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Axonal Degeneration in Retinal Ganglion Cells is Associated with a Membrane Polarity-Sensitive Redox Process

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Abstract

Axonal degeneration is a pathophysiological mechanism common to several neurodegenerative diseases. The slow Wallerian degeneration (Wld^S) mutation, which results in reduced axonal degeneration in the central and peripheral nervous systems, has provided insight for a redox-dependent mechanism by which axons undergo self-destruction. We studied early molecular events in axonal degeneration with single-axon laser axotomy and time-lapse imaging, monitoring the initial changes in transected axons of purified retinal ganglion cells (RGCs) from wild-type and Wld^S rat retinas using a polarity-sensitive annexin-based biosensor (annexin B12-Cys101,Cys260-N,N'-dimethyl-N-(iodoacetyl)-N'-(7-nitrobenz-2-oxa-1,3-diazol-4-yl) ethylenediamine). Transected axons demonstrated a rapid and progressive change in membrane phospholipid polarity, manifested as phosphatidylserine externalization, which was significantly delayed and propagated more slowly in axotomized Wld^S RGCs, compared to wild-type axons. Delivery of bis(3-propionic acid methyl ester)phenylphosphine borane complex, a cell-permeable intracellular disulfide-reducing drug, significantly slowed the onset and velocity of phosphatidylserine externalization in wild-type axons, replicating the Wld^S phenotype, while extracellular redox modulation reversed the Wld^S phenotype. These findings are consistent with an intra-axonal redox mechanism for axonal degeneration associated with the initiation and propagation of phosphatidylserine externalization after axotomy.

Significance Statement

Axonal degeneration is a neuronal process independent of somal apoptosis, the propagation of which is unclear. We combined single-cell laser axotomy with time-lapse imaging to study the dynamics of phosphatidylserine externalization immediately after axonal injury in purified retinal ganglion cells. The extension of phosphatidylserine externalization was slowed and delayed in Wallerian degeneration slow (Wld^S) axons, and this phenotype could be reproduced by intra-axonal disulfide reduction in wild-type axons and reversed by extra-axonal reduction in Wld^S axons. Together, these results are consistent with a redox mechanism for propagation of membrane polarity asymmetry in axonal degeneration.

Introduction

Axonal degeneration is a common feature of many traumatic and neurodegenerative diseases (Lingor et al., 2012). Axonal degeneration takes place in two directions, one toward the cell body (retrograde degeneration) and the other toward the distal axon terminal (Wallerian degeneration) (Waller, 1850; Luo and O'Leary, 2005). Morphologically degenerative changes of axons in Wallerian degeneration are well characterized, starting with axonal swelling followed by membrane beading, and finally fragmentation of the axon (Coleman and Freeman, 2010).

Acute axonal damage leads to the loss of the integrity of the membrane and axonal degeneration (Kerschensteiner et al., 2005; Wang et al., 2012). Asymmetry of the axonal membrane is an integral property of a healthy neuron, which is maintained by restriction of phosphatidylserine and phosphatidylethanolamine to the cytosolic (inner) leaflet of the plasma membrane, while phosphatidylcholine, sphingomyelin and glycosphingolipids are limited to the non-cytosolic (outer) leaflet (Verkleij et al., 1973; Rothman and Lenard, 1977; Maiese and Vincent, 2000; Fadeel and Xue, 2009; Leventis and Grinstein, 2010). Externalization of phosphatidylserine after axonal or soma injury is an early apoptotic marker and acts as a signal enabling microglia/macrophages to recognize and actively remove damaged somas and axons (Martin et al., 1995; Rimon et al., 1997; Fadok et al., 2001).

Although the processes that maintain asymmetric distribution of axonal lipids is well studied (van Meer et al., 2008), the mechanism by which axonal injury signals

phosphatidylserine externalization is not well understood. Using real-time confocal microscopy in living animals, we previously showed that optic nerve transection causes a burst of superoxide in retinal ganglion cells (RGCs) which precedes apoptosis (Kanamori et al., 2010). RGC axons form the optic nerve, which conducts visual information from the retina to the brain. RGC axonal injury leads to axonal degeneration, which can be ameliorated by redox-dependent disulfide reduction (Almasieh et al., 2011). Elevated levels of superoxide anion could result in oxidative modification of sulfhydryl groups on critical lipids and proteins in the axon. One such target is phosphatidylserine, which during apoptosis undergoes oxidation, resulting in production of oxidized phosphatidylserine (Matsura, 2014). It has been reported that oxidation of phosphatidylserine results in a significant increase in phosphatidylserine externalization (Tyurina et al., 2004). Therefore, in this study we investigate the hypothesis that the loss of axonal membrane asymmetry after damage is related to axonal redox status.

On average a transected wild-type mouse axon survives for up to 2 days. Remarkably, transected axons of delayed Wallerian degeneration (Wld^S) mutant mice survive for up to 3 weeks while maintaining the capacity to conduct action potentials (Perry et al., 1990; Tsao et al., 1999). Discovery of Wld^S mice provided support for the idea that a molecularly distinct self-destruct program is responsible for the axonal degeneration (Lunn et al., 1989; Perry et al., 1991; Raff et al., 2002). The Wld^S mutation results from the tandem triplication of nicotinamide mononucleotide adenylyltransferase 1 (NMNAT-1) and the N-terminal 70 amino acids of ubiquitination factor e4b (Lyon et al., 1993; Coleman et al., 1998). NMNAT-1 is a central enzyme in nicotinamide adenine

dinucleotide (NAD^+) biosynthesis (Mack et al., 2001), which plays an important role in cellular energy metabolism and redox reactions, acting as an oxidizing and reducing (NADH) agent in the respiratory chain and the production of ATP and reactive oxygen species (ROS) (Orrenius, 2007; Ying, 2008).

We hypothesized that the extended survival of Wld^S axons after axonal injury is a reflection of their ability to maintain the axonal redox status and by extension the membrane asymmetry of phosphatidylserine. To test this hypothesis, axons of purified RGCs from wild-type and Wld^S rat retinas were individually transected with an ultrafast laser. Using a polarity-sensitive annexin-based biosensor (pSIVA) with switchable fluorescence states (Kim et al., 2010a), the spatial and temporal pattern of axonal phosphatidylserine externalization in transected wild-type RGC axons was assessed and compared to Wld^S axons. Cell-permeable and cell-impermeable disulfide-reducing agents were used to demonstrate that phosphatidylserine externalization after axonal injury is redox-dependent.

Materials and Methods

Animals

All procedures were carried out in accordance with the guidelines of Association for Research in Vision and Ophthalmology and the Canadian Council on Animal Care for the use of animals in research and were approved by the Maisonneuve-Rosemont Hospital Research Centre animal care committee. The Wld^S transgenic rats were kindly provided to us by Dr. Michael Coleman (Babraham Institute, Cambridge, UK). To generate the Wld^S rats, Ube4b/Nmnat cDNA was cloned downstream of the beta-actin promoter in pHbetaAPr-1 plasmid and injected into rat embryo pronuclei of Sprague–Dawley (Mack et al., 2001; Adalbert et al., 2005). Wld^S pups were generated in an in-house breeding program. The WldS strain is on a Sprague-Dawley background, and is homozygous, precluding the use of littermate controls. Wild-type pregnant Sprague-Dawley rats were obtained from Charles River Canada (QC, Canada), and acclimated in the animal facility until litters were born.

