The influence of the commensal and pathogenic gut microbiota on prion disease pathogenesis

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Prion diseases are a unique group of transmissible, chronic, neurodegenerative disorders. Following peripheral exposure (e.g. oral), prions often accumulate first within the secondary lymphoid tissues before they infect the central nervous system (CNS). Prion replication within secondary lymphoid tissues is crucial for the efficient spread of disease to the CNS. Once within the CNS, the responses of innate immune cells within it can have a significant influence on neurodegeneration and disease progression. Recently, there have been substantial advances in our understanding of how cross-talk between the host and the vast community of commensal microorganisms present at barrier surfaces such as the gut influences the development and regulation of the host’s immune system. These effects are evident not only in the mucosal immune system in the gut, but also in the CNS. The actions of this microbial community (the microbiota) have many important beneficial effects on host health, from metabolism of nutrients and regulation of host development to protection from pathogen infection. However, the microbiota can also have detrimental effects in some circumstances. In this review we discuss the many and varied interactions between prions, the host and the gut microbiota. Particular emphasis is given to the ways by which changes to the composition of the commensal gut microbiota or congruent pathogen infection may influence prion disease pathogenesis and/or disease susceptibility. Understanding how these factors influence prion pathogenesis and disease susceptibility is important for assessing the risk to infection and the design of novel opportunities for therapeutic intervention.

Introduction

Prion diseases, or transmissible spongiform encephalopathies, are sub-acute neurodegenerative diseases that affect humans and certain domestic and free-ranging animal species (Table 1). Prion diseases are characterized by the presence of aggregations of PrPSc, an abnormally folded isoform of the host-encoded cellular prion protein (PrPC), in affected tissues (Bolton et al., 1982; Prusiner et al., 1982). Prions are unique amongst infectious agents in that they appear to lack nucleic acid, comprising solely the PrPSc protein (Legname et al., 2004; Wang et al., 2010). The accumulation of PrPSc in the central nervous system (CNS) of prion-infected hosts is accompanied by reactive microglial and astroglial responses, and significant levels of neurodegeneration. A diverse range of cellular functions have been ascribed to the cellular PrPC protein including maintenance of circadian rhythms (Tobler et al., 1996), signal transduction (Spielhauper & Schatzl, 2001), seizure sensitivity (Walz et al., 1999), cognition (Coitinho et al., 2003), maintenance of peripheral myelin (Bremer et al., 2010) and phagocytosis of apoptotic cells (de Almeida et al., 2005). However, the precise physiological role remains controversial as some, with the exception of peripheral myelin maintenance, have been since shown to be due to consequences of flanking-gene issues or spurious overexpression of Doppel protein in certain PrP-deficient mouse lines (Nuvolone et al., 2016, 2013; Steele et al., 2007).

Some prion diseases have an idiopathic aetiology, apparently arising spontaneously within the CNS (e.g. sporadic Creutzfeldt–Jakob disease; CJD). Others such as Gerstmann–Straussler–Scheinker syndrome are associated with polymorphisms within the PRNP gene (which encodes PrPC), which may predispose PrPC to abnormally fold into the pathogenic isoform, whereas other polymorphisms may protect against disease transmission (Asante et al., 2015). Many other prion diseases are acquired, such as following oral consumption of prion-contaminated food. These include natural sheep scrapie, bovine spongiform encephalopathy (BSE), chronic wasting disease (CWD) in cervid species such as deer and elk, and variant Creutzfeldt–Jakob disease (vCJD) in humans (Table 1).

The gut-associated lymphoid tissues (GALT) are a group of multi-follicular structures including the tonsils, Peyer’s patches, appendix, colonic and caecal patches, as well as individual follicular structures termed isolated lymphoid...
Table 1. Prion diseases of humans and animals

