ApoE-associated modulation of neuroprotection from Aβ-mediated neurodegeneration in transgenic Caenorhabditis elegans

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ABSTRACT

Allele-specific distinctions in the human apolipoprotein E (APOE) locus represent the best-characterized genetic predictor of Alzheimer’s disease (AD) risk. Expression of isoform APOEε2 is associated with reduced risk, while APOEε3 is neutral and APOEε4 carriers exhibit increased susceptibility. Using Caenorhabditis elegans, we generated a novel suite of humanized transgenic nematodes to facilitate neuronal modeling of amyloid-beta peptide (Aβ) co-expression in the context of distinct human APOE alleles. We found that co-expression of human APOEε2 with Aβ attenuated Aβ-induced neurodegeneration, whereas expression of the APOEε4 allele had no effect on neurodegeneration, indicating a loss of neuroprotective capacity. Notably, the APOEε3 allele displayed an intermediate phenotype; it was not neuroprotective in young adults but attenuated neurodegeneration in older animals. There was no functional impact from the three APOE isoforms in the absence of Aβ co-expression. Pharmacological treatment that examined neuroprotective effects of APOE alleles on calcium homeostasis showed allele-specific responses to changes in ER-associated calcium dynamics in the Aβ background. Additionally, Aβ suppressed survival, an effect that was rescued by APOEε2 and APOEε3, but not APOEε4. Expression of the APOE alleles in neurons, independent of Aβ, exerted no impact on survival. Taken together, these results illustrate that C. elegans provides a powerful in vivo platform with which to explore how AD-associated neuronal pathways are modulated by distinct APOE gene products in the context of Aβ-associated neurotoxicity. The significance of both ApoE and Aβ to AD highlights the utility of this new pre-clinical model as a means to dissect their functional inter-relationship.

This article has an associated First Person interview with the first author of the paper.

KEY WORDS: ApoE, Aβ, Neurodegeneration, Alzheimer’s disease, C. elegans

INTRODUCTION

Alzheimer’s disease (AD), characterized by the formation of insoluble amyloid-beta peptide (Aβ) plaques in the brain, accounts for nearly 70% of all late-life dementia. Although the causes, whether genetic or environmental, are not clearly defined, it is evident that the most predictive genetic association is variation in the gene encoding apolipoprotein E (ApoE). Although estimates vary based on study and ethnicity, ~40% of AD cases harbor the ε4 allele of APOE (Spinney, 2014). This allele is a significant risk factor for late-onset AD, where two copies of APOEε4 increases AD risk up to 15-fold relative to APOEε3. The APOEε2 allele appears to provide protection against AD via a mechanism that consists of more than the absence of the APOEε4 allele (Corder et al., 1994; Talbot et al., 1994). Indeed, there may be opposing actions of the APOEε2 and APOEε4 alleles, which would not be unprecedented, as APOEε2 and APOEε4 appear to have opposing activities in lipidation and aggregate stabilization (Hu et al., 2015). Despite this correlation, the mechanisms by which differences in APOE allelic function modify AD risk are not entirely understood.

There are many mechanisms proposed to explain how APOEε4 increases AD risk, including altered glucose and lipid metabolism. Most commonly, however, Aβ-dependent effects are considered within the context of the APOE alleles, where neurotoxicity and aggregation are examined. For example, mammalian models have yielded significant information on how ApoE and Aβ interact to affect cellular function and animal behavior, but the scale and complexity of the mammalian nervous system frustrate examination of quantifiable effects on individual neurons and their functional connectivity. The nematode Caenorhabditis elegans has been employed to generate models of neurodegenerative disorders, including AD (Griffin et al., 2017), Huntington’s disease (Muñoz-Lobato et al., 2014) and Parkinson’s disease (Martinez et al., 2017a). Because C. elegans is the only animal for which a connectivity map of its entire nervous system exists, it provides an unparalleled platform for the examination and quantitative characterization of neural interactions. Further, the genetic tractability of C. elegans offers a model receptive to genetic manipulation and transgenics. Importantly, specific worm models have proven highly predictive of both genetic and small molecule modifier results obtained in mammalian systems, including genome-wide association studies and induced pluripotent stem cells from patients (Cooper et al., 2006; Matlack et al., 2014; Mazzulli et al., 2011; Su et al., 2010; Tardiff et al., 2013, 2017; Treusch et al., 2011).

