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The slow Wallerian degeneration gene, *Wld*^{S}, inhibits axonal spheroid pathology in gracile axonal dystrophy mice

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Summary

Axonal dystrophy is the hallmark of axon pathology in many neurodegenerative disorders of the CNS, including Alzheimer's disease, Parkinson's disease and stroke. Axons can also form larger swellings, or spheroids, as in multiple sclerosis and traumatic brain injury. Some spheroids are terminal endbulbs of axon stumps, but swellings may also occur on unbroken axons and their role in axon loss remains uncertain. Similarly, it is not known whether spheroids and axonal dystrophy in so many different CNS disorders arise by a common mechanism. These surprising gaps in current knowledge result largely from the lack of experimental methods to manipulate axon pathology. The slow Wallerian degeneration gene, *Wld*^{S}, delays Wallerian degeneration after injury, and also delays 'dying-back' in peripheral nervous system disorders, revealing a mechanistic link between two forms of axon degeneration traditionally considered distinct. We now report that *Wld*^{S} also inhibits axonal spheroid pathology in gracile axonal dystrophy (*gad*) mice. Both gracile nucleus ($P < 0.001$) and cervical gracile fascicle ($P = 0.001$) contained significantly fewer spheroids in *gad*/*Wld*^{S} mice, and secondary signs of axon pathology such as myelin loss were also reduced. Motor nerve terminals at neuromuscular junctions continued to degenerate in *gad*/*Wld*^{S} mice, consistent with previous observations that *Wld*^{S} has a weaker effect on synapses than on axons, and probably contributing to the fact that *Wld*^{S} did not alleviate *gad* symptoms. *Wld*^{S} acts downstream of the initial pathogenic events to block *gad* pathology, suggesting that its effect on axonal swelling need not be specific to this disease. We conclude that axon degeneration mechanisms are more closely related than previously thought and that a link exists in *gad* between spheroid pathology and Wallerian degeneration that could hold for other disorders.

Keywords: axon; axonal spheroid; gracile axonal dystrophy; ubiquitin; Wallerian degeneration

Abbreviations: APP = amyloid precursor protein; *gad* = gracile axonal dystrophy; GFAP = glial fibrillary acidic protein; H & E = haematoxylin and eosin; NMJ = neuromuscular junction; PFA = paraformaldehyde; PNS = peripheral nervous system; *Wld*^{S} = slow Wallerian degeneration gene, mutation or mice; Wld^S = slow Wallerian degeneration protein; YFP = yellow fluorescent protein

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Introduction

Axonal dystrophy and spheroids are hallmarks of CNS axon pathology. Axonal spheroids are focal 10–50 μm diameter swellings, which are sometimes, but not always, terminal endbulbs, and are filled with disorganized neurofilaments,

tubules, organelles or multi-lamellar inclusions. Dystrophic axons are usually smaller swellings often associated with continuity of the axon. One or both of these aberrant axon morphologies is found in a wide range of CNS neurodegenerative disorders, including stroke (Dewar *et al*., 1999), myelin disorders (Griffiths *et al*., 1998), tauopathies (Lewis *et al*., 2000; Probst *et al*., 2000), amyotrophic lateral sclerosis (Tu *et al*., 1996; Oosthuyse *et al*., 2001; Howland *et al*., 2002), traumatic brain injury (Cheng and Povlishock, 1988), Alzheimer's disease (Brendza *et al*., 2003), Parkinson's disease (Galvin *et al*., 1999), Creutzfeldt–Jakob disease (Liberski and Budka, 1999), HIV dementia (Raja *et al*., 1997; Adle-Biassette *et al*., 1999), hereditary spastic paraplegia (Ferreirinha *et al*., 2004) and Niemann–Pick disease (Bu *et al*., 2002). They also occur during normal ageing and secondarily in some serious illnesses (Sung *et al*., 1981). In contrast, peripheral nervous system (PNS) axons undergo 'Wallerian-like' or 'dying-back' degeneration, even in diseases where CNS axons form swellings (Miura *et al*., 1993; Lewis *et al*., 2000; Oosthuyse *et al*., 2001), although swellings do also occur in some rare PNS disorders (Miike *et al*., 1986; Bomont *et al*., 2000).

The roles of axonal swellings in disease are poorly understood, as illustrated by the following examples. First, in multiple sclerosis, many large spheroids are terminal endbulbs of transected axons but there are also a few 'en passant' swellings of similar shape and dimension (Trapp *et al*., 1998) and many small dystrophic swellings (Ferguson *et al*., 1997; Kornek *et al*., 2000, 2001). It remains unclear whether these different types of swelling have common or different origins. Secondly, it is not clear whether disease-specific mechanisms lead to a common final pathway of axonal dystrophy, as in Alzheimer's disease, stroke and multiple sclerosis, and if so how they do this. Thirdly, it is not known why swellings predominate in distal axons in some diseases, such as gracile axonal dystrophy (*gad*) (Yamazaki *et al*., 1988; Mukoyama *et al*., 1989), caused by loss of ubiquitin C-terminal hydrolase l1 (*Uch-l1*) (Saigoh *et al*., 1999), while in other diseases they occur in proximal axons, as in amyotrophic lateral sclerosis (Tu *et al*., 1996) and tauopathy (Probst *et al*., 2000). Finally, a better understanding is needed of the relationship between axon swelling and impaired axonal transport. Amyloid precursor protein (APP) accumulates in axonal swellings and spheroids in stroke (Dewar *et al*., 1999), traumatic brain injury (Gentleman *et al*., 1993), multiple sclerosis (Ferguson *et al*., 1997), Creutzfeld–Jakob disease (Liberski and Budka, 1999), HIV dementia (Raja *et al*., 1997; Adle-Biassette *et al*., 1999) and *gad* (Ichihara *et al*., 1995), indicating that axonal transport is impaired. However, it is not known whether axon swelling in these disorders is simply a consequence of impaired axonal transport, or whether it causes the transport defect, or both. These and other important questions remain unanswered largely because experimental methods to manipulate axonal swelling have not been available.

A mutant mouse gene, *Wld*^{S}, blocks a rate-limiting step common to Wallerian degeneration and diverse PNS axon disorders, including dysmyelination (Samsam *et al*., 2003), motor neuronopathy (Ferri *et al*., 2003) and Taxol toxicity (Wang *et al*., 2002). Recently, *Wld*^{S} was reported to be effective in acute CNS lesions modelling stroke (Gillingwater *et al*., 2004) and Parkinson's disease (Sajadi *et al*., 2004) but its effect in a chronic CNS disease has not been reported. *Wld*^{S} is a chimeric gene (Conforti *et al*., 2000) formed by a stable triplication (Coleman *et al*., 1998; Mi *et al*., 2003) encoding the N-terminus of multiubiquitylation factor Ube4b fused in-frame to nicotinamide mononucleotide adenylyltransferase (Nmnat1) plus a short novel sequence (Mack *et al*., 2001). Nmnat1 appears to be sufficient to confer the phenotype *in vitro*, but it is not yet clear whether this holds *in vivo* (Coleman and Perry, 2002; Araki *et al*., 2004). Wld^S protein appears to be restricted to the nucleus, so its effect on axons is mediated by other factors (Mack *et al*., 2001), which may include the NAD-dependent deacetylase SIRT-1 (Araki *et al*., 2004).