<table>
<thead>
<tr>
<th>Prion disease</th>
<th>Affected species</th>
<th>Route of transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iatrogenic CJD</td>
<td>Human</td>
<td>Accidental medical exposure to CJD-contaminated tissues or tissue products</td>
</tr>
<tr>
<td>Sporadic CJD</td>
<td>Human</td>
<td>Unknown. Theories include somatic mutation or spontaneous conversion of PrP(^\text{Sc}) to PrP(^\text{C}).</td>
</tr>
<tr>
<td>Variant CJD</td>
<td>Human</td>
<td>Ingestion of BSE-contaminated food or transfusion of blood or blood products</td>
</tr>
<tr>
<td></td>
<td></td>
<td>from CJD-infected blood donor</td>
</tr>
<tr>
<td>Familial CJD</td>
<td>Human</td>
<td>Germ-line mutations of the PRNP gene</td>
</tr>
<tr>
<td>Gerstmann–Straussler–</td>
<td>Human</td>
<td>Germ-line mutations of the PRNP gene</td>
</tr>
<tr>
<td>Scheiniker syndrome</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kuru</td>
<td>Human</td>
<td>Ritualistic cannibalism</td>
</tr>
<tr>
<td>Fatal familial insomnia</td>
<td>Human</td>
<td>Germ-line mutations of the PRNP gene</td>
</tr>
<tr>
<td>Bovine spongiform</td>
<td>Cattle</td>
<td>Ingestion of contaminated food</td>
</tr>
<tr>
<td>encephalopathy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scapie</td>
<td>Sheep, goats,</td>
<td>Acquired. Ingestion, horizontal transmission, vertical transmission unclear</td>
</tr>
<tr>
<td></td>
<td>mouflon</td>
<td></td>
</tr>
<tr>
<td>Chronic wasting disease</td>
<td>Elk, deer, moose</td>
<td>Acquired. Ingestion, horizontal transmission, vertical transmission unclear</td>
</tr>
<tr>
<td>Transmissible mink</td>
<td>Mink</td>
<td>Acquired (ingestion) source unknown</td>
</tr>
<tr>
<td>encephalopathy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feline spongiform</td>
<td>Domestic and</td>
<td>Ingestion of BSE-contaminated food</td>
</tr>
<tr>
<td>encephalopathy</td>
<td>zoological cats</td>
<td></td>
</tr>
<tr>
<td>Exotic ungulate</td>
<td>Nyala, kudu</td>
<td>Ingestion of BSE-contaminated food</td>
</tr>
<tr>
<td>encephalopathy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BSE, bovine spongiform encephalopathy; CJD, Creutzfeldt–Jakob disease; PRNP, the gene that encodes PrP\(^\text{Sc}\).

folicles (ILFs). GALTs occur throughout the gastrointestinal tract and along with the mesenteric lymph nodes help maintain homeostasis within the gut and protect the host from pathogen infection. After oral exposure, the replication of prions within Peyer’s patches in the small intestine is crucial for their efficient transmission to the CNS (termed neuroinvasion) (Donaldson et al., 2015b). Within them, the prions replicate on the surfaces of stromal-derived follicular dendritic cells (FDCs) located within the B-cell folicles (Mabbott et al., 2000, 2003; McCulloch et al., 2011; Montrasio et al., 2000). The prions then infect neighbouring enteric nerves, and spread from them via the sympathetic and parasympathetic nervous systems to the CNS, where they cause neurodegeneration and the eventual death of the host (Beekes & McBride, 2000; Glatzel et al., 2001; Kujala et al., 2011; McBride et al., 2001).

The mammalian gastrointestinal tract is home to a vast community of commensal microorganisms, termed the microbiota (Sommer & Backhead, 2013), and the colon of a typical 70 kg human male is estimated to harbour approximately \(3.9 \times 10^{13}\) bacteria (Sender et al., 2015). The commensal gut microbiota provides many beneficial effects on host health including metabolizing nutrients (Russell et al., 2013), influencing the development and regulation of the immune system (Furusawa et al., 2013; Hooper et al., 2012), as well as outcompeting pathogens for nutrients or habitats (Kamada et al., 2012). Rapid advances in high-throughput sequencing technology have helped to provide a greater understanding of the true abundance and complexity of the commensal microbiota (Claesson & O’Toole, 2010). This, in turn, has helped reveal how factors such as diet, host genotype (Carmody et al., 2015), antibiotic use (Gibson et al., 2015), pathogen infection (Holm et al., 2015), host age and even the residential environment (Claesson et al., 2012) can affect both the composition of the gut microbiota and host health.

Disturbances to the abundance and complexity of the microbiota can dramatically affect immune regulation and function, and are contributory factors in the development of some inflammatory and autoimmune diseases (Frank et al., 2007). These influences extend far beyond the GALT, which have a close physical relationship with the microbiota. Remarkably, the gut microbiota can also affect the development of the CNS. The gut microbiota of mice can influence the development of certain neuronal circuits such as those involved in anxiety-like behaviour (Sudo et al., 2004), and constitutively controls the maturation and function of microglia within the CNS (Erny et al., 2015). Furthermore, diet-induced increases in bacteria from the order Clostridiales and a decrease in Bacteroidales, are associated with poor cognitive flexibility (Magnusson et al., 2015).

In this review, we discuss how imbalances to the composition or abundance of the host commensal microbiota, or congruent pathogen infection, may influence prion-disease pathogenesis and susceptibility.
Effect of changes to the abundance and complexity of the gut microbiota on prion disease

Effects on oral prion disease pathogenesis

Cross-talk between the host immune system and the microbiota is critical for the development of the immune system, especially the GALT, which can, in turn, regulate the microbiota. At the time of writing this review there were no published studies that had directly addressed the influence of the commensal gut microbiota on oral prion disease pathogenesis. Therefore, discussed below are studies which help to shed light on the effects that disturbances to the commensal gut microbiota may have.

