 2008). A recent study indicates that differential recruitment of wild-type PrP into PrPSc may contribute to phenotypic variability in atypical cases (Wadsworth et al., 2006).

Polymorphism at residue 129 of human PrP [where either methionine (M) or valine (V) can be encoded] not only affects susceptibility to sporadic and acquired human prion diseases (Palmer et al., 1991; Collinge et al., 1991; Lee et al., 2001; Mead et al., 2003), but can affect the age of onset and also modify the phenotypes of IPDs (Baker et al., 1991; Poulter et al., 1992; Goldfarb et al., 1992; Mead et al., 2006).

Early attempts to transmit IPDs in non-human primates (Brown et al., 1994) and wild-type mice (Tateishi et al., 1996) resulted in poor transmission rates, resulting in the important issue of whether or not all IPDs are experimentally transmissible being unresolved (Collinge, 1997).

Transgenic mice expressing high levels of mouse PrP 101L (equivalent to 102L in human PrP) spontaneously developed neurological dysfunction at 166 days of age (Hsiao et al., 1990). PrPSc levels were low or undetectable, and brain extracts from affected mice did not transmit CNS degeneration to wild-type mice, but transmission to hamsters and Tg(GSSPrP)196 mice, expressing lower levels of the same mutant transgene product, was reported (Hsiao et al., 1994; Telling et al., 1996a). These Tg(GSSPrP)196 mice have subsequently been reported to develop spontaneous disease at advanced age (Tremblay et al., 2004; Nazor et al., 2005). It therefore remains debateable as to whether prions had been generated in these transgenic mice or this simply represents acceleration of a spontaneous neurodegenerative disease already poised to occur in these mice (Nazor et al., 2005). Others generated transgenic mice expressing endogenous levels of mouse PrP 101L by the gene knock-in approach (Manson et al., 1999). These mice did not develop spontaneous neurodegeneration but were reported to show greater susceptibility to human P102L prions than wild-type mice (Barron et al., 2001).

However, we consider it essential to study this and other human pathogenic mutations in human PrP, rather than in mouse PrP where the mutation may have different structural consequences. With respect to such models it is important to demonstrate that human PrP is functionally active and can participate in prion propagation and pathogenesis in mouse cells. Human PrP can rescue a PrP null phenotype in mice (Whittington et al., 1995), confirming it is functionally active and human prions can replicate in transgenic mice expressing only human PrP, which develop spongiform neurodegeneration (Collinge et al., 1995).

Importantly, there are examples of IPD where the amino acid change thought to be pathogenic is found as a normal variant in other mammalian species (Butefisch et al., 2000; Lysek et al., 2004; Colucci et al., 2006). There is also direct experimental evidence that a human PRNP mutation on a mouse background would not necessarily have the same structural consequences in the expressed protein. The introduction of a tryptophan residue at amino acid position 175 in place of the native phenylalanine has been successfully used as an optical probe for studying the folding dynamics of the recombinantly expressed mouse PrP (Wildegger et al., 1999). The introduction of this probe had no measurable effect on the stability of the protein. However, in stark contrast, when we introduced the same mutation into the human PRNP gene, the resultant recombinant PrP was unable to fold into the native conformation (T. Hart, G. J. Jackson, A. R. Clarke & J. Collinge, unpublished data). The profoundly dissimilar consequences of the same mutation in mouse and human PrP questions the whole approach of modelling human
pathogenic mutations on non-homologous PrP sequences from other species. In particular, the destabilizing effects measured in a mouse protein cannot be assumed to be equivalent in the human protein. The present study differs from all previous reports because we have investigated the biological properties of naturally occurring mutations in human PrP itself expressed in transgenic mice.

We have now generated two transgenic mouse lines that are both homozygous for the human PrP P102L,129M expressing transgene on a homozygous mouse PrP gene (Prnp) null background (HuPrP P102L,129M+/+ Prnpneo/neo). Similarly, we have generated two further transgenic lines that are both homozygous for human PrP P200K,129M transgenes, again on a Prnpneo background (HuPrP P200K,129M+/+ Prnpneo/neo). Here, we report the relative susceptibilities of these transgenic mice to classical (sporadic and iatrogenic) CJD prions, homotypic IPD isolates and variant (v) CJD prions.

METHODS

Transgene construction. Briefly, the 759 bp human PrP ORF was amplified by PCR with Pfu polymerase from human genomic DNA with appropriate mutations, using forward primer 5’-GTGGCAAGCTTATGGCGGAAGCTT-3’ and reverse primer 5’-CTCGAGAAGAGCTTCCTCATCCACT-3’. Restriction sites SalI and XhoI (underlined) were introduced in the forward and reverse primers, respectively, for use in subsequent cloning steps. The blunt-ended PCR fragments generated by Pfu polymerase were subcloned into Smal-digested pSP72 vector and sequenced to ensure that no spurious alterations have been introduced by the PCR other than the expected existing point mutations. The mutant human PrP ORFs with the appropriate point mutation confirmed were then isolated by using SalI and XhoI. Subsequent subcloning into the cosmid vector SHACosTt (Scott et al., 1989) and preparation of high quality DNA of the insert was as described previously (Asante et al., 2002).