To study the relationship between axonal swelling and Wallerian degeneration, we crossed *Wld*^{S} and *gad* mice. *Wld*^{S} significantly reduced spheroid numbers without altering the first stages of *gad* pathogenesis, revealing a link between Wallerian degeneration and axonal spheroids in this disease that could extend to other disorders.

Methods

Origin, breeding and genotyping of mice

Homozygous C57BL/*Wld*^{S} spontaneous mutants were obtained from Harlan UK (Bicester, UK) and mated with heterozygous *gad* mice, kindly provided by Professor Keiji Wada and Dr Hitoshi Osaka (National Institute of Neuroscience, Tokyo, Japan), following a cross to C57BL/6 to ensure a more homogeneous genetic background. Thus, the genetic background of the experimental mice was 75% C57BL/6, 12.5% CBA/Nga, 12.5% RFM/Nga. Double heterozygotes were identified in the F1 generation by genotyping for *gad* (below) and intercrossed. *gad* homozygotes were identified by genotyping and selected for further study. *Wld*^{S} genotype was determined *post mortem* by pulsed-field gel electrophoresis of spleen DNA (Mi *et al*., 2002). Hemizygous yellow fluorescent protein (YFP) mice of line YFP-H were obtained from Jackson Laboratories (Bar Harbor, MN, USA) and mated with *gad*/*Wld*^{S} double heterozygotes. Triple heterozygotes were then mated to *gad*/*Wld*^{S} double heterozygotes to produce *gad* homozygotes that were heterozygous for both *Wld*^{S} and YFP-H. For *gad* genotyping, tail genomic DNA was extracted at 3 weeks using the Nucleon II kit (Amersham Pharmacia), digested with *Pvu*II, and Southern blotted. It was then hybridized with a ^{32}P-labelled 764-bp probe generated by PCR from *gad* homozygous genomic DNA using primers 5′-ATCCAGGCGGCCCATGACTC-3′ and 5′-AGCTGCTTTGCAGAGAGCCA-3′. Positively hybridizing fragments indicative of the *gad* (0.75 kb) and wild-type (1.6 kb) alleles were then identified by autoradiography. To genotype for inheritance of the YFP-H transgene, the skin of a 1–2 mm ear punch at 21 days was pulled apart and fluorescent axons identified using a Zeiss Axiovert S100 inverted fluorescent microscope through the FITC filter.

Assessment of Wallerian degeneration

gad homozygotes that were heterozygous for *Wld*^{S} and hemizygous for the *YFP-H* transgene were anaesthetized prior to the onset of hindlimb weakness using intraperitoneal Ketanest (100 mg/kg; Parke Davis/Pfizer, Karlsruhe, Germany) and Rompun (5 mg/kg; Bayer, Leverkusen, Germany). The right sciatic nerve (upper thigh) was transected and the wound closed with a single suture. Five days later the mice were killed by cervical dislocation, the swollen first 2 mm of distal sciatic nerve was discarded and the next 2 mm was used for western blotting for heavy neurofilament protein as previously described (Mack *et al*., 2001). The tibial nerve of the operated leg with a minimum of attached non-nervous tissue was processed for YFP fluorescence as follows. The nerve was stretched by ~10% by pinning onto a Sylgard (Du Pont) dish and fixed with 4% paraformaldehyde (PFA) (BDH Laboratory, UK) in 0.1 M phosphate-buffered saline (PBS) in the dark for 1 h. It was then incubated in 1% Triton X-100 (Sigma, Germany) in 0.1 M PBS for 10 min and washed three times with PBS before mounting in Vectashield (Vector Laboratories, USA). The degree of fragmentation of the representative subset of motor and sensory axons that are YFP-labelled was determined. For more detail, see Beirowski *et al*. (2004).

Preparation of gracile tract sections

Mice aged 126–130 days were anaesthetized using Ketanest and Rompun (100 mg/kg and 5 mg/kg intraperitoneally, respectively) or a higher dose as required for deep terminal anaesthesia. After sternotomy mice were killed by cardiac puncture and instantly intracardially perfused first with a solution containing 10 000 IE/l heparin (Liquemin N 25000; Hoffmann-La Roche) and 1% procainhydrochloride in 0.1 M PBS for 30 s and then with fixative (4% paraformaldehyde in 0.1 M PBS) for 10 min. Brain and spinal cord were carefully removed, further fixed in 4% PFA/0.1 M PBS overnight and extensively washed in 0.1 M PBS. Fixed tissues were extensively rinsed in fresh 0.1 M PBS, dehydrated in an ascending ethanol series and subsequently embedded in paraffin (Paraplast; Sherwood Medical Co., St Louis, MO, USA) applying standard histology techniques. Coronal serial sections (6 μm) were made using a Type HM355 microtome (Microm GmbH) from the entire gracile nucleus in medulla oblongata and cervical gracile fascicle starting at level 535 (Sidman *et al*., 1971). Serial paraffin sections were mounted on conventional glass slides for use in haematoxylin and eosin (H & E) staining or on poly-L-lysine-coated slides for use in Luxol Fast Blue staining and immunocytochemistry, alternating normally every 2–3 sections. Distinction between gracile nucleus and cervical gracile fascicle was made by applying histomorphological criteria for the typical shapes of coronal sections.

H & E staining and spheroid quantification

Six-micrometre sections were deparaffinized in xylol (Carl-Roth, Germany) for 10 min, rehydrated in a descending ethanol series and rinsed in deionized H_2O for 1 min. Sections were placed in haematoxylin for 5 min, rinsed in tap water for 1 min to allow stain to develop and then placed in eosin for 2 min, dehydrated and mounted in Entellan resin (Merck, Germany). The occurrence of clearly detectable eosinophilic spheroids, indicative of dystrophic axons (Yamazaki *et al*., 1988; Mukoyama *et al*., 1989; Kikuchi *et al*., 1990) was quantified in ~90 sections uniformly dispersed throughout the gracile nucleus of each individual and ~30 sections uniformly dispersed throughout the cervical gracile fascicle. Analysis of lateral columns was performed on these same 30 sections, counting the sum of spheroid numbers on both sides of the spinal cord. In this way, irregular results due to local deviations in spheroid numbers could be ruled out. H & E stained axonal spheroids were generally eosinophilic and appeared glassy or hyaline with a round or oval shape. They varied in diameter (5–50 μm) and sometimes reached a size larger than the nerve cells in gracile nucleus. All specimens were scored blind and agreed by two independent investigators.