A dramatic reduction in the microbiota at the time of oral prion exposure could potentially impede disease pathogenesis. One pronounced effect that the gut microbiota has on the host is the dynamic regulation of ILF development in the intestine (Donaldson et al., 2015a; Hamada et al., 2002) (Fig. 1). ILFs are inductive sites for immunoglobulin-A production and can be classified as either immature ILFs (primary B-cell follicles), or mature ILFs containing a single organized germinal centre, with a network of FDCs and an overlying epithelium containing M cells (Donaldson et al., 2015a; Glaysher & Mabbott, 2007a; Lorenz et al., 2003). ILF abundance is reduced in the small intestines of germ-free mice (which lack a gut microbiota), whereas ILF development is induced upon microbial colonization (Donaldson et al., 2015a). Our data show that ILFs are important sites of prion accumulation and neuroinvasion in the small intestine (Donaldson et al., 2015b; Glaysher & Mabbott, 2007b). Furthermore, oral prion-disease susceptibility is reduced in the specific absence of GALT (ILFs or Peyer’s patches) in the small intestine (Donaldson et al., 2015b; Glaysher & Mabbott, 2007b; Horiuchi et al., 2006; Prinz et al., 2003). These observations suggest that a microbiota-induced reduction in ILF density in the small intestine could impede disease pathogenesis by reducing the available sites of prion uptake, replication and neuroinvasion in the gut.

Unlike in the small intestine where the microbiota promotes ILF development, the microbiota inhibits ILF development in the large intestine (Fig. 1) (Donaldson et al., 2015a). However, our experiments in mice show that large intestinal GALT are not important sites of prion neuroinvasion after oral exposure (Donaldson et al., 2015a). Furthermore, an increased density of ILFs, specifically in the large intestine, does not influence oral prion-disease pathogenesis or susceptibility (Donaldson et al., 2015b). Large intestinal GALT are also not considered to be important early sites of prion accumulation in humans exposed to vCJD (Hill et al., 1999; Peden et al., 2004), sheep with natural scrapie and BSE (van Keulen et al., 2008a, b) and cervids with CWD (Spraker et al., 2006, 2009). The early accumulation of prions in the ileal Peyer’s patches of cattle experimentally exposed to BSE has also been described (Kaatz et al., 2012).

Pathogen infection can also disturb the composition of the commensal gut microbiota. For example, a chronic infection of mice with the large intestinal nematode Trichuris muris decreases bacterial diversity, and increases the relative abundance of Lactobacillaceae (Holm et al., 2015) (Fig. 2). However, congruent infection with T. muris at the time of oral prion exposure does not influence disease pathogenesis (Donaldson et al., 2015b) (Table 2). Therefore, unlike in the small intestine where microbiota-mediated changes to GALT status may influence disease susceptibility, these data suggest that alterations to the abundance or diversity of the commensal microbiota in the large intestine at the time of oral prion exposure are unlikely to have a significant impact on disease pathogenesis and susceptibility. However, this issue is not straightforward, as a dramatically reduced gut microbiota has other important effects on the host. Germ-free mice display substantially enlarged caeca, reduced spleen size (Reikvam et al., 2011) and altered gastrointestinal motility and transit time (Kashyap et al., 2013). Each of these could potentially influence oral prion-disease pathogenesis.

Effects on central nervous system prion disease

A bidirectional communication system, termed the gut–brain axis, integrates neural, hormonal and immunological signalling between these two distantly situated tissues. This enables the brain to influence a variety of physiological activities in the gut including motility and secretion, and the actions of the mucosal immune system (Collins et al., 2012). Conversely, gut- and microbiota-derived products can also influence the brain, for example, through the release of cytokines, hormones such as 5-hydroxytryptamine, or stimulation via afferent neural pathways of the vagus nerve and spinal cord. These, in turn, can influence the composition of the gut microbiota, either directly, or due to physiological effects on the intestine.

Once the prions enter the CNS, they cause extensive neuropathology which is characterized by the activation of microglia and astrocytes, accumulations of PrPSc and neurodegeneration (Fig. 3). Microglia are the tissue macrophages of the CNS and play important roles in maintaining neuronal homeostasis, synaptic remodelling, the removal of dead and dying cells, and as a first line of defence against pathogens (De Lucia et al., 2015; Kranich et al., 2010; Prinz & Priller, 2014; Zhan et al., 2014). A change in microglial status from resting to activated is one of the first pathological features observed in the CNS during prion disease and occurs long before the development of neuropathology (Vincenti et al., 2016).