Materials

Glass-bottom dishes for imaging were from MatTek Corporation (Ashland, MA), Goat anti-rabbit IgG (H+L) and goat anti-mouse IgM (μ-chain specific) were from Jackson ImmunoResearch Inc. (West Grove, PA; Cat# 111-005-003, RRID: AB_2337913 and Cat# 115-005-020, AB_2338450, respectively). Rabbit anti-rat macrophage sera was from Cedarlane (Burlington, ON; Cat# CLAD51240, RRID: AB_10059912). Thy-1 IgM was produced from the T11D7e2 hybridoma line (American Type Culture Collection,

Manassas, VA; Cat# TIB-103, RRID: CVCL_F769). Poly D-lysine, DNase I, insulin, Forskolin, BSA, trypsin, trypsin inhibitor, human apo-transferrin, progesterone, sodium selenite, putrescine, thyroxine (T3), N-acetyl-L-cysteine (NAC), 1,4-dithiothreitol (DTT), and tris (2-carboxyethyl) phosphine hydrochloride (TCEP) were from Sigma-Aldrich (St. Louis, MO). Cultrex mouse laminin I was from Trevigen (Gaithersburg, MD). Dulbecco's phosphate-buffered saline (DPBS) and fetal bovine serum (FBS) were from Invitrogen (Waltham, MA). Papain (Worthington Biochemical Corp., Lakewood, NJ). L-cysteine was from Wisent (Saint-Jean-Baptiste, QC). Neurobasal-A, penicillin/streptomycin, sodium pyruvate, and L-glutamine were from Gibco (Waltham, MA). hBDNF and CNTF were from Alomone Labs (Jerusalem, Israel). Recombinant human FGF-basic (154 aa) was from PeproTech (Rocky Hill, NJ). Defined serum supplement GS-21 was from MTI-GlobalStem (Gaithersburg, MD). Annexin B12-Cys101,Cys260-N,N'-dimethyl-N-(iodoacetyl)-N'-(7-nitrobenz-2-oxa-1,3-diazol-4-yl) ethylenediamine (annexin B12-IANBD) was from Novus Biologicals Canada (Oakville, ON). Bis(3-propionic acid methyl ester) phenylphosphine-borane complex (PB1) was synthesized according to our published methods (Schlieve et al., 2006) at the Keck-University of Wisconsin Comprehensive Cancer Center Small Molecule Screening Facility (Madison, WI). The purity of PB1 was >99% by HPLC.

Retinal ganglion cell purification and culture

Purified RGC cultures were produced from dissociated Sprague-Dawley or Wld^S P2-P7 pup retinas of either sex immunopurified with sequential anti-macrophage and anti-Thy-1 panning, using modified version of a protocol first developed by Barres (Barres et al.,

1988) and modified by Goldberg (Hu et al., 2010). Briefly, freshly dissected retinas were placed in a filtered DPBS solution containing 16.5 U/ml papain, 0.2 mg/ml L-cysteine, 124 U/ml DNase I, and 0.1% of a 1 N sodium hydroxide solution. The retinas were digested for 30 minutes at 37°C, gently swirling the solution at 15-minute interval. After digestion, the papain solution was gently aspirated, retaining the partially digested retinas. Ovomucoid (0.6 mg/ml) and BSA (0.6 mg/ml) was added to halt digestion, followed by anti-rat macrophage antibody. The retinas were gently triturated to produce a single cell suspension. After 10 minutes to allow antibody binding, the cells were pelleted by centrifugation and resuspended in DPBS containing 10 mg/ml of ovomucoid and BSA. Cells were pelleted again and resuspended in DBPS containing 0.2 mg/ml BSA and 5 µg/ml insulin.

The cell suspension was added to a 150 mm Petri dish that had been previously incubated overnight with goat anti-rabbit IgG in Tris-HCl, and incubated for 20 minutes at room temperature to allow macrophages to adhere to the plate, agitating after 10 minutes. Non-adherent cells were transferred to a second identical 150 mm dish and incubated for 45 minutes (agitating at 15 minutes) to further deplete macrophages. The binding of macrophages was confirmed on a microscope. Non-adherent cells were then gently shaken loose and seeded onto a 100 mm Petri dish that had been previously coated with goat anti-mouse IgM in Tris-HCl followed by supernatant from the T11D7e2 hybridoma line, containing anti-Thy-1 IgM. Cells were incubated 50 minutes at room temperature to allow binding of RGCs, agitating every 10 minutes. Non-adherent cells were then aspirated, and the plate was very gently rinsed 4-6 times with DPBS until only adherent cells remained, as assessed by microscopy.

The RGCs adherent to the anti-Thy-1 dish were removed with a trypsin incubation for 4 minutes at 37°C, followed by inactivation with 30% heat-inactivated FBS and dislodging by pipetting. Cells were collected in a 20 ml plastic tube, pelleted and resuspended in 500 µl of 30% FBS for counting on a hemocytometer, at which point the quality of isolation was estimated by uniformity, shape, and size of isolated cells.

The purified RGCs were plated on MatTek glass-bottom culture dishes that had been previously coated with poly-D-lysine (10 µg/ml) for at least 30 minutes, followed by laminin in Neurobasal A (2 µg/ml). The RGC culture media consisting of Neurobasal A supplemented with 2% GS-21 (a defined serum supplement), penicillin (100 U/ml), streptomycin (100 µg/ml), insulin (5 µg/ml), sodium pyruvate (1 mM), L-glutamine (1 mM), transferrin (100 µg/ml), BSA (100 µg/ml), progesterone (0.2 µM), putrescine (16 µg/ml), sodium selenite (40 ng/ml), T3 (40 ng/ml), N-acetyl cysteine (5 µg/ml), forskolin (5 µM), BDNF (50 ng/ml), CNTF (10 µg/ml) and bFGF (10 µg/ml). Cells were kept in a humidified 10% CO_2 incubator at 37°C for at least three days to allow time for the ganglion cells to adhere and extend processes, and fed every three days by removal of half the medium and replacement with fresh medium.

Single Axon Transection

We developed a platform for producing submicron ablations in cultured RGC axons using ultrafast lasers. A Spectra-Physics Mai Tai (Spectra-Physics, CA. USA) fully automated laser producing 3 W at 800 nm with 100 fs pulses at 80 MHz was coupled to an Olympus IX71 inverted fluorescence microscope with a custom-made Thorlabs scanning laser module. This permits alignment of a high-power beam directly through

the aperture of a 1.2 NA water immersion 60X objective coated for infrared wavelengths, which was used to focus the laser beam on axons to produce injury.

The motorized microscope stage and laser trigger were controlled by our custom-made LabVIEW program (National Instruments Corporation, TX, USA). The program moves the stage in the desired direction while simultaneously triggering the laser, guiding the axon through the path of the laser and thereby enabling axonal transection. At the beginning of each set of experiments, the following calibration protocol was followed to ensure consistency of experiments. The alignment of the laser beam was checked using a target so that the beam was centered on the axis of the lens. After centering the beam, the microscope was switched to the 60X objective and the laser power output at the focal point was adjusted to 65 mW using a power meter interface (Thorlabs PM100, Thorlabs Inc., NJ, USA) and sensor (Coherent LM-10 HTD, Coherent Inc., CA, USA). A MatTek glass-bottom dish clad with a thin gold film was placed in the micro-incubator (positioned on the microscope stage) at the same spot that RGC dish would sit. Then using the LabVIEW program, 3 lines (40 µm length, 1 µm width) were engraved into the gold film at 0°, 45°, and 90° to provide reference points for the laser transection start and end points (Fig. 1A). Axotomy was performed only on RGCs with clearly identifiable axons. After the RGC was selected, and prior to axotomy, the RGC soma and the full extent of its axon was captured in a series of bright-field images (60X objective), enabling calculation of the length of the axon and the distance of transection site to the soma (Fig. 1B). The axon was then positioned so that the intended transection site would be in the path of the laser beam, and images with 488 nm excitation and bright-field illumination were obtained, the former as a baseline for subsequent fluorescence

227 detection, and the latter to determine the diameter of axon at the transection site and as
228 a baseline for subsequent laser-induced morphological changes at the site of axotomy.
229 To perform the axotomy, all filters were removed from the optical path and the LabVIEW
230 program was used to simultaneously trigger the laser and move the stage, resulting in
231 axonal transection. Immediately following axotomy, a bright-field image was obtained
232 and then fluorescence imaging immediately commenced by restoring the FITC filter set
233 to the optical path. The bright-field image was used for measuring the lesion size (Fig.
234 2).