Luxol Fast Blue staining and densitometric quantification

Six-micrometre sections from equivalent points in *gad* and *gad/ Wld*^{S} cervical spinal cord and medulla oblongata were processed simultaneously as follows. Sections were deparaffinized in xylol (Carl-Roth, Germany) for 15 min, and processed twice through 100% ethanol for 2 min and 96% ethanol for a few seconds. Slides were transferred to Luxol Fast Blue solution [0.1% Luxol Fast Blue MBS chroma (Merck), 10% acetic acid all made up in 96% ethanol] and incubated at 60°C for 5 h. Sections were then rinsed in 95% ethanol and distilled water for 1 min each, dipped in 0.05% lithium carbonate (Merck) for 1 min, and differentiated in 70% ethanol for a further 1 min. After rinsing in distilled water, sections were examined under light microscope for suitable differentiation between white and grey matter. Nuclear Fast Red staining was carried out for 10 min in 5% aluminium sulphate, 0.1% Nuclear Fast Red followed by rinsing in distilled H_2O, 90% ethanol and 100% ethanol for 1 min each. Slides were incubated in xylol for 5 min and mounted in Entellan resin (Merck). Slides were examined under light microscopy (Nikon Eclipse E200) and evaluated using Bioscan OPTIMAS 6.0 software (Optimas Corp., WA, USA) according to the manufacturer's instructions. For densitometric quantitation, mean grey values were obtained for circumscribed areas of interest using a three-chip monochrome CCD camera, and the background grey value (tissue-free area) was subtracted. Since demyelination occurs selectively in the gracile tract and not in the cuneate tract of *gad* mice by 126–130 days (Mukoyama *et al*., 1989; our observations), we used cuneate fascicle as a reference area and expressed Luxol Fast Blue staining in gracile tract as a percentage of that in cuneate tract. We applied this procedure to representative Luxol Fast Blue-stained sections of cranial gracile tract: two sections from level C2/C3 representing the cervical gracile fascicle and two sections from level 535 representing the gracile nucleus (Sidman *et al*., 1971).

Immunocytochemistry of gracile tract

Six-micrometre paraffin sections from equivalent points in *gad* and *gad/Wld*^{S} cervical spinal cord and medulla oblongata were processed simultaneously as follows. Sections were deparaffinized, rehydrated in a descending ethanol series, washed several times in 0.05 M Tris-buffered saline (TBS), and treated with a solution of 6% H_2O_2 in methanol for 20 min to block endogenous peroxidase activity. They were then permeabilized with 0.1% Triton X-100 (Sigma) in 0.05 M TBS additionally containing 0.05 M NH_4Cl, rinsed in fresh TBS three times and subsequently immunoblocked with 5% bovine serum albumin (Sigma) in 0.05 M TBS

for 1 h. First antibody was polyclonal guinea pig anti-glial fibrillary acidic protein (GFAP) (1 : 400 dilution) (Progen, Germany) at 4°C overnight, while negative control sections were incubated without primary antibody. Secondary antibody was goat anti-guinea pig biotin conjugate (1 : 400 dilution) (Sigma) for 1 h at room temperature, and was followed by streptavidin-coupled horseradish peroxidase complex (Vector Laboratories; 1 : 200 dilution) for 1 h. After extensive washing, sections were developed under identical conditions for all specimens with 3,3-diaminobenzidine tetrahydrochloride (Sigma–Aldrich) in 0.1 M phosphate buffer until a clear dark-brown labelling of astrocytes in the gracile tract could be detected. In all cases the control sections without primary antibody incubation showed no labelling of astrocytes. For microscopic examination and TV densitometry, sections were dehydrated and mounted in Entellan resin (Merck). Quantitation was similar to that described for Luxol Fast Blue densitometry. GFAP immunostaining intensities in cranial gracile tract sections were expressed as percentage of GFAP staining intensity in wild-type sections at the same coronal level. We applied GFAP densitometry on representative cranial gracile tract sections from each examined mouse: two sections from level C2/C3 representing the cervical gracile fascicle and two sections from level 535 representing the gracile nucleus (Sidman *et al*., 1971).

Immunocytochemistry of sciatic nerves

Sciatic nerves from 15-week-old *gad*, *gad*/*Wld*^{S}, or control mice were immersion fixed in 4% PFA/0.1 M PBS for 1 h and washed extensively in 0.1 M PBS before paraffin embedding. Twenty-micrometre sections were immunostained using rabbit polyclonal antibody to ubiquitin (Sigma–Aldrich U5379) and Cy3-conjugated secondary antibody. Confocal images were obtained using a PerkinElmer UltraView LCI confocal microscope coupled to a Nikon Eclipse TE200 microscope, and processed using UltraView software (Perkin-Elmer Life Sciences Ltd, Cambridge, UK).

Statistical analysis of histopathology results

All data (axonal spheroid numbers, TV densitometry intensities) are presented as mean ± SD for the examined genotype groups. Data analysis was performed using PRISM for Macintosh or SPSS for Windows, including Student's *t*-test calculations for paired and unpaired data where appropriate. Significance was considered at $P < 0.05$ and high significance at a $P < 0.01$.

Analysis of neuromuscular pathology

Mice were killed by cervical dislocation and lumbrical muscles immediately dissected under oxygenated Ringer solution. Fixation, immunocytochemistry and signal imaging were then carried out as described previously (Gillingwater *et al*., 2002). The denervation rate was determined by counting 100–200 endplates in each of two to three lumbrical muscles and the mean value taken for each mouse.

Behavioural tests

The foot splay test (Norreel *et al*., 2001) was used to estimate the reflex reaction speed of the hind limbs. Mice were gently taken by the neck and tail, the plantar surface of their hind feet painted using a non-toxic children's painting set, and the mouse released from a height of 15 cm to land on white paper. Wild-type mice bring their legs together during descent to land in a controlled manner like a gymnast, whereas *gad* mice fail to do this and land with their feet far apart. The distance between the two hind heels was averaged from 10 successive trials on each testing date (9 and 13 weeks).

In the clasping test, the mouse was suspended by the tail >50 cm from any surface. Clasping time within a 1 min test was scored as flexing or folding of the hind limbs tightly towards the trunk plus any spasmodic stretching. Mice were examined once per week through the period from 6 to 16 weeks. No wild-type mice clasped, regardless of the presence of the *Wld*^{S} mutation.