This activation is characterized by increased expression of the anti-inflammatory cytokines TGF-β and PGE₂, signalling receptors including Trem2, SiglecF, CD200R, and Fcγ receptors, and the development of a highly branched morphology (Lunnon et al., 2011). These are characteristic of an anti-inflammatory profile such as that exhibited by macrophages following their engulfment of apoptotic cells.
Thus, instead of triggering neurodegeneration, the microglial response during prion disease may play an important neuroprotective or pro-neurogenic role in response to the damage caused by the infection (De Lucia et al., 2015). In support of this hypothesis, prion pathogenesis is accelerated when microglia are unable to sequester apoptotic cell remnants as in MFGE-8-deficient mice (Kranich et al., 2010), and delayed in mice deficient in CD14 (a component of the lipopolysaccharide receptor), where increased microglial activation and enhanced expression of anti-inflammatory cytokines such as IL-10 is observed during the preclinical phase (Sakai et al., 2013). Thus, alterations to this phenotype, through the sensing of bacterial LPS from commensal bacteria, could be sufficient to modify the anti-inflammatory/neuroprotective status of microglia during CNS prion disease towards a more pro-inflammatory disease-exacerbating phenotype.

Exciting data show that the development and function of microglia in the CNS is controlled by the gut microbiota. Microglial maturation is compromised in the brains of germ-free mice and coincides with reduced early responses

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**Fig. 1.** Effects of the microbiota on isolated lymphoid follicle (ILF) development in the intestine. (a) ILF abundance is reduced in the small intestines of germ-free mice, whereas their development is induced upon microbial colonization. This contrasts the situation in the large intestine where the microbiota suppresses ILF development. Tissues were whole-mount immunostained to detect B cell-containing ILFs (B220, green) and CD35 (red) to detect FDC-containing mature ILFs. White arrowheads, immature ILFs; red arrowheads, mature ILFs; Bar, 500 µm. (b) Total number of ILFs in the ileum of the small intestines of germ-free and conventionalized mice. Data adapted from Donaldson et al. (2015a). (c) Peyer’s patches and mature FDC-containing ILFs in the small intestine are important early sites of prion accumulation after oral exposure. Within these tissues, high levels of disease-specific PrP (PrP\text{d}, brown) are detected in association with FDCs (CD21/35, brown). Treatment of adjacent sections with proteinase K indicates the presence of relatively proteinase-resistant, prion-specific PrP\text{Sc} (blue/black). Images adapted from Donaldson et al. (2015b), copyright © American Society for Microbiology, J Virol (2015) 89, 9532–9547.
to LPS or virus infection (Erny et al., 2015). A similar impairment to microglial development and function after treatment of conventionally housed SPF mice with broad-spectrum antibiotics (cefoxitin, gentamicin, metronidazole and vancomycin), revealed that the gut microbiota constitutively maintains the homeostasis of microglia under steady-state conditions (Erny et al., 2015). These data imply that reductions in the complexity or abundance of the microbiota during CNS prion disease, such as prolonged use of broad-spectrum antimicrobial treatments, could affect the activation status of microglia and in doing so, impair the development of neuropathology.

Although originally undertaken over 40 years ago to address a separate issue (to define the nature of the scrapie agent), prion-disease pathogenesis has been studied in germ-free mice (Lev et al., 1971). Conventional mice and germ-free mice were each injected intracerebrally with the Chandler mouse-adapted scrapie isolate (50 µl of 10% scrapie brain homogenate, which had been lyophilized and irradiated at 6 Mrad to eliminate contaminating bacteria and viruses). Survival times were apparently extended in germ-free recipients when compared with conventional mice. On face value these data appear to support our suggestion above; that the impaired status of microglia in germ-free mice (Erny et al., 2015) might impede CNS prion pathogenesis. However, it is uncertain from data presented whether this effect was significant (Lev et al., 1971) (Table 3). Furthermore, a subsequent study by Wade et al. (1986) did not observe a difference in survival time after intracerebral injection of ME7 scrapie prions into germ-free mice, but a prolongation was observed after intraperitoneal exposure (Table 3). The inconsistencies between these studies are difficult to explain. However, it is noteworthy that in the Wade study, the effects on prion pathogenesis in germ-free mice were compared with those colonized with a restricted, defined, Gram-positive bacterial flora comprising particular species of Clostridium, Bacillus, Lactobacillus and Bacteroides. This may have particular importance, as the microglia in the brains of germ-free mice colonized with three strains of the altered Schaedler flora (Bacteroides distasonis, strain ASF 519; Lactobacillus salivarius, strain ASF 361; Clostridium cluster XIV, ASF 356) also display an immature phenotype (Erny et al., 2015).