Here, we present new neuronal models to assay ApoE activity in vivo that consist of nematodes expressing human APOEε2, APOEε3 or APOEε4 along with Aβ. Glutamate is a major excitatory neurotransmitter in the brain, and dysregulation of the glutamatergic system can lead to excitotoxicity, which, when chronic, has been
hypothesized to play a role in neurodegeneration (Lewerenz and Maher, 2015). Because the glutamatergic circuitry is severely disrupted in the brains of AD patients (Francis et al., 1993; Greenanmyre et al., 1988), the eat-4 (glutamate transporter) promoter was chosen for glutamatergic neuron-specific expression of Aβ and the respective APOE alleles. Effects on neuronal integrity were examined through quantitative fluorescent imaging of neurodegeneration and behavioral assays. Additionally, we modulated neurodegenerative effectors via pharmacological treatment and RNA interference (RNAi). By combining neuronal expression of APOE alleles with a transgenic nematode model of human Aβ toxicity, we can further understand the clinically significant relationship between ApoE and Aβ in neurotoxicity. Using these C. elegans models of progressive Aβ-mediated neurodegeneration, a strong attenuation of Aβ-mediated toxicity is revealed by the APOE ε2 allele, as well as a modest, yet significant, intermediate protection phenotype by APOE ε3 as animals age, in vivo. Strikingly, the neuroprotective activity of ApoE was abolished in animals co-expressing Aβ and APOE ε4. Furthermore, this shows that the allelic profile reflects the well-established clinical observation of ApoE-associated susceptibility. Pharmacological and post-transcriptional manipulation further demonstrate differential activities of APOE alleles observable through multiple phenotypic outputs. Though limited as an invertebrate system, C. elegans provides a platform that accelerates attainment of a more mechanistic understanding of how ApoE protein variants function to modulate neuronal degeneration and establishes a new pre-clinical model of AD to accelerate future drug discovery.

RESULTS

APOE allele-selective mitigation of Aβ-mediated neurodegeneration

The Aβ peptide is the product of sequential cleavage of the amyloid precursor protein (APP) either at the cell surface or within endosomes. Cleavage of APP is known to produce multiple peptide products, such as Aβ(1-40) and Aβ(1-42); however, the Aβ(1-42) peptide is the most toxic. Extracellular deposition of insoluble Aβ plaques is a pathological hallmark of AD, but intracellular Aβ has been shown to be far more toxic (Burdick et al., 1992; Cha et al., 2012; Esbjörner et al., 2014; Hu et al., 2009; Kounnas et al., 1995; Li et al., 2012; Liu et al., 2013b; Naj et al., 2011; Nakagawa et al., 2000; Okoshi et al., 2015; Reinders et al., 2016; Snyder et al., 2005; Takahashi et al., 2002; Treusch et al., 2011; Ulrich, 2015; Wang et al., 2000; Yang et al., 1998; Zhao et al., 2015). To reproduce the intracellular accumulation of Aβ in C. elegans, Aβ was cloned with promoters for tissue-specific multicopy expression and scored for toxicity. In C. elegans muscle expression models of Aβ toxicity, Aβ was found to form plaques (Link et al., 2001) and intramuscular inclusions (Fay et al., 1998; Link, 1995), and to induce paralysis via cytotoxicity (Dostal and Link, 2010; Fonte et al., 2002). Furthermore, we have shown that expression of Aβ in glutamatergic neurons results in progressive, age-dependent, neurodegeneration modulated by endocytic and endosomal regulators, including the established AD modifier PICALM (Griffin et al., 2018; Treusch et al., 2011), and is amenable to pharmacological treatment (Matlack et al., 2014; Tardiff et al., 2017). To examine the relationship between ApoE and Aβ, we utilized a C. elegans model in which an Aβ(1-42) construct, hereafter referred to as Aβ, was cloned for expression in the glutamatergic neurons and neurodegeneration was quantified with precision in the five glutamatergic neurons in the tail (Matlack et al., 2014; Treusch et al., 2011). Expression in the glutamatergic neurons was achieved using the promoter for the glutamate transporter eat-4, which does not significantly change in expression across larval stages (Lee et al., 1999).