Results

gad does not weaken the Wld^S *phenotype*

Before assessing the effect of *Wld*^{S} on *gad* pathology we first showed that *Wld*^{S} can protect axons, even in the presence of the *gad* mutation, by inducing Wallerian degeneration in *gad*/*Wld*^{S} mice. Before the lesion, there was no sign of axon degeneration in these nerves, confirming previous reports (Mukoyama *et al*., 1989). We bred *gad* mice that were heterozygous for *Wld*^{S} and hemizygous for a *YFP-H* transgene (Feng *et al*., 2000) to allow a rapid and quantitative assessment of Wallerian degeneration (Beirowski *et al*., 2004) and transected sciatic nerves before the onset of hindlimb weakness. Wallerian degeneration was assessed after 5 days both by western blotting to see degraded heavy neurofilament protein (Fig. 1A) and by fluorescence microscopy to see fragmented YFP-containing axons (Fig. 1B). Nerves unprotected by *Wld*^{S} degenerated as expected (Fig. 1A, middle lane, and Fig. 1B, lower panel) but a single allele of *Wld*^{S} was sufficient to prevent axon degeneration in both readout methods. Thus, *gad* does not significantly weaken the *Wld*^{S} phenotype and it is feasible to test the effect of *Wld*^{S} on *gad* pathology.

Axonal spheroid pathology is reduced by Wld^S

In order to determine the effectiveness of *Wld*^{S} on *gad* axonal spheroid pathology, we counted axonal spheroids in ~90 H & E stained 6-μm paraffin sections from throughout the gracile nucleus and 30 sections from throughout the cervical spinal cord of each 18-week-old *gad* mouse and *gad*/*Wld*^{S} double homozygote. Fifty per cent fewer spheroids were found in gracile nuclei of *gad*/*Wld*^{S} mice than in *gad* mice ($P = 0.0004$) and 63% fewer in cervical gracile fascicle ($P = 0.0011$) (Fig. 2). Intermediate values were observed in *Wld*^{S} heterozygotes, further supporting the result and no spheroids were observed in control animals of this age (data not shown). Spheroids have also been reported in the cervical lateral columns of *gad* mice (Kikuchi *et al*., 1990). We found far fewer spheroids here than in cervical gracile tract and gracile nucleus, but the number was also significantly reduced by homozygous *Wld*^{S} ($P = 0.046$; $n = 3$) (Fig. 2). We also observed a reduction in axonal spheroids in lumbar spinal cord, from 42 to six in the ventral column and from 13 to four

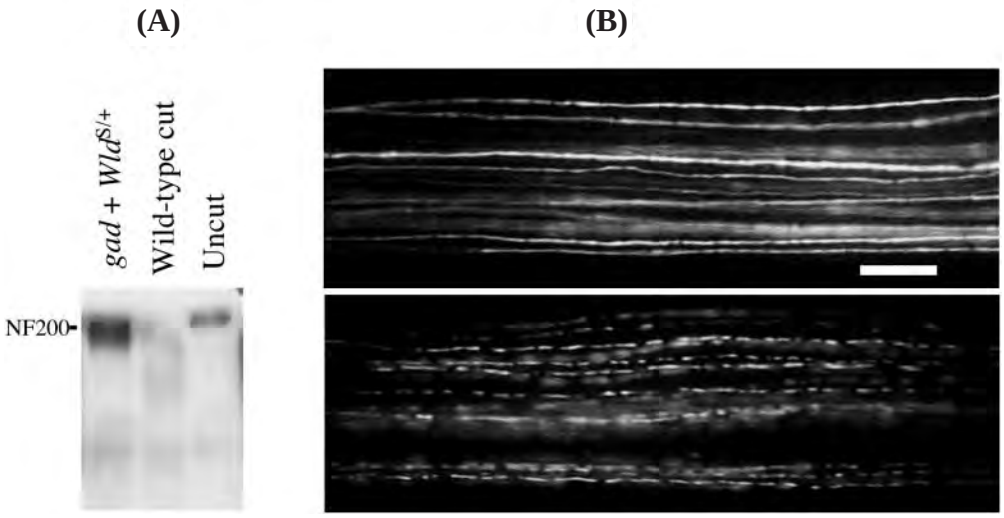

Fig. 1 A single allele of *Wld*^{S} is sufficient to delay Wallerian degeneration even in *gad* mice. (**A**) Western blot showing complete preservation of intact heavy neurofilament protein (NF200) in the distal stump of axotomized *gad* sciatic nerve by heterozygous *Wld*^{S} 5 days after lesion (lane 1). In contrast, no intact NF200 remains after 5 days in axotomized wild-type sciatic nerve (lane 2). Lane 3 is an uncut nerve showing the expected appearance of intact NF200 (gel loading differences probably account for the difference in intensity with lane 1). (**B**) Complete preservation of distal *gad* tibial nerve by heterozygous *Wld*^{S} 5 days after nerve lesion (upper panel), visualized using the *YFP-H* transgene. In contrast, no unfragmented axons remained in a tibial nerve lacking *Wld*^{S} 3 days after a lesion (lower panel). Unlesioned nerves appear exactly as in the upper image (Beirowski *et al*., 2004). Scale bar = 100 μm.

in the dorsal horn grey matter. Although lumbar regions of only a single *gad* and two *gad*/*Wld*^{S} mice were studied, these mice were independent of those used for the gracile tract analysis and 3 weeks younger, so these data independently support our conclusion that *Wld*^{S} reduces axonal spheroid pathology in several different regions of *gad* CNS well into late-stage disease.

A reduction in the number of axonal spheroids could result theoretically from either reduced axon pathology or pathology so extensive that the axons are completely destroyed. Kurihara *et al*. (2001) reported that when *gad* pathology was made worse by crossing with *Uch-l3* null mice, extensive axon pathology became detectable at more caudal locations in cervical and thoracic gracile fascicle. We did not observe this in the *Wld*^{S} cross, and *Wld*^{S} homozygotes maintain a rostral–caudal gradient of axonal spheroid pathology (Fig. 2E and F; and thoracic data not shown), indicating that *gad* remains a 'dying-back' pathology in *Wld*^{S} mice but that its progress is delayed.

Secondary measures of axon pathology are also reduced by Wld^S

Further evidence of a reduced loss of axon-myelin units in *gad*/*Wld*^{S} mice came from a significant reduction ($P = 0.018$) in secondary myelin loss in cervical gracile fascicle in the same animals (Fig. 3A–C). A similar protective trend in the medulla oblongata did not reach statistical significance ($P = 0.059$), probably due to the naturally weaker myelination in this region, but *Wld*^{S} clearly did not cause any deterioration, so the reduction in axonal spheroid numbers (Fig. 2) must reflect reduced pathology and not wholesale axon loss. Furthermore, as the rescued axons remain myelinated, they potentially retain normal conductance properties, at least in these locations. It is unlikely that *Wld*^{S} has any direct effect on myelin, because expression of *Wld*^{S} in glia does not alter Wallerian degeneration (Glass *et al*., 1993). Thus reduced myelin loss in *gad*/*Wld*^{S} mice is likely to reflect the maintenance of functional axon-myelin units. *Wld*^{S} also decreased GFAP signal in immunocytochemistry in *gad*, indicating a lower level of astrocyte activation in response to axon damage (Yamazaki *et al*., 1988) (data not shown). Thus, both direct and indirect measures of spheroidal axon pathology in the gracile tract are reduced by the *Wld*^{S} gene.