235 **Detection of phosphatidylserine externalization after axotomy**

236 To detect the initiation and spread of phosphatidylserine externalization, annexin B12-
237 IANBD was added to the medium prior to axotomy. Annexin B12 belongs to the family
238 of highly preserved cytosolic proteins that in the presence of Ca^{2+} bind exclusively to the
239 negatively charged membrane phospholipids in particular to the phosphatidylserine
240 (Gerke et al., 2005). Similar to the other members of annexin family, the annexin B12
241 structure has a main core consisting of four domains. Arrangement of these domains
242 gives the molecule a three-dimensional shape of a bent disc, with convex and concave
243 surfaces (Patel et al., 2005). Each domain is 70 amino acids long and contains five α-
244 helices, four of them (helices A, B, D, E) are arranged in a cylindrical formation and
245 perpendicularly positioned in the disc, while the fifth α-helix (C) covers the formation on
246 the concave surface (Isas et al., 2004). On the convex surface of annexin molecule,
247 there are amino acid loops that connect the helices (A to B and D to E) of each domain,
248 these loops contain the regions that provide the Ca^{2+} and membrane binding sites (Isas

et al., 2005). Kim and colleagues (Kim et al., 2010a) attached the thiol-reactive fluorophore IANBD to the cysteine residing in Ca^{2+} and membrane binding sites of the loop in annexin B12 to create an environment-sensitive fluorescent biosensor. IANBD amide only emits fluorescence when the molecule is in a nonpolar environment (e.g. the membrane-bound state of annexin) and the fluorescence is negligible ('off') when in solution. Binding of annexin B12- IANBD to membranes places the label in a nonpolar lipid enclosure and switches 'on' the fluorescence signal (Kim et al., 2010b). Use of annexin B12-IANBD in our study enabled extremely rapid detection of early membrane changes following axon transection. This provides a significant advantage over the use of conventional fluorescent-labeled annexin V (Sievers et al., 2003), which requires several washes to reduce the fluorescent background. These washes delay the detection of the signal and cause cell stress, which could confound the observations.

Quantification of axonal degeneration after axotomy

The fluorescent probe annexin B12-IANBD (4 µg/ml) was added to the medium of MatTek glass-bottom dishes to visualize externalization of phosphatidylserine along the axon. Following the laser axotomy, time-lapse imaging was used to record the progress of fluorescent signal along the axon length, corresponding to a wave of membrane lipid asymmetry along the length of axon (Fig. 3A).

Transection was followed immediately by real-time fluorescence imaging with the same 60X water immersion objective using a sensitive Retiga2000R video-rate camera. Initial images were captured every 10 seconds until fluorescence was visible, and then every 60 seconds to a total of 30 minutes. Images were used to measure the delay, initiation,

and velocity of the fluorescent signal of annexin B12-IANBD along the proximal and distal segments of the transected axon.

The length of the fluorescent segment of an axon as a function of time *l(t)* was fitted using an empiric mathematical model:

$$l(t) = A\left(1 - e^{-\frac{t-t_0}{t_c}}\right)H(t - t_0)$$

where *A* is a constant corresponding to the asymptotic value of the length of the fluorescent section of the axon (Fig. 3B). The time interval between axon transection and the first observation of fluorescence is defined as t_0. The time constant t_c characterizes the propagation of the fluorescent signal along the axon. *H(t)* is the Heaviside step function, defined as:

$$H(x) = \int_{-\infty}^{x} \delta(y)dy$$

where δ is the Dirac delta function. The three parameters (*A*, t_0 and t_c) were obtained with a linear least-square fit implemented in MATLAB. Axons that could not be fitted (based on the calculated *A* being longer than the axon itself or t_c less than one minute, both of which were physically impossible) were not analyzed. The excluded axons (8 of a total of 154 axons) were evenly distributed (by chi-squared and t-test analysis) across species, distal vs. proximal axons, long vs. short axons, distant vs near transection sites, age in culture, and age of animals.

The initial velocity was calculated as the right derivative of the length, evaluated at t_0:

$$\partial_+ l(t)|_{t_0} = {}^{A}/_{t_c}$$

288

289 Morphological evidence of axonal degeneration was based on the development of
290 swelling and beading propagating away from the transection site along the axon (Fig 4).

291 **Statistical analysis**

292 Because the velocity and delay distributions were not normally distributed, analyses
293 were with nonparametric methods. Comparison of 2 groups was performed with the
294 Wilcoxon test. Comparison of more than 2 groups was with Kruskal-Wallis followed by
295 Dunn nonparametric *post-hoc* testing with joint ranking for comparison of more than 2
296 groups against a control. More complex models were analyzed using Fit Model for
297 mixed models. All analyses were with JMP (SAS Institute Inc., NC, USA; RRID:
298 SCR_014242).

Results

Annexin B12-IANBD can be used to measure the velocity and delay until initiation of phosphatidylserine externalization in transected retinal ganglion cell axons

Within seconds following laser axotomy, the fluorescent signal of annexin B12-IANBD, reflected binding to externalized phosphatidylserine, was detected at the site of axotomy and to adjacent proximal and distal axonal segments (Fig.3A). This reflects the externalization of phosphatidylserine to the outer leaflet of the axonal membrane. The length of the fluorescent segment for each axon was fitted as a function of time to obtain the velocity values (μm/min) for each segment. In the first 30 minutes following axotomy, the annexin B12-IANBD signal progressed at similar rates in the proximal and distal segments, with a mean velocity of 12.68 ± 1.57 μm/min [n = 22] proximally compared to 10.49 ± 1.56 μm/min [n = 19] distally ($p = 0.346$).

The velocity of phosphatidylserine externalization along the axon is one measure of axonal degeneration, but we also observed differences in the delay from the time of axonal transection to the first detection of phosphatidylserine externalization. Assuming that this delay reflects intracellular processes to initiate phosphatidylserine externalization, while velocity reflects the transmission of the degeneration signal along the axon, it is likely that different mechanisms are being probed by measuring each process.

The delay until initiation of phosphatidylserine externalization in the wild-type axons was 3.18 ± 0.64 min [n = 42]. Together with the similar velocities of phosphatidylserine

externalization in the proximal and distal segments, this indicates that the dynamics of retrograde and Wallerian degeneration with respect to membrane polarization are similar.

Wld^S axons have significantly slower velocity of phosphatidylserine externalization after axotomy compared to wild-type axons

The slow degeneration of the distal axon after transection in Wld^S mutant animals is well documented (Mack et al., 2001; Adalbert et al., 2005). We hypothesized that slowed degeneration in Wld^S axons is mediated in part by differences in axonal degeneration, and particularly, would correlate with the polarity of phosphatidylserine in the axonal membrane after axotomy. The use of the fluorescent reporter annexin B12-IANBD allows direct imaging of the flipping of phosphatidylserine from the inner to outer leaflets (Fig. 5A).