The treatment of hamsters with tetracycline antibiotics (doxycycline, tetracycline or minocycline) increased survival time when administered prior to, or at the appearance of, clinical signs of prion disease (De Luigi et al., 2008), similarly supporting the hypothesis that microbiota-mediated

![Fig. 2. A chronic Trichuris muris infection in mice dramatically alters the composition of the commensal gut microbiota. (a) Bacterial taxa plots showing the family level changes in the composition of the microbiota within faeces at intervals up to 35 days after T. muris infection. (b) Comparison of the composition of the microbiota in faeces and the caeca of naïve mice and at 35 days after T. muris infection. This figure is reproduced from Holm et al. (2015) under the terms of the Creative Commons Attribution Licence 4.0 (http://creativecommons.org/licenses/by/4.0/).](http://jgv.microbiologyresearch.org)
impairments to microglia status (Erny et al., 2015) might impede CNS prion pathogenesis. In contrast, data from a clinical trial show that the daily treatment of clinical CJD patients with doxycycline did not significantly affect disease progression (Haik et al., 2014). However, it is difficult to determine a direct role for the effect of these antibiotics on the microbiota in these studies as tetracyclines can also inhibit PrPSc conversion and prevent neurotoxicity in cultured neurons (Tagliavini et al., 2000).

**Dietary effects on the microbiota**

Many mammalian species rely on constituents of the gut microbiota to break down indigestible dietary components. For example, *Bacteroidetes* and *Clostridia* metabolize the polysaccharides in dietary fibre into short chain fatty acids (SCFAs). Of these, butyrate plays an important role in regulating inflammation and maintaining the mucosal barrier (Furusawa et al., 2013), and the regulation of microglial homeostasis in the CNS (Erny et al., 2015). The administration of SCFAs to germ-free mice restores microglial development, whereas GPR43-deficient mice, which lack the receptor for these SCFAs, have severely malformed microglia (Erny et al., 2015). The ‘Western diet’ is typically high in fat and simple carbohydrates, and can dramatically and rapidly alter the microbiota composition (Turnbaugh et al., 2009), increasing the abundance of Firmicutes, and decreasing the abundance of *Bacteroidetes*, which are important providers of SCFAs (Magnuson et al., 2015; Turnbaugh et al., 2009). Thus, Western diet-induced changes to the microbiota could reduce the availability of microbial metabolites such as SCFAs, and in doing so, impair microglial development and function, influencing CNS prion disease. Although undertaken for a separate issue, the effects of a high-fat diet on CNS prion pathogenesis have been addressed (Zhu et al., 2015), but no significant effects on prion disease progression, PrPSc deposition in the brain, astrogliosis or microglial activation were observed.

Although further studies are necessary to reconcile certain discrepancies between studies, the available data suggest that dramatic changes to the abundance or complexity of the commensal gut microbiota have the potential to modify the development and function of microglia, and in doing so, influence CNS prion pathogenesis.

**Table 2. Congruent infection with the natural mouse, large intestinal, helminth pathogen *Trichuris muris* does not influence oral prion disease pathogenesis**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Day post-<em>T. muris</em> infection when mice were orally infected with prions†</th>
<th>Pathological effects of <em>T. muris</em> infection on large intestine</th>
<th>Mean prion disease duration (days±SE)</th>
<th>Disease incidence‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prions only</td>
<td>None</td>
<td>None</td>
<td>343±9</td>
<td>8/8</td>
</tr>
<tr>
<td><em>T. muris</em> + prions</td>
<td>0</td>
<td>None</td>
<td>350±7</td>
<td>7/7</td>
</tr>
<tr>
<td><em>T. muris</em> + prions</td>
<td>+7</td>
<td>Damage to gut epithelium</td>
<td>356±12</td>
<td>7/7</td>
</tr>
<tr>
<td><em>T. muris</em> + prions</td>
<td>+21</td>
<td>Influx of intra-epithelial macrophages</td>
<td>356±13</td>
<td>8/8</td>
</tr>
<tr>
<td><em>T. muris</em> + prions</td>
<td>+42</td>
<td>Approximately 7 days after <em>T. muris</em> expulsion</td>
<td>347±4</td>
<td>7/7</td>
</tr>
</tbody>
</table>

*Data adapted from Donaldson et al. (2015b).
†Mice were orally infected with *T. muris* and subsequently orally exposed to ME7 scrapie prions on the days indicated.
‡Incidence: no. animals displaying clinical signs of prion disease/no. animals tested.
SE, standard error of mean.
BSE-, CWD- and scrapie-infected hosts (Krüger et al., 2009; Maluquer de Motes et al., 2008; Safar et al., 2008; Tamgüney et al., 2009), and can survive passage through the gastrointestinal tracts of coyotes (Canis latrans) (Nichols et al., 2015) and crows (VerCauteren et al., 2012). One study has also proposed that bacterial components, such as LPS, may potentially enhance the abnormal folding of recombinant PrP (Saleem et al., 2014).