Wld^S *operates downstream of axonal ubiquitin depletion in gad*

gad causes axon degeneration through defective ubiquitin metabolism (Osaka *et al*., 2003), and *Wld*^{S} also interferes with ubiquitin metabolism (Mack *et al*., 2001; Coleman and Perry, 2002; Zhai *et al*., 2003). It was important to establish whether *Wld*^{S} blocks the ubiquitin defect in *gad*, an action that would suggest a protective effect restricted to *gad* and other ubiquitin defects, or whether it acts on a downstream step, raising the possibility of delaying axonal spheroid pathology in a wide range of CNS disorders (see above). Interpretation of any change in ubiquitin level in gracile tract would be complicated by the degeneration of those axon branches, so instead we carried out immunocytochemistry for ubiquitin epitopes in the peripheral branch of the same axons in sciatic nerve (Fig. 4). First, we confirmed that axonal ubiquitin was severely depleted in *gad* mice compared with wild-type controls ($P = 0.014$) (Osaka *et al*., 2003). We then found

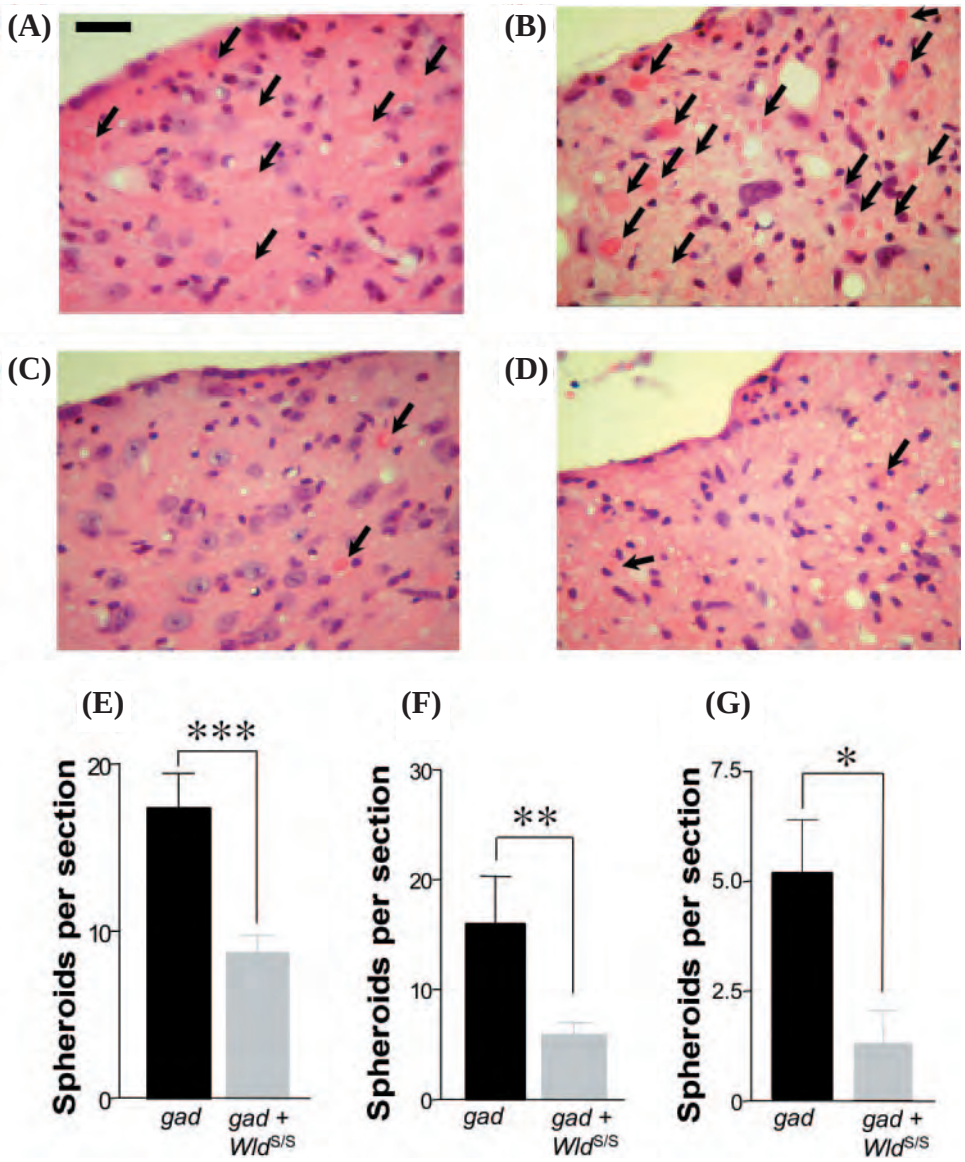

Fig. 2 *Wld*^{S} reduces spheroid body numbers in the gracile tract and lateral columns of *gad* mice. (**A** and **C**) Representative sections from gracile nucleus of (**A**) *gad* and (**C**) *gad*/*Wld*^{S} mice stained with H & E, showing a large reduction in the number of axonal spheroids (large pink swellings, indicated by arrows) when *Wld*^{S} is present. (**B** and **D**) Representative sections from cervical gracile fascicle of (**B**) *gad* and (**D**) *gad*/*Wld*^{S} mice. Scale bar (**A**–**D**) = 25 μm. (**E**–**G**) Quantitation (mean ± SD) of spheroid counting data in (**E**) gracile nucleus (n = 6), (**F**) cervical gracile fascicle (n = 6) and (**G**) cervical lateral columns (n = 3). *P < 0.05; **P < 0.01; ***P < 0.001.

that a similar defect was present in *gad*/*Wld*^{S} mice compared with *Wld*^{S} controls (P = 0.0004) and that *Wld*^{S} did not significantly increase the ubiquitin signal either in the presence (P = 0.902) or absence (P = 0.807) of *gad*. Thus, *Wld*^{S} does not correct the depletion of axonal ubiquitin in *gad* and instead operates at a downstream point in spheroid pathology that could be common to other CNS disorders.