We found that transected Wld^S axons had a significantly slower velocity of phosphatidylserine externalization along the axon compared to wild-type axons (Fig. 5B). In Wld^S axons, the mean velocity was 5.24 ± 1.29 μm/min [n = 30], compared to 11.67 ± 1.11 μm/min [n = 41] in wild-type axons ($p = 0.0001$). To see whether this difference was specific to retrograde vs. anterograde signaling, the data for the proximal and distal segments were analyzed separately. The mean velocity of phosphatidylserine externalization along the proximal segment of transected Wld^S axons was 6.14 ± 1.90 μm/min [n = 15] compared to 12.68 ± 1.57 μm/min [n = 22] for wild-type axons ($p = 0.011$). In the distal axon, phosphatidylserine externalization spread with a mean velocity of 4.35 ± 1.76 μm/min [n = 15] for Wld^S axons compared to 10.49 ± 1.56

342 μm/min [n = 19] for wild-type axons (p = 0.002). The velocity of phosphatidylserine
343 externalization in Wld^S axons was 48% slower for the proximal segment and 41%
344 slower in the distal segment, compared to wild-type axons (Fig. 5C). Finally, there was
345 no difference in velocity of signaling between proximal and distal segments of Wld^S
346 axons (p = 0.229), similar to what was observed in wild-type axons.

347 The initial morphological alterations resulting from laser axotomy were limited to a 2 to 3
348 micrometer area surrounding the focal point of the laser (Fig. 2), which became visible
349 within minutes after axotomy. With the progress of time, morphological changes
350 associated with axonal degeneration were detected along the axon (Fig. 4). To further
351 understand the difference in velocity of phosphatidylserine externalization between Wld^S
352 and wild-type axons, we compared it to morphological changes associated with axonal
353 degeneration, detected as swelling and beading along axon. The mean velocity of
354 axonal degeneration was 0.90 ± 0.15 μm/min in Wld^S axon and 1.51 ± 0.14 μm/min in
355 wild-type axons (p = 0.01).

356 We then measured the delay between the transection of the axon and the first detection
357 of the annexin B12-IANBD signal in wild-type and Wld^S axons, which represents the
358 time until the phosphatidylserine polarity first flips from internal-facing to external-facing.
359 In Wld^S axons, the mean delay was significantly longer than in wild-type axons (5.17 ±
360 0.71 min [n = 34] vs. 3.18 ± 0.64 min [n = 42]; p = 0.042). Therefore, in Wld^S axons the
361 velocity of spread of phosphatidylserine externalization was significantly slower, while
362 the delay from transection until the first evidence of externalization was significantly
363 longer (Fig. 5D).

Redox modulation significantly slows the velocity of phosphatidylserine externalization in transected wild-type axons

The mechanism by which phosphatidylserine externalization is slowed after axotomy in Wld^S axons could be related to the mutation's effect on redox signaling (O'Donnell et al., 2013). To explore this hypothesis, we used a cell-permeable intracellular disulfide reducing agent, PB1, (Fig. 6A) (Schlieve et al., 2006; Niemuth et al., 2016), which we had previously shown slows axonal degeneration (Almasieh et al., 2011). Pre-incubation of primary RGCs for 30 minutes prior to axotomy in medium containing PB1 (100 µM) affected the dynamics of phosphatidylserine externalization. The mean velocity following transection of axons in medium with PB1 was significantly slower (6.73 ± 2.14 µm/min [n = 15]) compared to control medium (11.66 ± 1.29 µm/min [n = 41]; p = 0.004) (Fig. 6B). In comparison, the mean velocity of morphological changes associated with axonal degeneration (swelling and beading) for PB1-treated wild-type axons was 0.81 ± 0.16 µm/min, compared to 1.51 ± 0.14 µm/min in untreated wild-type axons (p = 0.002), and similar to the 0.90 ± 0.15 µm/min observed in untreated Wld^S axons (p = 0.169).

To better understand these results, we analyzed the proximal and distal segments separately. The velocity of phosphatidylserine externalization was less slowed by PB1 along the proximal segment of transected wild-type axons (9.91 ± 3.36 µm/min [n = 7] vs 12.68 ± 1.89 µm/min [n = 22]; p = 0.47) than along the distal segment (3.91 ± 2.86 µm/min [n = 7] vs 10.97 ± 1.79 µm/min [n = 18]; p = 0.001) (Fig. 6C). There was a significant difference in delay until initiation of phosphatidylserine externalization

between PB1-treated wild-type axons and untreated wild-type axons (4.89 ± 0.69 min [n = 16] vs 3.18 ± 0.42 [n = 42]; p = 0.028) (Fig. 6D). These results demonstrate that the redox-dependent mechanism for initiation of phosphatidylserine externalization is similar to that for its propagation.

To test whether the signaling of redox modulation on phosphatidylserine externalization was occurring in the intracellular or extracellular compartments, the effects of PB1 was compared with two non-cell-permeable disulfide reducing agents, dithiothreitol (DTT) and tris(2-carboxyethyl) phosphine (TCEP). In contrast to the effects of PB1 in slowing velocity of phosphatidylserine externalization, pre-incubation of primary RGCs with DTT (100 μM) or TCEP (100 μM) for 30 minutes did not affect the velocity (8.93 ± 3.42 μm/min [n = 6]; p > 0.9 for DTT and 13.41 ± 2.41 μm/min [n = 12]; p > 0.9; for TCEP). Unlike PB1, which increased the delay until phosphatidylserine externalization after axonal transection, the delay was significantly decreased with DTT (0.24 ± 1.17 min [n = 6]; p = 0.013 vs. no treatment) and TCEP (1.08 ± 0.82 min [n = 12]; p = 0.042 vs. no treatment). Together, these findings are consistent with intracellular redox signaling of the spread of axonal degeneration after axotomy, and for extracellular redox signaling in its initiation.

In contrast to the effects of PB1 on wild-type RGCs after axotomy, PB1 treatment of Wld^S RGCs had no effect on the velocity (4.74 ± 1.26 μm/min [n = 8] vs 5.24 ± 0.65 μm/min [n = 30]; p > 0.9) (Fig. 6E) or delay (6.26 ± 2.05 min [n = 8] vs 5.17 ± 0.99 min [n = 34]; p = 0.665) until phosphatidylserine externalization after axotomy (Fig. 6F). On the other hand, pre-incubation of Wld^S RGCs with DTT and TCEP, which unlike PB1,

affect the extracellular redox state, reversed the Wld^S phenotype. Specifically, they significantly increased velocity (16.18 ± 2.06 μm/min [n = 16] and 17.17 ± 2.38 μm/min [n = 12]; p = 0.002 and 0.0001 vs. no treatment, respectively) and decreased the delay (1.44 ± 1.17 min [16] and 0.16 ± 1.35 min [n = 12]; p = 0.040 and 0.0001 vs. no treatment, respectively).

To study the interaction between the delay and the velocity of phosphatidylserine externalization in wild-type, Wld^S, and PB1-treated wild-type axons, we analyzed the two variables together using a mixed model approach. Delayed initiation of phosphatidylserine externalization was not correlated with the velocity of the signal in wild-type axons (r = 0.09; p = 0.58) or Wld^S axons (r = 0.08; p = 0.66), but was seen in PB1-treated wild-type axons (r = 0.62; p = 0.014). The mixed model analysis demonstrated an interaction between velocity/delay and whether an axon was Wld^S or PB1-treated wild-type (p = 0.0011) (Fig. 6G-I), suggesting that intra-axonal disulfide reduction recapitulates most but not all features of the Wld^S phenotype. These findings together suggest a common mechanism to the Wld^S mutation and intracellular redox signaling in slowing the signaling of axonal degeneration, with extracellular reduction having opposite effects.