Effects of congruent gastrointestinal pathogen infection on prion-disease pathogenesis

Effects on central nervous system prion disease

Congruent infection with a gastrointestinal pathogen and systemic inflammation can each dramatically influence the progression of certain neurodegenerative diseases. For example, systemic inflammation has been associated with increased cognitive decline in Alzheimer's disease (Holmes et al., 2009), and in pregnant mothers can promote abnormal cortical development in their offspring (Choi et al., 2016). A Th1-polarized systemic immune response following infection with the large intestine-restricted helminth T. muris can exacerbate ischemic brain damage in a stroke model (Denes et al., 2010). Conversely, helminth infections may also have beneficial effects and modulate immune responses and disease severity in multiple sclerosis patients (Correale & Farez, 2013).

The anti-inflammatory cytokine milieu in the brain during prion disease, characterized by elevated expression of TGF-β, acts to regulate the microglial response to minimize CNS inflammation (Cunningham et al., 2002). Consistent with this hypothesis are the demonstrations that CNS prion-disease pathogenesis is exacerbated in the absence of typical anti-inflammatory cytokines, including IL-4, IL-10 and IL-13 (Tamgüney et al., 2008; Thackray et al., 2004). However, the microglia can switch to a more pro-inflammatory profile upon systemic pathogen infection or

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**Fig. 3.** Neuropathology in the brains of mice with clinical prion disease. Once the prions enter the central nervous system the characteristic neuropathology they cause includes neurodegeneration (vacuolation in upper right-hand haematoxylin and eosin-stained (H&E) images) and extensive microglial activation (Iba1, brown, lower panels). Scale bars, 100 µm.

**Table 3.** Prion disease in two independent studies using germ-free mice

<table>
<thead>
<tr>
<th>Mouse microbiological status</th>
<th>Route of prion infection</th>
<th>Mean prion disease duration (days)</th>
<th>Disease incidence‡</th>
<th>Study</th>
<th>Reported P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional*</td>
<td>IC</td>
<td>N/A</td>
<td>15/18</td>
<td>Lev et al. (1971)</td>
<td></td>
</tr>
<tr>
<td>Germ-free</td>
<td>IC</td>
<td>N/A</td>
<td>8/19</td>
<td>&gt;0.05</td>
<td></td>
</tr>
<tr>
<td>Defined flora†</td>
<td>IC</td>
<td>151</td>
<td>N/A</td>
<td>Wade et al. (1986)</td>
<td></td>
</tr>
<tr>
<td>Germ-free</td>
<td>IC</td>
<td>148</td>
<td>N/A</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Defined flora</td>
<td>IP</td>
<td>190</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germ-free</td>
<td>IP</td>
<td>249</td>
<td>N/A</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

*In the study by Lev and colleagues, mice were observed for clinical signs of prion disease up to 23 weeks after exposure (Lev et al., 1971).
†In the study by Wade and colleagues, the effects in germ-free mice were compared with those colonized with a restricted, defined Gram-positive bacterial flora comprising of particular species of Clostridium, Bacillus, Lactobacillus and Bacteroides (Wade et al., 1986).
‡Incidence: no. animals culled due to clinical signs of prion disease/no. animals tested.
IC, intracerebral; IP, intraperitoneal; N/A, insufficient data reported.
exposure to pathogen-associated molecular patterns such as bacterial LPS (Combrinck et al., 2002; Cunningham et al., 2005; Lunnon et al., 2011). These changes to microglial status acutely exaggerate the cognitive decline, impair motor coordination and accelerate CNS prion disease progression (Combrinck et al., 2002; Cunningham et al., 2005, 2009).

**Effects on prion uptake and neuroinvasion from the lumen of the small intestine**

A congruent gastrointestinal pathogen infection may have a wide range of effects on oral prion disease pathogenesis and susceptibility. For example, lesions to the mucosa can enhance the oral transmission of prions (Denkers et al., 2011). Pathogen exposure can also modify the expression of PrPC and innate immunity genes in the gut mucosa (Dervishi et al., 2015; Sigurdson et al., 2009). Therefore, gastrointestinal pathogen-mediated damage to the gut mucosa may exacerbate disease pathogenesis by enhancing prion uptake from the lumen. Increased damage to the gut epithelium may also exacerbate the amount of prions shed into the environment (Bessen et al., 2012). Discussed below are the many ways in which a congruent gastrointestinal pathogen infection may affect oral prion disease pathogenesis and susceptibility.