Microinjection. The purified PRNP transgenes for P102L and E200K both with M at polymorphic codon 129 were microinjected (Hogan et al., 1994) into single cell eggs of a strain of mice (FVB x SV129 x C57) in which the murine PrP gene has been ablated. This was achieved by back-crossing ZH1 Prnp knockout line (Bueller et al., 1992) to FVB/N for five generations, breeding out Prnp and restoring homozygosity of the knockout allele. The injected eggs were cultured to the two-cell stage and then surgically transferred to F1 (CBA x C57BL/6) recipient females. Two homozygous lines were established for P102L designated Tg27 and Tg33 with mutant transgene expression levels of three and one and a half times, respectively, compared with pooled normal human brain levels. Similarly, two homozygous lines were established for E200K designated Tg23 and Tg49 with relative expression levels of three- and twofold, respectively.

Genotyping. Tail biopsies were taken from putative transgenics and screened by PCR using human PrP-specific primers (5’-GTGGGCA-GATGGAGTACGCGGCTC-3’ and 5’-GGACCCTCCAGCAT-GTACC-3’). Founders were confirmed by Southern blotting using a 900 bp 3’ UTR fragment as a radiolabelled probe. Lines were bred to homozygosity and 20 mice were set aside for long-term neurological observation.

Transmission studies. All procedures were carried out in a microbiological containment level III facility with strict adherence to safety protocols. A panel of inocula comprising four inherited P102L, three sporadic and three iatrogenic CJD cases used for the 102L transgenic mice. For the 200K transgenic mice, two inherited E200K and one iatrogenic CJD inocula were used. Inocula were prepared from the brain of neuropathologically confirmed cases of sporadic and inherited CJD with consent from relatives and with the approval from the Institute of Neurology/National Hospital for Neurology and Neurosurgery Local Research Ethics Committee. Mice were anaesthetized with a mixture of halothane and O2, and intracerebrally inoculated into the right parietal lobe with 30 μl of a 1% (w/v) brain homogenate prepared in PBS. All mice were thereafter examined daily for clinical signs of prion disease. Mice were killed if exhibiting any signs of distress or once a diagnosis of prion disease was established.

Neuropathology and immunohistochemistry. Neuropathology and immunohistochemical analyses were done as described previously (Asante et al., 2002, 2006) with the exception that abnormal PrP accumulation was examined using anti-PrP monoclonal antibody ICSM 18 (D-Gen Ltd) for P102L detection, and ICSM 35 (D-Gen Ltd) was used for E200K detection because the latter antibody does not recognize human PrP 102L (Wadsworth et al., 2006). Appropriate controls were used throughout.

Immunoblotting. Brain homogenates (10%, w/v) were prepared in Dulbecco’s PBS lacking Ca2+ and Mg2+ ions (D-PBS) by serial passage through needles of decreasing diameter. Aliquots were analysed with or without proteinase K digestion (50 or 100 μg ml−1 final protease concentration, 1 h, 37 °C) by electrophoresis and immunoblotting as described previously (Wadsworth et al., 2001, 2008; Hill et al., 2003, 2006). Blots were probed with anti-PrP monoclonal antibody 3F4 (Kascak et al., 1987). For quantification and analysis of PrP glycoforms, blots were developed in chemifluorescent substrate (AttoPhos; Promega) and visualized on a Storm 840 phosphoimager (Molecular Dynamics) (Wadsworth et al., 2001; Hill et al., 2003, 2006). Quantification of PrPsc glycoforms was performed using ImageQuant software (Molecular Dynamics).

RESULTS

Transgenic mice expressing HuPrP 102L or 200K do not develop spontaneous disease

We generated two homozygous transgenic mouse lines designated Tg(HuPrP P102L,129M+/+ Prnpneo/neo)-27 and Tg(HuPrP P200K,129M+/+ Prnpneo/neo)-33 that expressed human PrP 102L,129M at three and one and a half times the human endogenous PrPsc levels, respectively (Table 1), but not mouse PrP.

In order to assess the possibility of spontaneous neurodegeneration, we monitored an ageing cohort of 20 uninoculated mice from each 102LL (homozygous for proline to leucine 102 mutation) transgenic line. Mice that died before 90 days were considered to be still normal. The mice of both lines did not develop any neurological impairment and all were confirmed to be disease free. As expected, mice that died after 90 days showed clinical signs of prion disease with or without neuropathological confirmation. Some of these mice developed clinical signs of disease before the 102LL transgenic mice. This is not surprising because we have shown previously (Asante et al., 2002, 2006) that the PrP 102L transgenic mice do not develop spontaneous disease.