Axon length significantly slows the velocity and increases the delay until phosphatidylserine externalization in axotomized RGCs

Neurons with long axons have more cell surface and time for axonal transport to carry retrograde and anterograde survival signals, and therefore may be more susceptible to axonal injury, as seen in some peripheral neuropathies with respect to energy

metabolism along the axon, recent evidence indicates a reduced mobility of mitochondria in the distal segment of axons as they mature (Lewis et al., 2016), and similar slowed mitochondrial movement has been shown to contribute to the initiation of neurodegenerative disease (Takihara et al., 2015). We therefore investigated whether axonal length affects the velocity or delay of phosphatidylserine externalization following axotomy. The median of all axon lengths was calculated (717 μm), and RGCs with axons shorter than the median were placed in the short axon group and RGCs with axons longer than the median were placed in the long axon group. The short axons had a mean length of 524.5 ± 16.6 μm, compared to long axons with mean length of 1004.0 ± 48.5 μm. The minimum length of an axon included in the short group was 182.6 μm and the maximum length was 714.3 μm. The minimum length of an axon included in the long group was 720 μm and the maximum length was 2677 μm. The mean diameter of short axons was slightly greater than the mean diameter of long axons (1.03 ± 0.02 vs. 0.94 ± 0.03; p=0.01), although the diameter did not correlate with axonal length (r = 0.0625; p = 0.63).

Short wild-type axons had a significantly faster velocity of phosphatidylserine externalization compared to their longer counterparts (13.00 ± 1.66 μm/min [n = 28] vs. 8.27 ± 2.66 μm/min [n = 11]; p = 0.04) (Fig. 7A). However, short wild-type axons were significantly slower to initiate externalization compared to long axons (3.51 ± 0.47 min [n = 28] vs. 1.56 ± 0.76 min [n = 11]; p = 0.021) (Fig. 7B).

To study the redox-dependency of the effect of axon length on velocity and delay, RGCs were treated with PB1 and then axotomized. Pre-incubation of RGCs with PB1 significantly slowed the velocity of phosphatidylserine externalization in short axons, from 13.00 ± 1.78 μm/min [n = 28] in control media to 4.89 ± 3.86 μm/min [n = 6] with PB1 treatment (p = 0.01) (Fig. 7A), but had no effect in long axons (8.27 ± 1.75 μm/min [n = 11] to 7.94 ± 1.93 μm/min [n = 9]; p = 0.196). Conversely, PB1 significantly delayed the onset of phosphatidylserine externalization in long axons by increasing the delay from 1.56 ± 0.76 min [n = 11] in control axons to 5.90 ± 0.67 min [n = 10] (p = 0.001) (Fig. 7B), but had no effect in short axons (3.51 ± 0.53 min [n = 11] in control axons vs. 4.02 ± 1.14 μm/min [n = 6] with PB1 treatment; p = 0.984). Together, these findings imply that the difference in the redox mechanisms underlying phosphatidylserine externalization initiation and propagation extends to differences between short and long axons.

Given that PB1 slowed velocity in short, but not long, wild-type axons, we compared phosphatidylserine externalization in short and long Wld^S axons to wild-type axons. Short Wld^S axons had a significantly slower velocity of phosphatidylserine externalization than short wild-type axons (4.58 ± 2.42 μm/min [n = 12] vs. 13.00 ± 1.6 μm/min [n = 28]; p = 0.001), but this difference was not as pronounced between long Wld^S axons and long wild-type axons (5.68 ± 0.98 μm/min [n = 18] vs. 8.27 ± 1.26 μm/min [n = 11]; p = 0.069) (Fig. 7A). The greater effect of the mutation in short vs. long axons paralleled what had been seen with PB1 treatment. We also found that short Wld^S axons had a significantly longer delay until the onset of phosphatidylserine externalization compared to their wild-type counterparts (8.60 ± 1.27 min [n = 12] vs.

3.51 ± 0.83 min [n = 28]; p = 0.002). The delay in the onset of signal was not significantly different between long Wld^S and wild-type axons (3.06 ± 0.69 min [n = 18] vs. 1.56 ± 0.88 min [n = 11]; p = 0.227) (Fig. 7B). Finally, we compared short and long Wld^S axons, and although the velocity of phosphatidylserine externalization was not significantly different between short and long Wld^S axons (4.58 ± 1.04 μm/min [n = 12] vs. 5.68 ± 0.85 μm/min [n = 18]; p = 0.421), there was a longer delay in its initiation in short compared to long Wld^S axons (8.60 ± 1.40 min [n = 12] vs. 3.06 ± 1.20 min [n = 18]; p = 0.01) (Fig. 7A). This suggests that there are differences in the nature of redox-dependent phosphatidylserine externalization that are related to axon length.

Distance from transection site to soma affects the dynamics of phosphatidylserine externalization along the axon

Previous studies demonstrated that the distance from the site of axonal injury to the soma affects the rate of neuronal death, based on studies of RGCs after intraorbital vs. intracranial axonal injury (Villegas-Perez et al., 1993). The magnitude of depolarization recorded at the soma following axotomy is also dependent on the distance of the axotomy site from the soma (Berdan et al., 1993). The neuronal soma contains most of the metabolic machinery to support the axon, and is the recipient of retrograde positive and negative signals. We hypothesized that the distance from soma to site of axonal injury would affect the dynamics of axonal degeneration signaling. To test whether the relationship of the axotomy site to the cell body affects the velocity and delay of phosphatidylserine externalization, we performed laser axotomy at different distances from the RGC soma and studied the time course of annexin B12-IANBD binding. The

closest distance from axotomy site to soma was 95 μm and the furthest was 2272 μm from the soma. Analysis was performed by dividing all axons into “near” or “distant” based on whether the distance from soma to axotomy was less than or greater than the median distance of 343 μm, determined from all axons that were studied. The mean distance for the near group was 230.9 ± 7.9 μm and for the distant group was 568.2 ± 42.5 μm.

The distance of the axotomy from the soma significantly affected the velocity of phosphatidylserine externalization in wild-type RGC axons, with axotomy near the soma producing a significant increase in velocity compared to distant locations (14.46 ± 1.64 μm/min [n = 24] vs. 8.61 ± 1.93 μm/min [n = 14]; p = 0.029 (Fig. 7C). Axotomy near the soma also resulted in a significantly delay until first detection of phosphatidylserine externalization compared to axotomy distant from the soma (3.93 ± 0.54 min [n = 22] vs. 1.78 ± 0.65 min [n = 15]; p = 0.013) (Fig. 7D).

To determine whether the association of velocity and distance from the soma was redox-dependent, RGCs were pre-incubated with PB1 (100 μM) for 30 min and then axotomized. PB1 did not interact with the effect of distance from axotomy to soma on the velocity of phosphatidylserine externalization (p = 0.304) (Fig. 7C). However, PB1 treatment significantly prolonged the delay until detection of the annexin signal for transections distant from the soma (5.42 ± 0.93 min [n = 10] vs. 1.78 ± 0.65 min [n = 15]; p = 0.010) but not near the soma (4.00 ± 1.34 min [n = 6] vs. (3.93 ± 0.54 min [n = 22]; p = 0.846) (Fig. 7D.

Given the above results and the likelihood that the Wld^S phenotype causes slowed axonal degeneration via a redox-dependent mechanism, we studied the velocity of phosphatidylserine externalization in Wld^S axons that were axotomized near and distant to the soma. Wld^S axons transected near the soma had a significantly slower velocity of phosphatidylserine externalization compared to wild-type axons (3.88 ± 2.14 μm/min [n = 14] vs. 14.46 ± 1.64 μm/min [n = 24]; p = 0.0001) (Fig. 7C). When axons were transected distant from the soma, there were minimal differences in the velocity of phosphatidylserine externalization between Wld^S and wild-type (6.43 ± 1.09 μm/min [n = 16] vs. 7.46 ± 1.06 μm/min [n = 17]; p = 0.377) (Fig. 7C). The same pattern of Wld^S affecting axons axotomized near the soma was observed with respect to the delay until the first detection of phosphatidylserine externalization. There was no significant difference between Wld^S and wild-type axons in delay when axons were transected near (7.64 ± 1.25 min [n = 14] vs. (3.93 ± 0.54 min [n = 22]; p = 0.197) or distant from the soma (3.75 ± 0.83 [n = 18] vs. 1.78 ± 0.65 min [n = 15]; p = 0.261) (Fig. 7D). Finally, pre-incubation of Wld^S RGCs with PB1 had no effect on the interaction between transection site distance from soma and velocity, suggesting that pharmacological modulation of redox signaling overlaps with the intracellular mechanism(s) affected by the Wld^S mutation.