Motor pathology

Despite the reduction in axonal spheroids in the gracile tract, there was no apparent reduction in the severity of *gad* symptoms when *Wld*^{S} was present, with no significant difference in hindlimb clasping, (P = 0.82; n = 9) or splay test (P = 0.33; n = 7). Thus, either prevention of swelling in the gracile tract does not preserve the function of those axons, or pathology elsewhere limits any improvement in phenotype of *gad*/*Wld*^{S} mice. In the absence of any tests to specifically target the function of gracile tract axons, we investigated neuromuscular junction (NMJ) pathology, where dying-back of motor nerve terminals has previously been reported (Miura *et al*., 1993). At 15 weeks, the degree of denervation was similar between the two strains, with 56.0 ± 6.0% of lumbrical NMJ fully or partially denervated in *gad* mice and 53.5 ± 11.8% in *gad*/*Wld*^{S} (Fig. 5C and D). This may be because protection of motor nerve terminals at the NMJ by *Wld*^{S} after axotomy is weaker than that of the axon trunk, especially in older mice (Gillingwater *et al*., 2002). However,

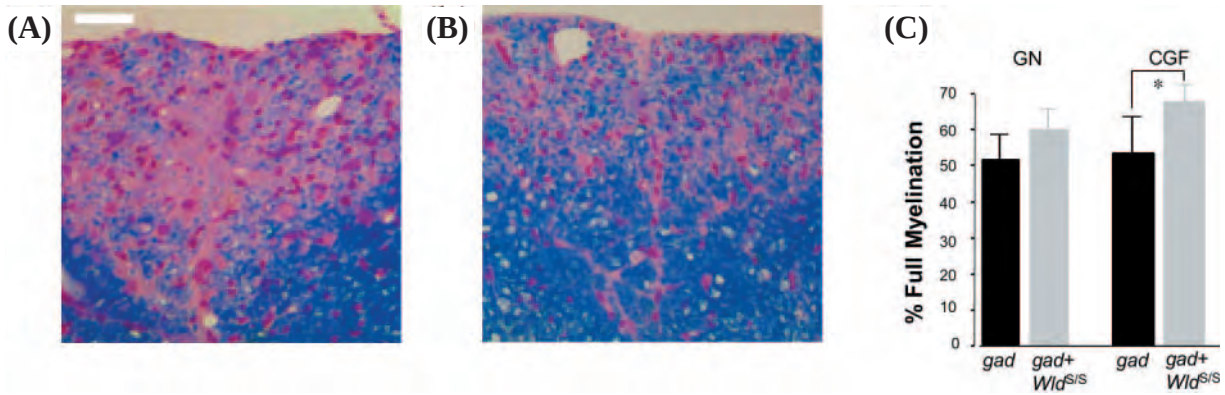

Fig. 3 *Wld*^{S} reduces also secondary demyelination in the gracile tract. (**A** and **B**) Representative cervical gracile fascicles of (**A**) *gad* and (**B**) *gad*/*Wld*^{S} mice stained with Luxol Fast Blue and Nuclear Fast Red, showing the reduction in myelin loss when *Wld*^{S} is present. Scale bar (**A** and **B**) = 25 μm. (**C**) Densitometric quantification (mean ± SD) of Luxol Fast Blue staining (n = 5). *P < 0.05.

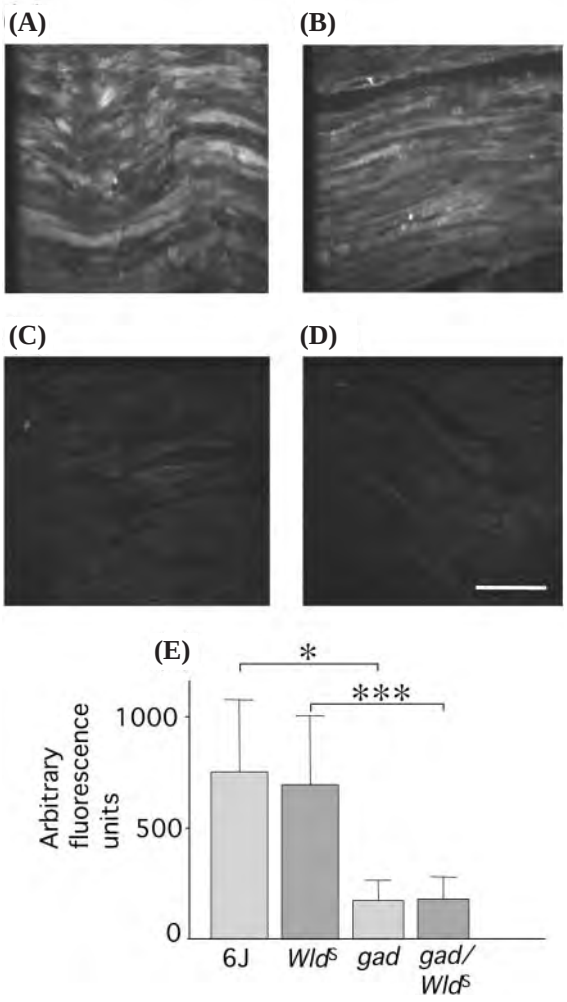

Fig. 4 *Wld*^{S} does not correct the severe depletion of axonal ubiquitin in *gad*. Ubiquitin immunostaining in both (**A**) wild-type and (**B**) *Wld*^{S} mice is greatly reduced in **C** and **D**, respectively, where *gad* is also present. Comparison of **A** with **B** and **C** with **D** also shows that *Wld*^{S} does not alter ubiquitin signal either in the presence of absence of *gad*. (**E**) Quantitation (mean ± SD) of ubiquitin signal. *P < 0.05; ***P < 0.001. 6 J, n = 4; *Wld*^{S}, n = 4; *gad*, n = 4; and *gad*/*Wld*^{S}, n = 10. Scale bar = 50 μm.

at 9 weeks, an age where *Wld*^{S} does protect axotomized motor nerve terminals, neither strain showed any denervation of NMJ in lumbrical muscles (Fig. 5A and B), so there was no time window when both *Wld*^{S} and *gad* exert their opposing effects at the NMJ. Thus, the fact that *Wld*^{S} does not alleviate NMJ pathology in the older mice could explain why *gad* symptoms are not reduced.

Discussion

We report that *Wld*^{S} reduces the occurrence of axonal spheroids in *gad*. This is the first indication that *Wld*^{S} can alleviate axon pathology in chronic CNS disease, thus extending observations made in the PNS that *Wld*^{S} protects axons not only after injury (Lunn *et al*., 1989) but also in disorders where no physical injury takes place (Wang *et al*., 2002; Ferri *et al*., 2003; Samsam *et al*., 2003). We conclude that axonal spheroid pathology in *gad* and Wallerian degeneration are not independent events and axon degeneration mechanisms are more uniform than morphology would suggest. It follows that Wallerian degeneration, or processes related to it, could contribute to many other CNS disorders where its involvement has not previously been suspected.