To model ApoE activity in C. elegans, complementary DNAs (cDNAs) encoding the three distinct human APOE alleles (APOE ε2, APOE ε3 and APOE ε4) were recombined with the artificial constitutive her-1 secretion signal, and expression was driven by the glutamatergic neuron-specific eat-4 promoter. These three constructs were microinjected into wild-type (N2) animals, integrated into the genome and crossed with Aβ-expressing animals after outcrossing. Overexpression of Aβ induced neurodegeneration of glutamatergic neurons (Fig. 1A), as has been observed previously (Griffin et al., 2018; Tardiff et al., 2017), while expression of APOE ε2, APOE ε3 or APOE ε4 in glutamatergic neurons did not impact neurodegeneration in the absence of Aβ (Fig. 1A).

Because the ε2 allele is associated with protective phenotypes (Bu, 2009; Liu et al., 2013a), we hypothesized that co-expression of APOE ε2 with Aβ would attenuate Aβ-induced neurodegeneration. At both days 3 and 7 post-hatching, nearly 100% of all animals expressing GFP alone have all five normal glutamatergic neurons. However, when co-expressed with Aβ, the APOE ε2 allele suppressed Aβ-mediated neurodegeneration by ~30% at days 3 and 7 post-hatching (Fig. 1B,C). Furthermore, because the APOE ε3 allele appears functionally neutral in humans, and ε4 is associated with increased neurotoxicity (Bu, 2009; Corder et al., 1993; Huang and Mucke, 2012; Liu et al., 2013a), we hypothesized that APOE ε3 would elicit marginal or no neuroprotective effect, while APOE ε4 would increase neurodegeneration. At day 3, there was no statistically significant difference in neurodegeneration between animals expressing Aβ alone or co-expressing APOE ε3, but, at day 7, APOE ε3 significantly reduced Aβ-mediated neurodegeneration by ~10%, which was significantly less than the protection afforded by APOE ε2. This protection was also significantly greater than that provided by the ApoE ε4 strain, in which there was no change in neurodegeneration at either day 3 or day 7 (Fig. 1B,C). Although co-expression with APOE ε4 did not enhance neurodegeneration in this model, it was not statistically different from Aβ alone at days 3 or 7 ($P = 0.9369$, respectively), but was significantly different from the Aβ+ε4 strain at day 7, thereby confirming earlier reports that there may be alternative mechanisms of action between these two alleles (Corder et al., 1994; Talbot et al., 1994).

As a secondary readout for glutamatergic neuronal dysfunction, we turned to a behavioral assay, as altered mechanosensory touch response is indicative of glutamatergic neuron dysfunction. In C. elegans, a pair of glutamatergic tail neurons have processes extending from the tail to the mid-body, to control forward escape in response to posterior gentle touch (Chalfie et al., 1985). In worms expressing Aβ in glutamatergic neurons, this posterior gentle touch response is defective (Fig. 1D). However, in worms expressing APOE alleles without Aβ, gentle touch response is not defective, indicating that the APOE alleles on their own are not pathogenic (Fig. 1D). When worms co-overexpressing Aβ and ApoE ε2 were assayed in the touch response assay, there was a significant mitigation of this mechanosensory defect (Fig. 1E). Recovery was not observed by ApoE ε3 or ApoE ε4 co-expression since they were not significantly reduced compared with the Aβ+ε2 strain (Fig. 1E). These data also suggest that, since there is a significant difference between Aβ+ε2 and Aβ alone, but not between Aβ alone and either the Aβ+ε3 or Aβ+ε4 strains, there might be alternative
mechanisms of action among these alleles that can be teased out using this assay. For example, although Aβ+ApoEε appeared to have a neuroprotective effect at later stages (day 7; Fig. 1B), the seemingly protected neurons in animals co-expressing ApoEε demonstrated reduced mechanosensory sensitivity. This suggests that ApoEε may confer moderate protection of neuronal structure that does not ameliorate loss of neuronal function by Aβ.