We also established two homozygous transgenic lines designated Tg(HuPrP P200K,129M+/+ Prnpneo/neo)-23 and Tg(HuPrP P102L,129M+/+ Prnpneo/neo)-49 that expressed human...


Table 1. Characterization of mutant human PrP transgenic lines

For each line, a cohort of mice was set aside for long-term observation. 102LL homozygous for proline to leucine 102 mutation; 200KK homozygous for glutamic acid to lysine 200 mutation; ND, not determined.

<table>
<thead>
<tr>
<th>PrP sequence</th>
<th>Tg-line</th>
<th>Transgene copy number</th>
<th>Expression level†</th>
<th>Age of oldest mouse (days)</th>
<th>Mean survival (days ± SEM)</th>
<th>Development of spontaneous neuropathy‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>102LL, 129MM</td>
<td>Tg27</td>
<td>11</td>
<td>3</td>
<td>870</td>
<td>736 ± 36 (n=9)</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Tg33</td>
<td>5</td>
<td>1.5</td>
<td>870</td>
<td>679 ± 43 (n=13)</td>
<td>No</td>
</tr>
<tr>
<td>200KK, 129MM</td>
<td>Tg23</td>
<td>5</td>
<td>3</td>
<td>960</td>
<td>832 ± 34 (n=14)</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Tg49</td>
<td>ND</td>
<td>2</td>
<td>862</td>
<td>753 ± 60 (n=5)</td>
<td>No</td>
</tr>
</tbody>
</table>

*Transgene copy number was determined in hemizygous mice.
†Expression levels presented here are homozygous levels and are relative to pooled normal human brain homogenate levels.
‡Each brain was scored negative for disease-related PrP by immunohistochemistry and immunoblotting.

PrP 200K, 129M at three and two times, respectively (Table 1), compared with endogenous PrPC levels in a pooled normal human brain homogenate. We again set aside 20 mutant mice from both 200KK (homozygous for glutamic acid to lysine 200 mutation) lines and observed them long-term. Mice that died earlier than 400 days from intercurrent illnesses showed no evidence of prion-related neuropathology. Again, mice in the cohort survived to an advanced age without clinical or neuropathological signs of prion disease or detectable PrPSc, with the oldest mouse living to more than 955 days (mean survival shown in Table 1). For both 102LL and 200KK mutant PRNP transgenic lines, Western blot analysis (data not shown) of samples from the brain of uninoculated mice showed equivalent proportions of di-, mono- and non-glycosylated PrP to that seen in Tg35 and Tg45 transgenic mice expressing wild-type human PrP 129M (Asante et al., 2002). These data establish that the PRNP point mutations do not selectively destabilize a particular PrP glycoform. It is worth noting that Tg45 mice expressing human PrP 129M at four times wild-type levels do not develop spontaneous disease at a similar age (Asante et al., 2002).

Transgenic mice expressing HuPrP 102L are more susceptible to prions from patients with IPD (P102L) than to classical CJD prions

To assess the susceptibility of human PrP 102L-expressing transgenic mice to human prions, we inoculated groups of Tg27 and Tg33 mice intracerebrally with isolates from patients with classical CJD and IPD (P102L). Clinical disease with high attack rates and short incubation periods ranging from 185 to 191 days accompanied the transmission of four different IPD P102L cases to Tg27 transgenic mice (Table 2). In sharp contrast, challenge of Tg27 mice with four classical CJD isolates, all resulted in incomplete clinical attack rates and prolonged and highly variable incubation periods ranging from 342 to 717 days. However, with the exception of one inoculum, I026, where two mice were not affected, all sporadic and iatrogenic CJD-inoculated mice were scored as positive for prion infection by one or more of the following criteria: typical clinical signs, presence of PrPSc on Western blot analysis or abnormal PrP immunohistochemistry (Table 2).

A similar pattern of differential susceptibility to prions from patients with IPD P102L and classical CJD was also observed in Tg33 mice, which have lower expression of human PrP 102L (Table 3). However, compared with Tg27, the incubation periods for prions from patients with IPD P102L in Tg33 mice were longer by about 160 days and clinical attack rates were lower, but this difference is consistent with the lower transgene expression levels in this line of transgenic mice. Importantly, the apparent transmission barrier to classical CJD relative to IPD P102L prions was again clearly observed, with mean incubation periods for sporadic and iatrogenic CJD prions being about 200 days longer than for IPD P102L cases (Table 3).