Effect of the age and time in culture on the velocity of phosphatidylserine externalization after axotomy

For purified RGC cultures we harvested retinas from postnatal day 4 pups and older (up to P6) because younger RGCs have a higher rate of survival in culture because of ease

539 in enzymatically dissociating the retina. However, the process of removing the retina
540 from the eye severs the RGC axons in the retinal nerve fiber layer. Early postnatal
541 RGCs are not fully developed neurons and maintain the capacity to regenerate a new
542 axon in culture in the presence of trophic factors (Goldberg et al., 2002). This axonal
543 regeneration in culture is the basis of studying axonal degeneration *in vitro.*

544 However, a potential confounding factor is that developmental RGC target-dependent
545 death occurs from soon after birth in rats. The majority of RGC death occurs between
546 P0 and P5, and although RGC death continues to P10, the numbers are negligible
547 (Potts et al., 1982; Galli-Resta and Ensini, 1996). It was therefore critical to assess
548 whether the velocity of the axonal degeneration was dependent on age of the animal,
549 and specifically, whether there was a difference if RGCs were derived from pups before
550 vs during the time of development-associated degeneration. To do this, the
551 measurements of phosphatidylserine externalization were analyzed with respect to age
552 and time in culture.

553 There was no significant age-dependent difference in the velocity of phosphatidylserine
554 externalization after transection among RGCs harvested from pups ranging from P2 to
555 P7 ($p = 0.286$) (Fig. 8A). The length of axons obtained from young (P2-5) pups was
556 about 25% less than those from older (P6-7) pups (652 ±48 vs. 813 ± 40; $p = 0.047$).
557 Age-dependent increases in cellular neurotrophic levels are thought to promote higher
558 survival rate for neurons in postnatal injury models (Pollin et al., 1991; Kuzis et al.,
559 1999). However, the present data do not support a difference in the rate at which axonal
560 degeneration spreads *in vitro* in these neurons.

Laser axotomy was performed on cultured RGCs 3 days after plating to allow the growth of identifiable axons. The length of time that RGCs were in culture before cutting the axon ($r = 0.37$; $p = 0.0228$) correlated with the velocity of phosphatidylserine externalization after axotomy, but with lower velocity in older cells (Fig. 8B). In contrast, in a study of axotomized dorsal root ganglion (DRG) axons, the time in culture had a significant effect on the velocity of the Wallerian degeneration, with greater velocity when there was greater time in culture (Buckmaster et al., 1995; Sievers et al., 2003). The differences between the results seen in DRG axons and the velocity of phosphatidylserine externalization after RGC axotomy could be related to differences in peripheral and central nervous system axon responses to injury, or other factors.

Discussion

RGC axotomy *in vivo* induces intracellular superoxide generation followed by phosphatidylserine externalization, with both events occurring over days (Kanamori et al., 2010). In the present study, the combination of single-cell laser axotomy with time-lapse imaging enabled the study of the dynamics of phosphatidylserine externalization beginning within minutes after the onset of axonal injury. These findings help improve our understanding of the mechanisms which maintain the asymmetry of lipids in the axonal membrane, and its dysregulation after axonal injury.

In this study we demonstrated an immediate change in axonal membrane lipid asymmetry of cultured RGCs following axotomy, manifested as phosphatidylserine externalization into the outer leaflet of the axonal membrane, which was redox-sensitive and was approximately 8X faster than the rate of axonal degeneration. Movement of lipids between the inner and outer leaflets of axonal membrane is mediated by two categories of transmembrane lipid transporters. The first category are ATP-dependent carriers transporting lipids in a single direction. Depending on the direction of transport, these are referred to as flippases (from the outer leaflet to the inner leaflet) or floppases (from the inner leaflet to the outer leaflet) (Pomorski and Menon, 2006). In addition to ATP, the activity of these transporters is regulated by caspases 3, 6 and 7 (Segawa et al., 2014). The second category, scramblases, transport lipids bidirectionally without requiring energy. Scramblases are either constitutively active (Goren et al., 2014) or regulated by intracellular signals such as Ca^{2+} (Suzuki et al., 2010; Williamson, 2015),

592 making Ca^{2+} entry into the axon both an initiator of axonal degeneration (George et al.,
593 1995; Knoferle et al., 2010; Vargas et al., 2015) and a major factor in loss of asymmetry
594 of membrane lipids because its influx triggers externalization of phosphatidylserine by
595 scramblases (Bevers and Williamson, 2010).

596 It is unclear what regulates the velocity by which phosphatidylserine externalization
597 propagates down the injured axon, which in wild-type RGC axons is approximately 12
598 μm/min and in Wld^S axons 5 μm/min. Sievers et al (2003) demonstrated spread of
599 annexin-A5 binding at 5-6 μm/min in DRG explants where the axons were transected
600 with a microscalpel, similar to the present findings. This rapid propagation of
601 phosphatidylserine externalization is unlikely to be related to axonal conduction, which
602 for unmyelinated axon occurs at 0.5 to 10 m/s, approximately 8 orders of magnitude
603 faster. Nor does correlate with the velocity by which the transient calcium wave
604 propagates down an axon after axotomy which is around 2.7-16 μm/s (160-960 μm/min)
605 (Ziv and Spira, 1993; Rishal and Fainzilber, 2014; Vargas et al., 2015). The calcium
606 increase lasts about 30 seconds and returns to normal levels within a minute after the
607 onset of axonal injury (Knoferle et al., 2010), after this initial transient calcium wave,
608 there is a gradual increase in intra-axonal calcium 4 to 6 hours later which remains
609 elevated and leads to axonal fragmentation via activation of calpains (LoPachin et al.,
610 1990; Vargas et al., 2015). The tempo for this secondary calcium elevation also does
611 not correlate with the velocity of phosphatidylserine externalization down the axon.

612 The mechanisms responsible for the decreased axonal degeneration in Wld^S animals
613 are not well understood. One theory suggests that the Wld^S mutation maintains low

axoplasmic Ca^{2+} levels following axonal damage. Immediately following axotomy, a transient calcium elevation occurs in both wild-type and Wld^S axons, but Wld^S axons do not show a second elevation in calcium levels (Adalbert et al., 2012). This theory could explain the small difference between wild-type and Wld^S axons in the delay until initial detection of phosphatidylserine externalization. The absence of the second axonal calcium wave could be due to the greater buffering capacity of Wld^S mitochondria (Avery et al., 2012). On the other hand, a comparable degree of mitochondrial membrane potential loss occurs in Wld^S and wild-type mitochondria incubated with calcium, suggesting that Wld^S mitochondria do not buffer calcium differently from wild-type (Barrientos et al., 2011). Axotomy of wild-type neurons *in vivo* also affects the redox state of mitochondria, resulting in a rapid increase of ROS production that can be prevented by transgenic expression of Wld^S (O'Donnell et al., 2013).