To ensure that the APOE-allele-specific phenotypes we observed are functionally driven and are not simply due to transgenic expression level differences, APOEε2, APOEε3 and APOEε4 mRNA levels were quantified by reverse-transcription quantitative polymerase chain reaction (RT-qPCR: Fig. 1F). There were no statistically significant differences in relative normalized APOE transcripts between ApoEε2 and ApoEε4 samples (\(P=0.2107\)) or ApoEε3 and ApoEε4 samples (\(P=0.1280\)). However, APOEε3 transcripts were significantly higher than APOEε2 transcripts (\(P=0.0127\)). Taken together with the neurodegeneration analyses, these results indicate that ApoEε2 neuroprotection is likely not due to disproportionate overexpression compared with ApoEε3.

**APOE-allele-specific modulation of calcium homeostasis**

To observe whether ApoE confers a physiologically relevant effect in our model, we examined the relationship between calcium homeostasis, Aβ and ApoE. In rat hippocampal neurons and chick sympathetic ganglia, ApoEε2 and ApoEε3 have no effect on N-methyl-D-aspartate (NMDA)-mediated calcium influx, but incubation with ApoEε4 results in massive NMDA-mediated calcium influx (Hartmann et al., 1994; Qiu et al., 2003; Tolar...
Values represent the mean±s.e.m. of three independent biological ns, nonsignificant.

Fig. 1. Overexpression of Aβ induces neurodegeneration that is mitigated by ApoEα2 and ApoEα3, but not ApoEα4. (A) Expression of GFP from the eat-4 promoter (strain DA1240[adls1240[P::eat-4:GFP::lin-15+]]) illuminates the glutamatergic neurons. The five tail glutamatergic neurons are assayed for neurodegeneration. Glutamatergic co-expression of Aβ [UA189(baln34::P::eat-4::Aβ, P::mCherry); adls1240[P::eat-4::GFP]] mitigates neurodegeneration in synchronized hermaphrodite populations at day 3 post-hatching (P<0.0001), while overexpression of ApoEα2 (UA353) (adls1240[P::eat-4::GFP::lin-15+]; baln30[P::APoE2, Punc-54::tdTomato]) results in no significant difference from GFP expression only (P=0.5391, P=0.8284, respectively). There was no difference between APOE2 and ApoEα3 (P=0.8255), ApoEα2 and ApoEα4 (P=0.9824), or ApoEα3 and ApoEα4 (P=0.9825). n=90 for each strain; one-way ANOVA with Tukey’s post hoc test. These data are reported as means±s.e.m. All nematodes were grown at 20°C.

(B) Animals expressing GFP alone display no neurodegeneration at days 3 or 7, in contrast to animals expressing Aβ that exhibit significant neurodegeneration at days 3 (P<0.0001) or 7 (P<0.0001). Co-expression of Aβ and ApoEα2 (UA351[baln52[P::eat-4::APoE2, Punc-54::tdTomato]; baln34[P::eat-4::Aβ, P::mCherry]; adls1240[P::eat-4::GFP]]) significantly attenuated neurodegeneration at days 3 (P=0.3937) and 7 (P=0.0002) post-hatching, whereas co-expression of APOE3 (UA353[baln34::P::eat-4::Aβ, Punc-54::tdTomato]; baln34[P::eat-4::Aβ, P::mCherry]; adls1240[P::GFP]) resulted in no significant difference from Aβ alone at day 3 (P=0.0264). However, day 7 post-hatching co-expression of ApoEα3 yielded a significant reduction in Aβ-mediated neurodegeneration (P=0.0102). In contrast, co-expression of APOE4 (UA365[baln52[P::eat-4::APoE4, Punc-54::tdTomato]; baln34[P::eat-4::Aβ, P::mCherry]; adls1240[P::eat-4::GFP]]) resulted in no significant difference from Aβ alone at days 3 (P=0.9579) or 7 (P=0.9369) post-hatching. At day 3, there was no significant difference between Aβ+APoEα2 and Aβ+APOE3 (P=0.5048). Aβ+APoEα2 and Aβ+APOE4 (P=0.5225), or Aβ+APOE2 and Aβ+APOE4 (P=0.5787). However, at day 7 post-hatching, protection by APOE2 was significantly higher than that by ApoEα3 (P=0.028) and APOE4 (P=0.0001). Additionally, at day 7 post-hatching, protection by APOE3 was significantly higher than that by APOE4 (P=0.0049). n=90 for each strain; one-way ANOVA with Tukey’s post hoc test. These data are reported as mean normalized to GFP animal±s.e.m. All nematodes were grown at 20°C.