The mechanism by which *Wld*^{S} protects axons is still under investigation (Mack *et al*., 2001; Coleman and Perry, 2002; Zhai *et al*., 2003; Araki *et al*., 2004), but appears to involve nuclear Wld^S protein and a factor(s) that communicates its effect to the axon. What is already becoming clear, however, is that *Wld*^{S} directly or indirectly blocks a central step of axon pathology onto which various pathological mechanisms converge (Fig. 6). This is indicated both by the wide range of disorders in which *Wld*^{S} protects axons, as it is inconceivable that *Wld*^{S} blocks different initial events in each case, and by our direct evidence, that early steps of *gad* pathogenesis are unaltered (Fig. 4). Intriguingly, it now seems that a number of different pathological manifestations result from the step delayed by *Wld*^{S}. These are axonal spheroids in *gad*, dying-back axon loss without swelling in peripheral

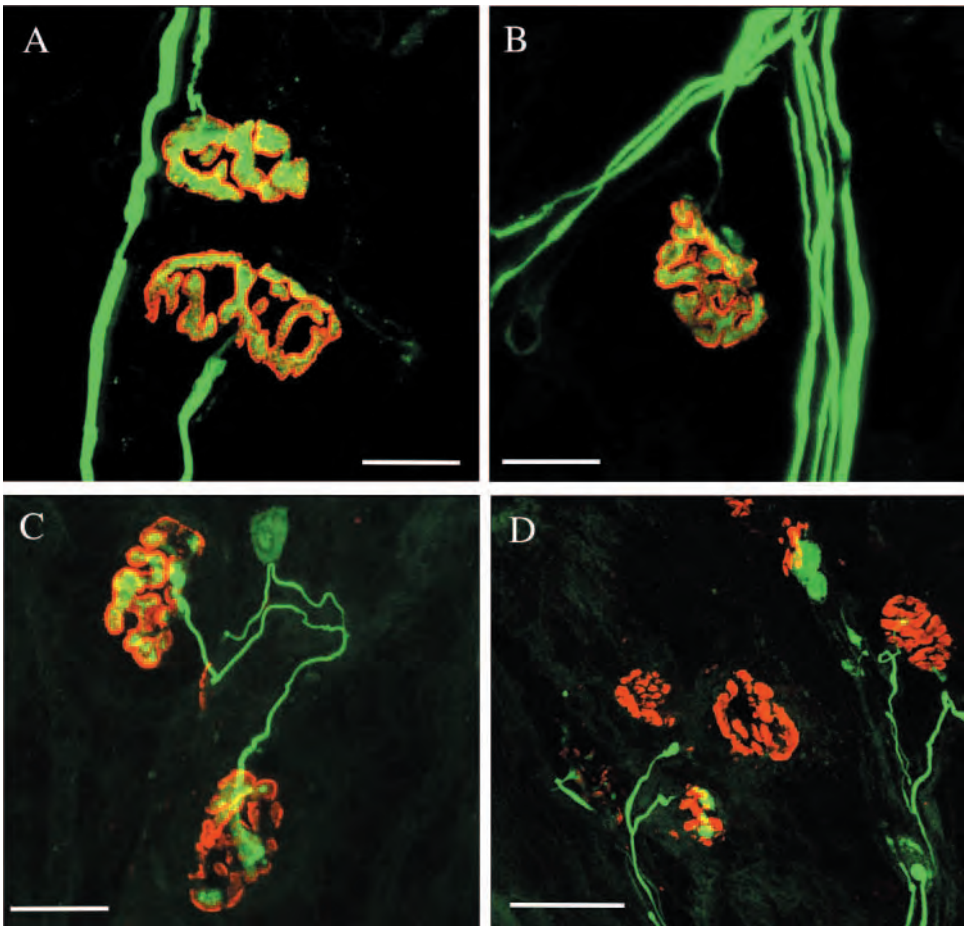

Fig. 5 Denervation at the NMJ. Presynaptic structures labelled with SV2 and neurofilament antibody are shown in green, and postsynaptic structures labelled with TRITC-α-bungarotoxin are in red. At 9 weeks, denervation has hardly begun in (**A**) *gad* or (**B**) *gad*/*Wld*^{S}. At 15 weeks, both strains show extensive denervation (**C** and **D**, respectively), with partial occupancy of endplates by motor nerve terminals occurring frequently. Scale bar = 25 μm.

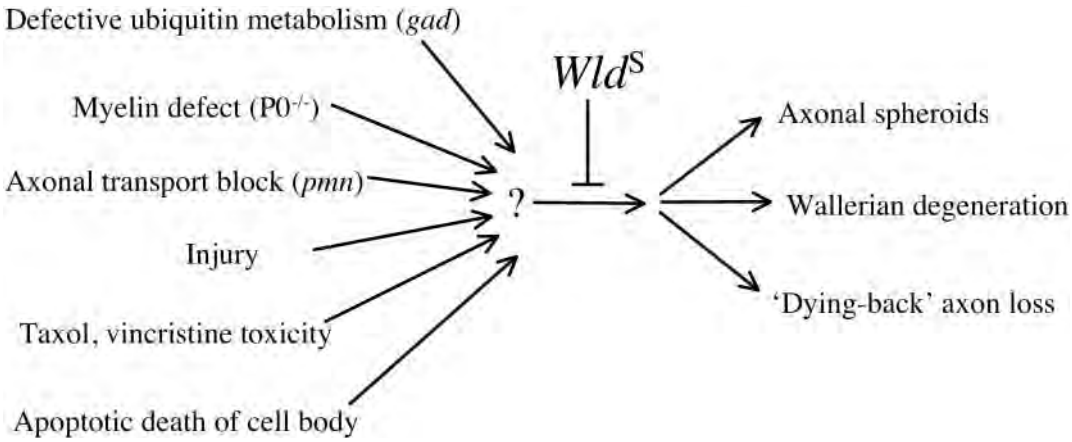

Fig. 6 *Wld*^{S} delays a central step of axonal pathology that lies after the convergence point of multiple degenerative stimuli but upstream of the divergence of several pathological manifestations.

neuropathy and motor neuronopathy, and Wallerian degeneration in CNS and PNS injury. The divergent morphology and topology in these disorders previously suggested independent mechanisms, but the results of directly probing the mechanism using *Wld*^{S} challenge this interpretation.

Many CNS disorders in which there is axonal swelling show accumulation of amyloid precursor protein in the swellings,

indicating impairment of axonal transport in each case and suggesting that their axon degeneration mechanisms are to some extent related. *gad* is one of these disorders, and the others include brain trauma (Gentleman *et al*., 1993), stroke (Dewar *et al*., 1999) and other forms of ischaemia (Hughes *et al*., 2003), multiple sclerosis (Ferguson *et al*., 1997), and HIV dementia (Medana and Esiri, 2003). This similarity with *gad* suggests that axon degeneration in other disorders may also be related to Wallerian degeneration, a possibility that should now be tested using *Wld*^{S} mice or, where appropriate, the newly generated *Wld*^{S} rat model (Adalbert *et al*., in press). However, it is unlikely that *Wld*^{S} will stop all forms of axonal swelling, as it appears unable to do so in *Plp* null mice (Edgar *et al*., 2004). Thus, it should be possible to categorize CNS axonal swelling disorders into those that are altered by *Wld*^{S} and those that are not. This will then enable disorders to be grouped together for mechanistic studies rather than focusing on each disorder in isolation.