Neuropathological examination was performed to investigate whether the differential susceptibility to prions from classical CJD and IPD P102L cases would be associated with the development of distinct patterns of neuropathology. However, there was no discernible neuropathological difference between Tg27 and Tg33 mice challenged with either classical CJD or inherited P102L prions (data not shown). Using Tg27 as a representative line, transmissions of both classical and IPD P102L prions were characterized by generalized synaptic PrP deposits in the cerebral cortex, basal ganglia, hippocampus, thalamus (Fig. 2d) and to a lesser extent, in the brain stem and cerebellum (Fig. 2a, b). The main difference between classical CJD- and IPD P102L-prion-inoculated transgenic mice was quantitative, in that mice inoculated with classical CJD prions had more intense staining than recipients of IPD P102L prions (Fig. 2a, b). In mice with high levels of PrP deposition, PrP deposits were evident in the white matter. There was widespread spongiosis in almost all grey matter areas, with only the frontal lobes being spared. Multicentric plaques, a characteristic feature of GSS and associated with IPD (P102L) than to classical CJD prions

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Table 2. Classical CJD and IPD P102L prion transmissions to human PrP 102LL 129M Tg27 transgenic mice

IHC, Immunohistochemistry; IB, immunoblotting; DM, dura mater; GH, growth hormone; ND, not determined.

<table>
<thead>
<tr>
<th>Aetiology</th>
<th>Inoculum</th>
<th>Tg(HuPrP&lt;sup&gt;102L,129M&lt;/sup&gt;+/&lt;sup&gt;-&lt;/sup&gt; Prnp&lt;sup&gt;o/o&lt;/sup&gt;)-27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>PRNP 129 genotype</td>
<td>Human PrP&lt;sup&gt;Sc&lt;/sup&gt; type*</td>
</tr>
<tr>
<td>IPD P102L</td>
<td>I1087</td>
<td>MV§</td>
</tr>
<tr>
<td></td>
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<td>I1476</td>
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<td>MM</td>
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<td>MM</td>
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<td></td>
<td>I1020 (GH)</td>
<td>MV</td>
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</tr>
<tr>
<td>vCJD</td>
<td>I1336</td>
<td>MM</td>
</tr>
</tbody>
</table>

*According to the classification of Hill et al. (2003).
†Primary antibody was monoclonal ICSM 18 because monoclonal antibody ICSM 35 does not recognize 102L PrP<sup>Sc</sup> (Wadsworth et al., 2006).
‡Positive either by clinical signs, Western blot analysis and/or immunohistochemistry.
§PRNP mutation is on the 129M allele (Hill et al., 2006).
||Glycoform profile for all samples showed a shift towards diglycosylated dominance (Hill et al., 2006).
¶All positive samples propagated T4 PrP<sup>Sc</sup> (Hill et al., 2003).

Table 3. Classical CJD and IPD P102L prion transmissions to human PrP 102LL 129M Tg33 transgenic mice

IHC, Immunohistochemistry; IB, immunoblotting; DM, dura mater.

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<tr>
<th>Aetiology</th>
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<th>Tg(HuPrP&lt;sup&gt;102L,129M&lt;/sup&gt;+/&lt;sup&gt;-&lt;/sup&gt; Prnp&lt;sup&gt;o/o&lt;/sup&gt;)-33</th>
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<tr>
<td>Code</td>
<td>PRNP 129 genotype</td>
<td>Human PrP&lt;sup&gt;Sc&lt;/sup&gt; type*</td>
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<tr>
<td>IPD P102L</td>
<td>I1087</td>
<td>MV§</td>
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<td></td>
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<td></td>
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<td>Sporadic CJD</td>
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<td>MV</td>
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<td></td>
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<td>MV</td>
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<tr>
<td>Iatrogenic CJD (DM)</td>
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</table>

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‡Positive either by clinical signs, Western blot analysis and/or immunohistochemistry.
§PRNP mutation is on the 129M allele (Hill et al., 2006).
||Glycoform profile for all samples was the inherited PrP<sup>Sc</sup> pattern (Hill et al., 2006).
¶Glycoform profile for all samples showed a shift towards diglycosylated dominance (Hill et al., 2006).
#Two samples had the inherited PrP<sup>Sc</sup> glycotype and differed significantly from the classical CJD type (Hill et al., 2006).
**No sample was positive by IB.
††Signal was too weak to allow assignment of glycotypes.
punctate PrP staining only being observed in the hippocampus (Fig. 2e).

**Transgenic mice expressing HuPrP 200K show similar susceptibilities to IPD (E200K) and classical CJD prions**

Groups of Tg23 and Tg49 transgenic mice were challenged with brain homogenates from two different human IPD E200K cases, one homozygous for PRNP 129M (designated E200K-129MM) and the other homozygous for PRNP 129V (designated E200K-129VV). In addition, we transmitted one case of iatrogenic CJD to both lines in order to investigate its interactions with human PrP 200K.