(C) Representative images of C. elegans glutamatergic tail neurons containing GFP (DA1240), Aβ alone (UA189), Aβ+ApEα2 (UA351), Aβ+APOE3 (UA353) and Aβ+APoE4 (UA355). Arrows point to intact neurons, whereas arrowheads indicate sites of neurons that have degenerated. Scale bars: 10 µm. (D) Expression of Aβ (UA356, UA357, UA358) alone, without Aβ co-expression, does not affect mechanosensory response (P>0.9999). P=0.9971, P=0.9999, respectively. Additionally, expression of the APOE alleles alone showed no statistically significant difference between APOE2 and APOE3 (P=0.9914), APOE2 and APOE4 (P=0.9994), or APOE3 and APOE4 (P=0.9994). The difference between Aβ-expressing animals and any of the APOE alleles alone was statistically significant (P=0.001) in each comparison (P>0.9999 for each strain; one-way ANOVA with Tukey’s post hoc test. These data are reported as means±s.e.m. (E) Glutamatergic expression of Aβ hampers the gentle touch response (P<0.0001). Aβ+APoE2 mitigates loss of mechanosensory function (P=0.0095), but there was no significant difference between Aβ and either APOE3 (P=0.747) or APoE4 (P=0.644).

Additionally, there was no difference between Aβ+APoE2 and Aβ+APOE3 (P=0.1429), Aβ+APOE2 and Aβ+APoE4 (P=0.1875), or Aβ+APOE3 and Aβ+APoE4 (P=0.9997). n=90 for each strain; one-way ANOVA with Tukey’s post hoc test. These data are reported as means±s.e.m. (F) Expression of APoE was determined by RT-qPCR of mRNA isolated from 100 animals for each of APOE2, APOE3 and APoE4. Amplification and Cq quantification by quantitative PCR shows twofold higher expression of APOE4 than APoE2 that is not statistically significant (P=0.2107). The fourfold higher expression of APOE3 than APoE2 was statistically significant (P=0.0127), but the difference between APOE3 and APoE4 was not statistically significant (P=0.1280). Values represent the means±s.e.m. of three independent biological replicates each with three technical replicates: one-way ANOVA with Tukey’s post hoc test. * denotes statistical significance; ns, nonsignificant. et al., 1999). In cultured mouse cortical neurons, the opposite effect is observed, wherein NMDA-mediated calcium influx is inhibited by ApoE4 but exacerbated by ApoE2 and ApoE3 (Chen et al., 2010). Nevertheless, in both mammalian scenarios the functional impact of Aβ neurotoxicity was not assessed. To test the relationship between calcium, ApoE and Aβ in our model, we utilized thapsigargin, which increases cytosolic calcium concentrations by inhibiting the endoplasmic reticulum (ER) Ca2+-ATPase sca-1. Indeed, calcium influx induced by APOE has been partially attributed to ER calcium stores (Tolar et al., 1999). Animals expressing GFP alone were not impacted by thapsigargin treatment (Fig. 2A). Thapsigargin treatment of animals expressing Aβ attenuated neurodegeneration by nearly 20% compared with vehicle control at days 3 and 7 (Fig. 2A). There was no additive reduction in neurodegeneration by thapsigargin treatment with expression of either APOE2 or APOE3 at either day 3 or 7, suggesting that ApoE may potentially allay neurodegeneration in the same pathway as ER-derived calcium. As previously observed, the effect of ApoE4 was significantly reduced when compared with ApoEα2 at both days 3 (P<0.0001) and 7 (P=0.0177), but together with thapsigargin, ApoE4 showed protection similar to Aβ+ApEα2 at both time points. No effect was observed from treatment of GFP animals expressing APOE without Aβ (Fig. 2B). These data suggest that ApoEα2 is neuroprotective through an interaction with ER-derived calcium and that this interaction is lost with the ApoE4 protein variant.