It is important to consider the spatial and temporal relationship between axonal swelling and axonal breakdown in the light of our data. The lack of good methods for longitudinal imaging of CNS axons has made it difficult to determine whether spheroids first occur as terminal endbulbs of axons whose distal ends have degenerated, or as localized swellings on otherwise morphologically normal axons. Preliminary data from our laboratory using axons of *gad*/YFP-H mice (Adalbert and Coleman., unpublished) suggest that many spheroids in *gad* are not terminal endbulbs, at least in the early stages of the disease. Thus, one model to account for the effect of *Wld*^{S} in *gad* is that an 'en passant' spheroid is the first step in pathology, leading to degeneration of the distal axon due to the blockage of axonal transport, a process that fixes the spheroid as a terminal endbulb. In this model, *Wld*^{S} might block the Wallerian-like degeneration of the distal end for long enough to allow the spheroid to resolve and the axon to recover. Thus, our data suggest that *Wld*^{S} could be used to address the question of whether swollen axons can recover or whether they are destined, inevitably, to degenerate. In a wider context, this is an important issue in several CNS disorders where axonal spheroids occur, including brain trauma and multiple sclerosis (Cheng and Povlishock, 1988; Ferguson *et al*., 1997).

The above model assumes that Wallerian-like degeneration and axonal swelling in *gad* are separated in space and time, with one causing the other. Alternatively, the mechanism of the axonal swelling itself in *gad* may be related to that of Wallerian degeneration. In support of this model, there are a number of disorders in which CNS axons swell and PNS axons of the same animal degenerate by Wallerian-like degeneration without extensive swelling. In *gad* mice, this occurs even within the same cell, as gracile tract central projections of lumbar primary sensory neurons have spheroids, while peripheral muscle spindles degenerate without swelling (Oda *et al*., 1992). Similarly, amyotrophic lateral sclerosis (ALS) in humans (Tu *et al*., 1996; Takahashi *et al*., 1997), mice (Tu *et al*., 1996; Oosthuyse *et al*., 2001) and rats (Howland *et al*., 2002), together with tauopathy in mice (Lewis *et al*., 2000; Probst *et al*., 2000), all show axonal swelling in spinal cord and other CNS areas, but extensive 'Wallerian-like' degeneration without swelling in ventral roots and peripheral nerves. Even injury-induced Wallerian degeneration shows different morphology depending on experimental circumstances. For example, when injured gracile tract axons undergo Wallerian degeneration they swell to up to 10 times their normal diameter, quite unlike Wallerian degeneration in the PNS (George and Griffin, 1994). Thus, a number of observations support a direct mechanistic link between axonal swelling and Wallerian degeneration.

It is not yet clear how related mechanisms might cause swelling in spheroids but axon fragmentation in Wallerian degeneration. Cytoskeletal changes are common to both, so a loosening of cytoskeletal structure could cause disorganized cytoskeleton to accumulate in spheroids but to undergo rapid granular disintegration in Wallerian degeneration. Wallerian degeneration of injured gracile tract axons displays elements of both processes, possibly having an intermediate mechanism: like spheroids, these axons dilate considerably but, typical of Wallerian degeneration, they also rapidly lose their cytoskeletal proteins (George and Griffin, 1994). In traumatic brain injury, observation of Wallerian degeneration and spheroids in the same transverse thin section has been interpreted as degenerating axons having a more proximal spheroid that blocks axonal transport (Cheng and Povlishock, 1988). In view of our findings, an additional explanation needs to be considered, that spheroids and Wallerian degeneration are alternative responses of different axons to the same lesion. Methods for real-time or long-range longitudinal analysis of individual spheroid-containing axons are required to resolve this, similar to new methods already applicable in PNS axons (Pan *et al*., 2003; Beirowski *et al*., 2004). What determines whether an axon develops a spheroid or undergoes Wallerian degeneration? Possible explanations include the different glial and haematopoietic cell content of the CNS and the lower rate of axonal transport there (Wujek and Lasek, 1983), but injury type may also be important. Finally, since the discovery of the *Wld*^{S} mouse, Wallerian degeneration is no longer considered a passive wasting of distal axons but a regulated self-destruction programme (Buckmaster *et al*., 1995; Raff *et al*., 2002). The reduction of axonal spheroid pathology in *gad* by the same gene raises similar questions: rather than being a passive consequence of blocked axonal transport axonal swelling could be, like Wallerian degeneration, a programmed response to axon damage.

Altered ubiquitin metabolism plays important roles in neurodegenerative diseases of the CNS. Genetic mutations in Parkinson's disease include an E3 ligase (Kitada *et al*., 1998) and possibly *UCH-L1*, the human homologue of the gene mutated in *gad* (Leroy *et al*., 1998). Ubiquitin-positive inclusions and other evidence indicate abnormal ubiquitylation in Alzheimer's disease (Mori *et al*., 1987;

van Leeuwen *et al*., 1998), polyglutamine disorders (DiFiglia *et al*., 1997; Cummings *et al*., 1999; Bence *et al*., 2001) and ALS (Tu *et al*., 1996; Bruijn *et al*., 1997). Axons and synapses are particularly vulnerable, as proteasome inhibitors cause specific degeneration of distal neurites (Laser *et al*., 2003) and ubiquitin-related mutations alter synapse growth (DiAntonio *et al*., 2001) and stability (Wilson *et al*., 2002). As *Wld*^{S} can counter a downstream effect of defective ubiquitin metabolism, it now becomes important to study its effects on the above disorders.

Wld^S did not alleviate the symptoms of *gad* mice. Unfortunately, methods do not currently exist to assess the function of gracile tract axons, so we cannot rule out the possibility that blocking spheroid formation did not preserve axon function. However, it is likely that continued neuromuscular pathology in *gad/Wld*^{S} mice also contributes to the symptoms. These mice suffered extensive synapse loss by 15 weeks (Fig. 5), whereas axon pathology was still strongly reduced 3 weeks later (Fig. 2). This supports the hypothesis that different mechanisms underlie synaptic and axonal degeneration, with *Wld*^{S} affording only limited protection to synapses, particularly in older mice (Gillingwater and Ribchester, 2001; Gillingwater *et al*., 2002). Similarly, the synapses of gracile tract axons may have been lost even when those axons are preserved. Our data suggest that synapse pathology is a limiting factor when axons are protected by *Wld*^{S}, a finding likely to be important in other models (Ferri *et al*., 2003; Samsam *et al*., 2003).

In summary, we conclude that *Wld*^{S} alleviates chronic CNS axon pathology in *gad* mice and that formation of distal axonal spheroids in this disease shares features with Wallerian degeneration and 'dying-back' axon loss without spheroids. The effect of *Wld*^{S} on other CNS disorders with ubiquitylation deficits and CNS axonal swelling disorders should now be studied. Finally, our data emphasize the importance of finding a way to protect synapses as strongly as *Wld*^{S} protects axons.

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