IPD E200K-129MM inoculum (I1091) transmitted clinical disease to 8/8 of Tg23 mice, with a short mean incubation period of 184 ± 3 days (Table 4). In sharp contrast, the second IPD E200K inoculum (I093) (E200K-129VV) produced clinical disease in only 1/4 inoculated mice with a relatively prolonged incubation period of 437 days. There was however 100% total infection rate because the three clinically asymptomatic mice, which died at 410, 518 and 538 days post-inoculation, had clear evidence of subclinical prion infection as determined either by PrP immunohistochemical or Western blot analysis (Table 4). The transmission properties of classical CJD in Tg23 mice were distinct from that observed in human PrP 102L-expressing transgenic mice. Here, iatrogenic CJD 129MM inoculum (I026) produced 100% clinical attack rate and with relatively short mean incubation period of 184 ± 7 days that was remarkably similar to the mean incubation period for IPD E200K-129MM inoculum I1091. These data suggest that, providing there is homology at residue 129 between the inoculum and the host PrP, the E200K mutation does not introduce a transmission barrier for classical CJD prions.

The prion transmission pattern for transgenic line Tg49 that had a lower level of expression of human PrP 200K, also followed a similar trend, being characterized by high clinical attack rates and almost identical incubation periods of 344 days for iatrogenic CJD inoculum I026, and 348 days for IPD E200K-129MM inoculum I1091 (Table 5). The transmission barrier associated with 129V was also evident in Tg49 mice, as challenge of this line with IPD E200K-129VV inoculum (I093) was also characterized by only 1/6 clinical attack rate and a prolonged incubation period of 552 days, about 200 days longer than that observed for iatrogenic CJD (129MM) in the same line (Table 5). The apparent low transmission efficiency of IPD E200K-129VV inoculum (I093) in both Tg23 and Tg49 mice was not due to low prion titre, because the same inoculum caused clinical disease in 11/11 Tg152 transgenic mice expressing human PrP 129V with a short incubation period of 187 ± 9 days (data not shown). PBS-inoculated transgenic mice did not develop clinical disease, with most mice dying from intercurrent illnesses at advanced ages with no neuropathology.

Neuropathological examination of affected brains revealed synaptic type PrP deposits in the cortex and thalamic nuclei of iatrogenic CJD-inoculated Tg23 and Tg49 mice (data not shown), and this pattern of neuropathology closely resembled that produced in both transgenic lines by IPD E200K-129MM inoculum (I1091) (Fig. 2g, j). Interestingly, the only discrete PrP plaques seen were associated with IPD E200K-129VV inoculum I093 and these were predominantly located in the cortex and corpus callosum (Fig. 2h, k). There were comparatively more of

### Table 4. Classical CJD and IPD E200K prion transmissions to human PrP 200KK 129M Tg23 transgenic mice

<table>
<thead>
<tr>
<th>Aetiology</th>
<th>Inoculum</th>
<th>PRNP 129 genotype</th>
<th>Human PrPSc type*</th>
<th>Clinical signs</th>
<th>Incubation period (days ± SEM)</th>
<th>Positive by IHC†</th>
<th>Positive by IB†</th>
<th>Total affected‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iatrogenic CJD  (DM)</td>
<td>I026</td>
<td>129MM</td>
<td>T2</td>
<td>8/8</td>
<td>184 ± 7</td>
<td>2/2</td>
<td>5/5§</td>
<td>8/8</td>
</tr>
<tr>
<td>IPD E200K</td>
<td>I091</td>
<td>129MM</td>
<td>T1</td>
<td>8/8</td>
<td>184 ± 3</td>
<td>2/2</td>
<td>4/4I</td>
<td>8/8</td>
</tr>
<tr>
<td>IPD E200K</td>
<td>I093</td>
<td>129VV</td>
<td>T3</td>
<td>1/4</td>
<td>437</td>
<td>3/3</td>
<td>4/4§</td>
<td>4/4</td>
</tr>
<tr>
<td>vCJD</td>
<td>I236</td>
<td>129MM</td>
<td>T4</td>
<td>3/6</td>
<td>578</td>
<td>3/3</td>
<td>5/5#</td>
<td>6/6</td>
</tr>
</tbody>
</table>

*According to the classification of Hill et al. (2003).
†Primary antibody was monoclonal ICSM 35.
‡Positive either by clinical signs, Western blot analysis and/or immunohistochemistry, primary antibody was ICSM 35.
§Four samples propagated inherited PrPSc pattern (Hill et al., 2006), one sample was positive but signal was too weak to assign glycotype.
||Three samples propagated inherited PrPSc pattern (Hill et al., 2006), one sample was positive but signal was too weak to assign glycotype.
¶All positive samples propagated the inherited PrPSc pattern (Hill et al., 2006).
#All positive samples propagated a novel human PrPSc type (designated PrPSc type 8) with lower molecular mass fragment size than type 4 PrPSc (Hill et al., 2003).
these discrete PrP plaques in the Tg49 transgenic line with lower expression level (Fig. 2h, k) than in the higher expressing Tg23 line (data not shown).