We had previously shown a redox-dependent role for RGC apoptosis after axonal injury (Kanamori et al., 2010; Almasieh et al., 2011). We hypothesized there may be a redox component to the axonal degeneration for which Wld^S may be protective. The present studied demonstrated that RGC cultures incubated in the redox-modulating compound PB1 resulted in significantly slower velocity of phosphatidylserine externalization and a longer delay until the detection of the first signal. These data are consistent with a mechanism whereby an intra-axonal oxidative reaction, possibly related to mitochondrial depolarization (Sievers et al., 2003)) initiates and propagates phosphatidylserine externalization after axotomy. This is supported by the data of Fadeel et al, who elicited robust phosphatidylserine externalization when incubated Raji, HL-60 and other non-

636 neuronal cell lines were incubated with the oxidants N-ethylmaleimide (NEM) and
637 diamide (Fadeel et al., 1999).

638 Evidence for a redox-dependent mechanism for phosphatidylserine externalization is
639 provided by studies of flippases in oxidative and apoptotic conditions. As mentioned
640 previously, constant activity of flippases is required to move phosphatidylserine from the
641 outer leaflet to the inner leaflet in order to maintain its asymmetric distribution (Pomorski
642 and Menon, 2006). Segawa et al., demonstrated that the cleavage of ATP11C (a
643 flippase) by caspases 3, 6, and 7 during apoptosis blocked its activity and led to
644 exposure of phosphatidylserine in the outer leaflet (Segawa et al., 2014). The inhibition
645 of caspases by the pan-caspase inhibitor z-VAD-fmk did not prevent phosphatidylserine
646 exposure induced by the oxidizing agents N-ethylmaleimide or pyridyldithioethylamine
647 (PDA) (Balasubramanian et al., 2007), suggesting oxidizing agents trigger
648 phosphatidylserine exposure in an apoptosis-independent manner. It is thought that
649 PDA oxidizes a sensitive site in flippases and blocks the association of transporter and
650 phosphatidylserine, thereby resulting in accumulation of phosphatidylserine in the outer
651 leaflet of membrane (Connor and Schroit, 1990, 1991). Conversely, incubation of
652 cultures with a high concentration of the disulfide-reducing dithiol dithioerythritol (DTE),
653 an epimer of DTT, resulted in inhibition of calcium-activated transfer of
654 phosphatidylserine from the inner to outer leaflet, i.e. flopping, whereas incubation with
655 the oxidizing agent NEM increased externalization (Kamp et al., 2001).

656 DTT and TCEP are poorly membrane-permeable, and when added to the culture
657 medium act as extra-axonal disulfide reducing agents. This differs from the effect of

PB1, which is only active when its methyl esters are hydrolyzed by intra-axonal esterases, and therefore has intra-axonal disulfide reducing activity. We found that the delay to initiation of phosphatidylserine externalization was longer with PB1 and shorter with DTT and TCEP. The effects of PB1 on wild-type axons were similar to that of the Wld^S mutation with respect to velocity of phosphatidylserine externalization, delay until onset, and velocity of propagation of morphological evidence of axonal degeneration. A model that explains these results is depicted in Figure 9.

In addition to the effects of reduction on the oxidation status of the transporters slowing externalization (Castegna et al., 2004; de Jong and Kuypers, 2006), the oxidation status of phosphatidylserine itself also has a significant effect on the rate of its externalization (Kagan et al., 2000; Tyurina et al., 2004). The observation that PB1, a membrane-permeable disulfide reducing agent, was effective in slowing the rate of phosphatidylserine externalization is consistent with the target of redox modification inside the damaged axon being phosphatidylserine itself.

The faster velocity of phosphatidylserine externalization in shorter axons could reflect the state of axonal maturity. Axon maturation involves several changes that stabilize the membrane, including formation of protein-lipid complexes (Ledesma et al., 1998), upregulation of sphingomyelin synthesis (Tiveron et al., 1994; Ledesma et al., 1999), reduced expression of membrane trafficking proteins like Sar1 (Aridor and Fish, 2009) and distribution of proteins like Thy-1 along the membrane (Xue et al., 1991; Rege and Hagood, 2006; Smrz et al., 2007). Given that both the Wld^S mutation and PB1 slowed phosphatidylserine exposure in short axons more than long axons, it is possible that a

680 less mature axonal membrane or actively growing axon amplifies the effect of redox
681 modulation. Another possibility is that short axons had slightly greater diameters than
682 long axons, and even slight differences in the surface/volume ratio could interact with
683 redox processes. Finally, proximity to the soma is associated with improved axonal
684 regeneration because of soma-derived signals (Benfey and Aguayo, 1982; Plunet et al.,
685 2002; Conta Steencken et al., 2011). The effect of Wld^S on slowing velocity of
686 phosphatidylserine externalization was mostly seen in transections near the soma. This
687 could either be from a difference in redox signaling that depends on distance to the
688 soma, or the effect of a soma-derived factor that counteracts a redox injury process.

689 The propagation of phosphatidylserine externalization in transected RGC axons in the
690 present study (11.7 μm/min) was several times faster than the spread of morphological
691 axonal degeneration (1.5 μm/min). Similar results were seen *in vivo* by Knöferle et al in
692 an optic nerve crush model, where the velocity of morphological changes of RGC
693 axonal degeneration *in vivo* was 1.2 μm/min (Knoferle et al., 2010), similar to the 1.5
694 μm/min observed *in vitro* in the present study. Phosphatidylserine externalization was 8
695 times faster than the morphological changes associated with axonal degeneration,
696 raising the question of how phosphatidylserine externalization relates to consequent
697 axonal degeneration. The exposure of negatively charged lipids such as
698 phosphatidylserine into outer leaflet of the membrane increases ion influx through Ca^{2+}-
699 activated potassium channels (Tillman and Cascio, 2003), while at inner leaflet,
700 phosphatidylserine facilitates cellular functions such as exocytosis, endocytosis,
701 membrane scaffolding and G-protein signaling (Swairjo and Seaton, 1994). It is likely
702 that prolonged loss of asymmetric distribution of phosphatidylserine across the inner

and outer leaflets of the axonal membrane could initiate degeneration of the damaged axon.

The present study used an *in vitro* model of axotomized purified RGCs to study the role of membrane lipid asymmetry and redox state in axonal degeneration. However, those factors can also be affected by elements missing from this system, i.e. astrocytes, oligodendrocytes, microglia, and vascular cells. For example, phosphatidylserine externalization triggers phagocytic removal of injured axons by activated microglia and astrocytes (Nguyen et al., 2011; Brown and Neher, 2014). Neuron-glial co-culture improves the survival of RGCs by releasing antioxidants (Skytt et al., 2016; Vecino et al., 2016). Use of *in vitro* myelination models such as oligodendrocyte-neuron co-cultures could provide helpful information about degenerative events in myelinated axons (Callizot et al., 2011; Pang et al., 2012). However, detailed study of axonal membrane polarity in disease is difficult to reproduce *in vitro*, yet imaging techniques do not currently provide single-axon resolution to allow study *in vivo*.

In summary, the initiation and propagation of phosphatidylserine externalization after axotomy is associated with an intra-axonal redox mechanism for axonal degeneration. Redox-active drugs which could decrease the oxidation of phosphatidylserine and its transfer to the outer leaflet may be candidates for axonal protection in diseases characterized by axonal degeneration, such as glaucoma, multiple sclerosis, peripheral neuropathies, and others.

Acknowledgments

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Figure Legends

Figure 1. Example of the axonal extent and soma of a rat retinal ganglion cell in culture. Retinal ganglion cells were isolated from a cell suspension of P2-P7 rat pup retinas by immunopanning and placed on PDL/laminin-coated glass bottom dishes in neurotrophin-enriched medium. A, The laser beam was used to engrave 3 lines into a gold film, each starting from point 0 in three directions (indicated by 1, 2 and 3) to provide reference points for positioning the axon before transection. B, a wild-type retinal ganglion cell 3 days in culture with a full-length axon captured in series of bright-field images (60X water immersion objective). The arrow shows the RGC soma at the lower right corner of the frame. The axon extends with few branches, The axon terminal is indicated by an asterisk. Scale bars, 40 μm.