**Effects on M cells**

The majority of the epithelial cells in the lining of the intestine function to absorb nutrients from the lumen. However, M cells within the epithelia overlying the GALT, are specialized to acquire and transfer particulate microbial antigens across the intestinal epithelium (termed transcytosis). The transcytosis of particulate antigens by M cells is important for their delivery to other immune cells in the GALT for the induction of efficient mucosal immune responses (Mabbott et al., 2013). M cells are also important early sites of prion uptake from the intestinal lumen, and oral prion disease susceptibility is reduced in their absence (Donaldson et al., 2012; Heppner et al., 2001; Takakura et al., 2011). Infection with pathogenic microorganisms such as Salmonella or stimulation from pathogen-derived effector molecules such as cholera toxin enhance the density of M cells in the intestinal epithelium (Savidge et al., 1991; Tahoun et al., 2012; Terahara et al., 2008). Thus an increased abundance of M cells in the gut epithelium as a consequence of a congruent pathogen infection could enhance the uptake of prions from the gut lumen and increase disease susceptibility.

**Effects on mononuclear phagocytes (MNPs)**

After transcytosis into GALT by M cells, the prions are then conveyed to the FDCs within the B-cell follicles. The mechanism by which this occurs is uncertain, but the prions are subsequently acquired by MNP (a heterogeneous population of macrophages and classical dendritic cells) in the underlying sub-epithelial dome region (Kujala et al., 2011). These MNPs have been proposed to act as ‘Trojan horses’ and shuttle prions towards the FDCs (Huang et al., 2002; Mabbott & Bradford, 2015; Raymond et al., 2007). In the steady state, the MNP are typically restrained within the gut lumen.
lamina propria of the gut (the thin layer of connective tissue immediately beneath the epithelium) (Fig. 4a, b). However, the presence of certain pathogenic microorganisms such as *Salmonella* or *Aspergillus* within the lumen of the small intestine stimulates the recruitment of MNPs to the epithelium where they open the tight junctions between epithelial cells and insert their dendrites directly into the lumen to sample the contents (Farache *et al.*, 2013; Niess *et al.*, 2005; Rescigno *et al.*, 2001; Vallon-Eberhard *et al.*, 2006). Thus, the enhanced uptake of luminal antigens in response to congruent pathogen infection in the small intestine may enhance the uptake of prions from the gut lumen, increasing disease susceptibility.

In the absence of tissue macrophages, the accumulation of prions in the Peyer’s patches (Maignien *et al.*, 2005) and spleen is enhanced (Beringue *et al.*, 2000), suggesting that some MNP populations play a protective role by degrading prions (MacPherson *et al.*, 2004). Therefore, a significant

**Fig. 5.** Oral infection of mice with the nematode parasite *Trichuris muris* causes pathology specifically within the caecum. Mice were orally infected with approximately 200 infective *T. muris* eggs and tissues collected at the intervals indicated for further analysis. (a) *T. muris* establishes infection in the caecal epithelium. Left-hand panels show autofluorescent immature worms adhered to the caecal epithelium in whole-mount-prepared tissue specimens. Arrowheads, ILFs (B220+ cells, green). H&E image shows the close association of *T. muris* with the caecal epithelium/lamina propria (arrows) and sites of damage the parasite causes to the gut epithelium. (b) Pieces of ileum and caecum were collected at intervals after *T. muris* exposure and immunostained to detect macrophages (CD11b+ cells, green). *T. muris* infection stimulates the influx of macrophages into the lamina propria of the caecum, but not in the ileum of the small intestine. (c) The distal 8 cm of ileum and the entire caecum from control mice, or *T. muris*-infected mice (28 days post-infection), were whole-mount immunostained to detect isolated lymphoid follicles (individual B cell follicles; B220+ cells, green). This analysis shows that *T. muris* infection stimulates the development of abundant isolated lymphoid follicles (arrows) in caecum. In the ileum, in contrast, the number and density of isolated lymphoid follicles was unchanged after *T. muris* infection. Figure adapted from Donaldson *et al.* (2015b), copyright © American Society for Microbiology, *J Virol* (2015) 89, 9532–9547.
influx of macrophages into the lamina propria of intestine, as occurs in response to certain pathogen infections (deSchoolmeester et al., 2003; Little et al., 2005) (Fig. 5b), could decrease disease susceptibility by enhancing prion sequestration.