**Table 5.** Classical CJD and IPD E200K prion transmissions to human PrP 200KK 129M Tg49 transgenic mice

<table>
<thead>
<tr>
<th>Aetiology</th>
<th>Code</th>
<th>PRNP 129 genotype</th>
<th>Human PrPSc type</th>
<th>Tg(HuPrP&lt;sup&gt;200K,129M&lt;/sup&gt;+/+ Prnp&lt;sup&gt;0/0&lt;/sup&gt;-49)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Clinical signs</td>
</tr>
<tr>
<td>Iatrogenic CJD</td>
<td>I026</td>
<td>129MM</td>
<td>T2</td>
<td>6/9</td>
</tr>
<tr>
<td>(DM)</td>
<td>I1091</td>
<td>129MM</td>
<td>T1</td>
<td>5/8</td>
</tr>
<tr>
<td>IPD E200K</td>
<td>I1093</td>
<td>129VV</td>
<td>T3</td>
<td>1/6</td>
</tr>
<tr>
<td>vCJD</td>
<td>I336</td>
<td>129MM</td>
<td>T4</td>
<td>2/6</td>
</tr>
</tbody>
</table>

*Primary antibody was monoclonal ICSM 35.
†Positive either by clinical signs, Western blot analysis and/or immunohistochemistry; primary antibody was ICSM 35.
‡All positive samples propagated the inherited PrP<sup>Sc</sup> pattern (Hill et al., 2006).
§All positive samples propagated a novel PrP<sup>Sc</sup> type (designated PrP<sup>Sc</sup> type 8) with lower molecular mass fragment size than type 4 PrP<sup>Sc</sup> (Hill et al., 2003).

**PrP glycoform profiles in transgenic mice challenged with classical CJD and IPD prions**

Within the framework of the protein-only hypothesis, the different phenotypes associated with prion strains are thought to be determined by the propagation of distinct PrP<sup>Sc</sup> isoforms with divergent physico-chemical properties (Bessen & Marsh, 1994; Collinge et al., 1996b; Telling et al., 1996b; Safar et al., 1998; Prusiner, 1998; Hill & Collinge, 2000; Collinge, 2001; Gambetti et al., 2003; Collinge & Clarke, 2007). IPDs with P102L and E200K mutations are associated with a unique PrP<sup>Sc</sup> glycoform ratio that differs significantly from those seen in classical CJD and vCJD (Collinge et al., 1996b; Hill et al., 2003, 2006; Wadsworth et al., 2006). We therefore analysed PrP<sup>Sc</sup> glycoform ratios propagated in human PrP 102L- and 200K-expressing transgenic mice challenged with a range of human prions. Mice inoculated with either IPD isolates or classical CJD isolates propagated PrP<sup>Sc</sup> with a predominance of both di- and monoglycosylated PrP (Fig. 1). This finding is of particular interest in recipients of classical CJD prions where a change in PrP<sup>Sc</sup> glycoform ratio is apparent on transmission (see Fig. 1b lanes 3 and 6; and Table 6). While the primary transmission data suggest that there are statistically significant differences in the glycoform ratios of PrP<sup>Sc</sup> propagated in human PrP 102L- and 200K-expressing transgenic mice inoculated with IPD isolates (data not shown) or classical CJD prions (Table 6), further subpassage to transgenic mice expressing either mutant or wild-type PrP will be required to fully interpret this observation because of the heterogeneous nature of the primary IPD inocula from patients’ brains used in these
primary transmissions (Hill et al., 2006; Wadsworth et al., 2006; Wadsworth & Collinge, 2007).

**PRNP point mutations in association with 129M do not prevent propagation of the vCJD prion strain**

To date all neuropathologically confirmed vCJD cases have been associated with 129M homozygosity (Collinge et al., 1996a; Collinge, 2005). We and others have reported previously that PrP 129M homozygosity is required for the experimental recapitulation of abundant florid plaque formation from BSE and vCJD prion infection (Crozet et al., 2001; Asante et al., 2002; Wadsworth et al., 2004; Bishop et al., 2006). Notably, overexpression is not required for florid plaque formation (Asante et al., 2006). Furthermore, 129V has a dominant-negative effect on the formation of florid plaques in the PRNP 129MV heterozygous genotype, leading to dissociation between the propagation of type 4 PrPSc and florid plaque formation (Asante et al., 2006). To investigate if PRNP point mutations would affect the propagation of...
vCJD prions and expression of characteristic pathology, we challenged Tg27, Tg23 and Tg49 transgenic mice (all of which are homozygous for 129M) with a previously characterized vCJD isolate designated I336 (Tables 2, 4 and 5).