Figure 2. In vitro axotomy of cultured retinal ganglion cells. A pulse laser at 800 nm with 100 fs pulses at 80 MHz was directed through the scanning laser module of an Olympus IX71 inverted fluorescence microscope to provide a high-power beam directly through the aperture of a 1.2 NA water immersion 60X objective. Axon transection was achieved by photo-disruption, a phenomenon in which electrons within the tissue absorb the incident photons and their energy exceeds the ionization potential, resultant plasma creates a cavitation bubble and shock wave that cleaves the tissue at the focal point of laser. A, The bright-field image of cultured wild-type RGC axon before axonal transection. The white arrow shows the future site of axotomy, which is magnified in the insert. The diameter of the axon at the site axotomy is 1.16 μm. B, The same axon 6

753 minutes after laser axotomy. The transection site is indicated by the white arrow and
754 magnified in the insert. The width of the incision is 0.76 μm. Scale bars, 40 μm; 5 μm
755 (insert).

756 **Figure 3.** Phosphatidylserine externalization in a transected wild-type axon. A, The first
757 frame shows a bright-field image of the site of axotomy taken immediately before axonal
758 transection of cultured wild-type RGCs, followed by a selection of fluorescent time-lapse
759 images showing progression of phosphatidylserine externalization visualized by the
760 polarity-sensitive annexin-based biosensor, annexin B12-IANBD. The arrow shows the
761 site of axotomy, with proximal indicating the propagation of signal toward the soma and
762 distal indicating propagation toward the axon terminal. Scale bar, 40 μm. B, Derivation
763 of the velocity (slope) and t_0 (delay) of propagation from the time-course of annexin
764 B12-IANBD fluorescence.

765 **Figure 4.** Morphological changes of axon following axotomy. A, A bright-field image of
766 cultured wild-type RGC axons before axotomy. The axon at left was subject to axotomy,
767 with the site of axotomy indicated by a white arrow. The axon at right indicated by an
768 asterisk, belong to a different RGC and was not transected. B, 45 min after the axotomy
769 the beading and swelling of the transected axon are clearly visible. The white arrow
770 shows the site of axotomy, the white arrowheads at the right side of transected axon
771 show the beading of distal segment and the arrowheads at the left side show the
772 beading of proximal segment of transected axon. There were no morphological changes
773 in a control non-transected (asterisk) axon. Scale bar, 40 μm.

774 **Figure 5.** Phosphatidylserine externalization propagates more slowly along transected
775 Wld^S axons compare to wild-type axons. A, Time-lapse series of images from a
776 transected Wld^S axon show significantly slower propagation of phosphatidylserine
777 externalization. B, Wld^S transected axons had significantly slower phosphatidylserine
778 externalization compared to wild-type axons. C, Slowed velocity of phosphatidylserine
779 externalization was seen in both the proximal and distal axon segments. D, Compared
780 to wild-type axons, there was a significantly longer delay before the onset of
781 phosphatidylserine externalization signal in WldS axons. $P < 0.05$ *; $P < 0.01$ **; $P <$
782 0.001 ***; Scale bar, 40 μm.

783 **Figure 6.** A, Structure of the cell-permeable redox-modulating compound bis(3-
784 propionic acid methyl ester) phenylphosphine-borane complex (PB1), used for intra-
785 axonal disulfide reduction. B, Incubation of wild-type RGCs in 100 μM PB1 significantly
786 slowed the propagation of phosphatidylserine externalization compare to untreated
787 cultures. C, Analysis of the proximal and distal segments showed that the velocity of
788 phosphatidylserine externalization was significantly slowed by PB1 along the distal
789 segments of transected wild-type axons. D, PB1 treatment significantly delayed the
790 initiation of phosphatidylserine externalization. E, F, Pre-incubation of Wld^S cultures with
791 PB1 did not affect the delay or velocity of phosphatidylserine externalization. G, H, I,
792 Mixed model analysis of the interaction between the velocity/delay relationship and
793 Wld^S or PB1 treatment. $P < 0.05$ *; $P < 0.01$ **; $P < 0.001$ ***.

794 **Figure 7.** Axon length and distance between the axotomy site and the soma affects the
795 velocity and delay until onset of phosphatidylserine externalization. A, Short wild-type

axons had a significantly faster velocity of propagation of phosphatidylserine externalization after transection, compared to longer axons, to short PB1-treated axons, and to short Wld^S axons. The effect of PB1 treatment and the Wld^S mutation vs. wild-type were significantly less in longer axons. B, Short wild-type axons had a longer delay until initiation of phosphatidylserine externalization compared to long wild-type axons. This pattern was also seen in Wld^S axons, but not PB1-treated axons. C, Wild-type axons with the axotomy site near the soma had a significantly faster velocity of phosphatidylserine externalization compared to where the axotomy site was distant from the soma. The velocity was also significantly slower for Wld^S axons transected near the soma compare to wild-type. When axotomy was distant from the soma, neither PB1 treatment nor the Wld^S mutation affected velocity, compared to wild-type untreated axons. D, Axotomy near the soma in wild-type axons resulted in a longer delay until initiation of phosphatidylserine externalization, compared to distant transections. This pattern was also seen in Wld^S axons, but not PB1-treated axons. $P < 0.05$ *, $P < 0.01$ **, $P < 0.001$ ***.

Figure 8. Age of rat pups used for RGC cultures and length of time in culture did not affect the velocity of phosphatidylserine externalization. A, There was no significant difference in the velocity of annexin B12-IANBD signal among RGCs harvested from pups ranging from P2 to P7. B, Length of time in culture for RGCs used in axotomy experiments ranged between 3 and 8 days. There was no significant effect on the velocity of phosphatidylserine externalization.

Figure 9. Diagram illustrating a putative mechanism by which intra-axonal disulfide reduction with PB1 and the Wld^S mutation promote axonal protection. A, In the intact axon, the distribution of phosphatidylserine (red circles) is actively restricted to the cytosolic (inner) leaflet of the plasma membrane. Scramblases (ovals) randomly shuffle phosphatidylserine between the inner and outer leaflet of membrane. Floppases (blue triangles) move the phosphatidylserine from the inner leaflet to the outer leaflet of the membrane, while flippases (beige triangles) actively remove phosphatidylserine from the outer leaflet and insert them in the inner leaflet. The net effect is to maintain phosphatidylserine asymmetry in the inner leaflet. B, Following axotomy, the generation of intracytoplasmic ROS affects these transporters, and the balance shifts with floppases moving more phosphatidylserine to the outer leaflet while the rate of inward transport of phosphatidylserine by flippases slows. Scramblases possibly increase their rate of shuffling. The result is a net accumulation of phosphatidylserine in the outer leaflet of membrane. The exposure of phosphatidylserine to the outer leaflet and its interaction with annexin B12-IANBD (gray circles) switches “on” the fluorescence signal (green circles). C, Either the Wld^S mutation or intra-axonal disulfide reduction with membrane-permeable PB1 (which is inactive outside the axon) can inhibit the effects of ROS on flippases, floppases, and scramblases and are thereby able to maintain the asymmetry of phosphatidylserine across the membrane. D, The poorly permeable disulfide reducing agents DTT and TCEP reduce extra-axonal disulfides and inhibit transporter activity, with the effect on flippases maintaining phosphatidylserine at the outer leaflet, thereby reversing the Wld^S phenotype.

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