**Congruent pathogen infection in the large intestine**

Although prions do not accumulate within the large intestinal GALT during the early stages of infection (Donaldson et al., 2015b; González et al., 2009; Thomsen et al., 2012; van Keulen et al., 2000), pathogen-induced pathology in the large intestine might influence disease susceptibility by enhancing the uptake of prions into GALT within it. Infection with the helminth *T. muris* is entirely restricted to the caecum and proximal colon (Fig. 5). We reasoned that pathology caused by *T. muris* as it burrows within the gut epithelium (Wakelin, 1967) could increase disease susceptibility by increasing the uptake of prions (Fig. 5a). Expulsion of the parasite at the later stages of infection coincides with the influx of large numbers macrophages into the lamina propria of the caecum (deSchoolmeester et al., 2003; Little et al., 2005) (Fig. 5b). This might decrease oral prion disease susceptibility due to the increased sequestration of prions by macrophages (see above). *T. muris* infection also stimulates ILF development in the large intestine (Donaldson et al., 2015b; Little et al., 2005) (Fig. 5c). However, pathogen infection in the large intestine did not significantly affect survival time after oral prion exposure, irrespective of the time at which mice were co-exposed with prions in relation to the *T. muris* infection (Donaldson et al., 2015b) (Table 2).

An independent study has reported that congruent infection with *Salmonella typhimurium* exacerbated oral prion disease (Sigurdson et al., 2009). In this study, the effects on prion disease pathogenesis were attributed to the acute inflammation that infection with the bacterium causes in the colon. However, whereas *T. muris* infection in mice is entirely restricted to the caecum, as discussed above, *S. typhimurium* infection can affect M cells (Tahoun et al., 2012) and MNPs (Farache et al., 2013; Rescigno et al., 2001; Vallon-Eberhard et al., 2006) in the small intestine which have key roles in oral prion disease pathogenesis. Thus, although these data appear to contradict those describing the effects of *T. muris* infection on oral prion-disease pathogenesis (Donaldson et al., 2015b), congruent *S. typhimurium* infection may also have enhanced the uptake of prions from the small intestine.

**Changes to the microbiota in other tissues**

**Mammary gland and mastitis**

The lactating mammary gland and breast milk contain complex ecosystems of commensal bacteria including *Firmicutes*, *Bacteroidetes*, *Actinobacteria* and *Proteobacteria* (Jeurink et al., 2013). Chronic inflammatory conditions such as mastitis can induce the extravasation of inflammatory lymphoid follicles containing FDCs in the inflamed tissue (Gommerman & Browning, 2003). The ectopic lymphoid follicles within the mammary glands of sheep with mastitis and coincident scrapie infection can act as ectopic sites of prion replication (Ligios et al., 2005). Furthermore, scrapie-affected sheep with congruent lentiviral mastitis secrete prions into their milk at levels sufficient to transmit disease to suckling lambs (Ligios et al., 2011).

**Influence of prion disease on the gut microbiota**

At the time of writing we were not aware of any published data describing the effects of prion infection on the gut microbiota. Clinically affected individuals often display loss of appetite, dehydration, constipation and abnormal faecal transit time during the clinical phase. This could dramatically alter the diversity of the microbiota in clinically affected individuals. However, whether this influences the progression or onset of clinical signs remains to be determined and will depend on the magnitude and nature of the microbial species affected.

**Concluding remarks**

In this review we have drawn together data from a wide range of studies which, directly or indirectly, enable us to assess how changes to the gut microbiota could influence prion-disease pathogenesis and susceptibility. Although further studies are necessary to resolve certain discrepancies or address important knowledge gaps, the available data suggest that dramatic changes to the abundance or complexity of the commensal gut microbiota (e.g. after prolonged use of antibiotics) have the potential to modify the development and function of microglia, and in doing so, influence CNS prion pathogenesis. Studies have also shown that a congruent pathogen infection or systemic inflammation can dramatically alter prion disease progression and susceptibility. Within the CNS, these effects appear to be mediated through the modification of the microglial response to the prion infection, whereas in the intestine, data suggest that congruent pathogen infection in the small intestine may enhance the uptake of prions from the gut lumen. Pathogen-mediated pathology, specifically in the large intestine, in contrast, has little effect on prion pathogenesis.

Following the emergence of BSE in the 1980s, estimates suggest that more than 500,000 infected cattle may have entered the UK food chain (Valleron et al., 2001; Wilesmith, 1993). Despite this apparent widespread exposure of the UK population to the BSE agent through the food chain, the number of confirmed clinical cases of vCJD fortunately remains low (Bishop et al., 2013). However, data from the retrospective analyses of PrPSc accumulation in archived appendiceal samples (Gill et al., 2013) suggest that
prevalence of vCJD infection may be much higher. This implies the potential existence of a subclinical carrier state (Clewley et al., 2009, Garske & Ghani, 2010). Understanding how this preclinical phase is maintained will be important in determining the factors that influence the risk of developing clinical prion disease, and the design of novel opportunities for therapeutic intervention. Thus, it will be important to determine whether factors such as dramatic changes to the commensal microbiota (such as use of broad-spectrum antibiotics or dietary changes) or congruent pathogen infection can enhance disease progression in these subclinical individuals.

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