Transmission of vCJD prions to Tg27 mice resulted in only 2/11 clinical attack rate with prolonged incubation periods greater than 482 days post-inoculation (Table 2), but 11/11 total infection rate (positive either by clinical scoring, immunoblot or immunohistochemistry), mirroring transmission properties of the same vCJD inoculum in homozygous human PrP 129MM-expressing Tg35 and Tg45 mice (Asante et al., 2002). Similarly, transmission of vCJD to Tg23 and Tg49 transgenic mice resulted in 3/6 and 2/6 clinical attack rates, respectively, and with prolonged incubation periods (Tables 4 and 5), and these were again accompanied by 100% total infection rate in both lines, as determined either by clinical scoring, Western blot analysis or immunohistochemistry. Affected Tg27 mice propagated PrPSc that was closely similar to type 4 PrPSc present in vCJD-inoculated Tg152 mice (Fig. 1d, lanes 1 and 3) and distinct from type 5 PrPSc seen in vCJD-inoculated Tg152 mice expressing human PrP 129V (Hill et al., 1997; Wadsworth et al., 2004) (Fig. 1d, lane 2). In keeping with this finding, vCJD-inoculated Tg27 mice showed neuropathological changes that were characteristic of the vCJD prion strain with extensive plaque deposition many of which were of the florid type (Fig. 2c, f).

In vCJD challenged human PrP 200K-expressing transgenic mice Tg23 (data not shown) and Tg49 (Fig. 2i, l), abundant florid plaques were also observed that were indistinguishable from the florid plaques generated in transgenic mice expressing wild-type human PrP 129MM, Tg35 or Tg45 (Asante et al., 2002). Interestingly, the lower human PrP 200K-129M-expressing Tg49 line had a higher PrP plaque load than Tg23 mice, suggesting that PrP plaque density may be related to the kinetics of PrPSc formation. Notably, however, both human PrP 200K-129M-expressing lines Tg23 and Tg49 propagated PrPSc with a slightly lower molecular mass fragment size than type 4 PrPSc seen in the vCJD inoculum (Fig. 1d, lanes 4 and 5). We have provisionally designated this new PrPSc isoform, that generates proteinase K-resistant fragments sharing the glycoform ratio of types 4 and 5 PrPSc but with a smaller fragment size than type 4, as human PrPSc type 5. Serial passage studies will be required to establish if, like type 5 PrPSc, this novel PrPSc type represents a distinct vCJD-derived prion strain. In this regard, it will be interesting to see whether this distinct PrPSc conformer, that is associated with abundant florid plaques in human PrP 200K-expressing transgenic mice (Fig. 2i, l), can be maintained on subpassage in transgenic mice expressing wild-type human PrP.

**DISCUSSION**

In these studies, we have used transgenic mice homozygous for two different human PrP mutations and devoid of murine PrP, in order to allow a comparative study of the transmission properties of PRNP mutations in the absence of the confounding effects of endogenous murine PrP. Our study differs from previous reports (Hsiao et al., 1990; Hegde et al., 1998; Chiesa et al., 1998; Manson et al., 1999), in that we have modelled PRNP disease-associated mutations on human PrP, rather than superimposing the human mutations on rodent PrP. This is particularly important because destabilizing effects measured in a mouse protein cannot be assumed to be equivalent in the human protein (Wildegger et al., 1999; T. Hart, G. J. Jackson, A. R. Clarke & J. Collinge, unpublished data).

Our data show that while the P102L mutation is permissive to homotypic IPD P102L prions, there appears to be a barrier limiting the transmission of classical CJD prions. In contrast, the E200K mutation is equally permissive to homotypic IPD E200K and classical CJD prions, providing there is no mismatch at PRNP codon 129. Neither mutation appears to influence the propagation of the vCJD prion strain.

Previously we have shown that cases of IPD caused by the PRNP point mutations P102L, D178N and E200K have a unique PrPSc glycoform ratio following proteinase K digestion, which differs significantly from PrPSc glycoform ratios observed in sporadic, iatrogenic and vCJD or IPD caused by octapeptide repeat insertion mutations (Hill et al., 2004).}

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**Table 6. Transmission of classical CJD leads to a significant alteration in PrPSc glycoform ratios in 200KK and 102LL transgenic mice**

<table>
<thead>
<tr>
<th>PRNP mutation</th>
<th>Classical CJD T2 MM</th>
<th>200KK 129M Tg23</th>
<th>200KK 129M Tg49</th>
<th>102LL 129M Tg27</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>19.6 ± 1.0*</td>
<td>32.6 ± 2.0</td>
<td>40.9 ± 4.0</td>
<td>50.8 ± 5.0</td>
</tr>
<tr>
<td>Diglycosylated PrPSc</td>
<td>32.6 ± 2.0 P&lt;0.0001</td>
<td>E200K</td>
<td>40.9 ± 4.0 P&lt;0.0001</td>
<td>50.8 ± 5.0 P&lt;0.0001</td>
</tr>
<tr>
<td>Monoglycosylated PrPSc</td>
<td>47.9 ± 1.0</td>
<td>48.3 ± 2.0 P=0.8</td>
<td>37.0 ± 2.0 P&lt;0.0001</td>
<td>36.5 ± 2.0 P&lt;0.0001</td>
</tr>
<tr>
<td>Unglycosylated PrPSc</td>
<td>32.6 ± 1.0</td>
<td>19.1 ± 1.0 P&lt;0.0001</td>
<td>21.8 ± 2.0 P&lt;0.0004</td>
<td>12.6 ± 3.0 P&lt;0.0001</td>
</tr>
</tbody>
</table>

*Glycoform ratios of PrPSc propagated in transgenic mice (n=3 per line) inoculated with classical CJD isolate I026 [type 2 PrPSc 129MM (T2 MM)] are compared with the human T2 MM glycoform ratio (n=11) (Hill et al., 2006). Data show mean ± SEM. P values relate to comparison with classical CJD T2 MM (unpaired two-tailed t-test).
et al., 2006; Wadsworth et al., 2006). These data suggested that point mutations in PRNP either destabilize non-glycosylated PrP, in turn reducing its relative abundance (Petersen et al., 1996), or directly dictate the stoichiometry and packing order of the three PrP glycoforms into disease-related fibrils or other aggregates. The latter explanation is consistent with a conformational selection model of prion transmission barriers (Collinge, 1999; Hill & Collinge, 2003; Collinge & Clarke, 2007) that predicts that coding changes in PrP act to specify structural preferences for disease-related PrP isoforms. The full spectrum of effects that different pathogenic PRNP mutations may have still remains unclear (Hill et al., 2006).

Importantly, our data now show that the PrPSc glycoform ratio of classical CJD prions is not maintained on passage in transgenic mice expressing PRNP 102L or 200K point mutations. Instead PrPSc propagates with a glycoform ratio closely similar to those seen in patients with P102L and E200K IPD that is significantly different from the PrPSc types present in the classical CJD inoculum. These data support the hypothesis that prion strains propagated in IPDs are distinct from those propagated in classical (sporadic and iatrogenic) CJD (Hill et al., 2006). As equivalent proportions of the PrP glycoforms are seen in uninoculated wild-type or mutant PRNP transgenic mice, this change in PrPSc glycoform ratio is consistent with the PRNP point mutations acting to directly dictate the stoichiometry and packing order of the three PrP glycoforms into disease-related fibrils or other aggregates (Hill et al., 2006). Furthermore, previous immunoprecipitation studies using a panel of monoclonal antibodies suggested that the proportion of each glycoform incorporated into PrPSc is probably controlled in a strain-specific manner (Khalili-Shirazi et al., 2005).

The interpretation of primary transmission data for IPD isolates is complicated by the heterogeneous composition of disease-related PrP isoforms that may be present in the primary inoculum (Hill et al., 2006; Wadsworth et al., 2006; Wadsworth & Collinge, 2007). For example in P102L IPD, it is now apparent that three isoforms of protease-resistant PrP with divergent physico-chemical properties can be propagated. Two distinct abnormal conformers derived from PrP P102L generate protease-resistant fragments of either approximately 21–30 or 8 kDa (Parchi et al., 1998; Piccardo et al., 1998, 2007; Muramoto et al., 2000; Hill et al., 2006; Wadsworth et al., 2006), while abnormal conformers of wild-type PrP appear to generate protofibrillary fragments of only approximately 21–30 kDa (Wadsworth et al., 2006). Glycoform ratios of approximately 21–30 kDa proteolytic fragments generated from PrP P102L and wild-type PrP are not only distinct from each other, but are also distinct from those generated from wild-type PrP in sporadic or acquired CJD (Wadsworth et al., 2006). Differences in neuropathological targeting of these distinct disease-related PrP species, together with differences in their abundance and potential neurotoxicity, provide a molecular mechanism for generation of multiple phenotypes in P102L IPD (Wadsworth et al., 2006; Piccardo et al., 2007). Propagation of particular PrPSc isoforms in a new host will also be determined by host genetic background, PRNP sequence and prion strain type (Collinge & Clarke, 2007). These data have significant implications for interpreting the transmission properties of IPD isolates in both conventional and transgenic mice and may in part explain the historical differences seen in previous transmissions of IPD isolates (Brown et al., 1994; Tateishi et al., 1996). Serial passage studies of the prion isolates generated here should help to clarify the major influencing factors limiting the transmission of IPD, and how many strains may be associated with IPDs.

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Prion transmissions in transgenic mice


isoform of the prion protein enciphering and propagating prion diversity. Science 274, 2079–2082.