To confirm that the observed effect by thapsigargin is related to its inhibition of sca-1, a Ca2+ ATPase and target of thapsigargin, we generated a conditional RNAi-sensitive strain, in which RNAi is restricted to the glutamatergic neurons. This strain was then crossed into the Aβ and Aβ+apoE backgrounds, so that genetic targets can be depleted with co-expression of Aβ and ApoE (Table 1). As previously observed, thapsigargin treatment reduced neurodegeneration in animals expressing Aβ alone and co-expressing Aβ+ApEα4, but not in either Aβ+ApEα2 or Aβ+ApEα3 animals (Fig. 3). Depletion of sca-1 in Aβ alone was neuroprotective when compared with empty vector (EV) control, but there was no additional protection conferred by a combination of sca-1 RNAi and thapsigargin treatment, suggesting that protection by thapsigargin, redundant with ApoEα2 and ApoEα3, is not independent from its target, sca-1. In contrast, sca-1 RNAi was protective in the backgrounds expressing Aβ alone and Aβ+APOE4. Taken together, these data suggest that there is a genetic relationship between APOE2 and sca-1 that is lost in the APOE4 genetic background.

Thapsigargin-induced alterations in ER-derived Ca2+ dynamics have been reported to also increase autophagy (Huyer-Hansen et al., 2007). Conversely, thapsigargin has also been observed to block degradation of autophagosomes without altering basal autophagy or maturation of autophagosomes (Ganley et al., 2011). To examine the relationship between thapsigargin, autophagy, Aβ and ApoE, neurodegeneration was examined in the conditional RNAi-sensitive strains with depletion of atg-7, which is required for the initiation of autophagy. Depletion of atg-7 increased neurodegeneration in animals expressing Aβ alone (Fig. 3), but the difference was no longer statistically significant by day 7 (Fig. 3). With atg-7 RNAi, thapsigargin treatment was significantly protective (Fig. 3) until day 7 (Fig. 3). Depletion of atg-7 also increased neurodegeneration in both Aβ+ApEα2 and Aβ+ApEα3 backgrounds, but with significantly less degeneration than Aβ alone with atg-7 RNAi, suggesting that protection by ApoEα2 and ApoEα3 is independent of autophagy. There was also no additional protection afforded by thapsigargin in the Aβ+ApEα2 or Aβ+ApEα3 backgrounds with...
atg-7 RNAi, further indicating that ApoEε2 and ApoEε3 participate with calcium homeostasis to mediate protection. In contrast, atg-7 RNAi increased neurodegeneration in the Aβ+ApoEε4 background, but was attenuated with thapsigargin treatment, further revealing the dysfunctional relationship between ApoEε4 and calcium homeostasis.

Fig. 2. Thapsigargin treatment reduces neurodegeneration with Aβ and Aβ+ApoEε4, but has no additive neuroprotective effect with either ApoEε2 or ApoEε3. (A) At day 3 post-hatching, thapsigargin (T) has no effect on synchronized hermaphrodite populations expressing GFP alone in the glutamatergic neurons (DA1240; P>0.9999), but it attenuates neurodegeneration with Aβ compared with vehicle (V) control (UA198; P<0.0022). There was no observable difference between vehicle and thapsigargin treatments in Aβ+ApoEε2 (UA351; P=0.9995) or Aβ+ApoEε3 (UA353; P=0.9888). However, thapsigargin treatment reduced neurodegeneration in Aβ+ApoEε4 compared with vehicle (UA355; P=0.0011). This rescue was statistically insignificant when comparing Aβ+ApoEε2 with vehicle (P=0.8007). Similarly, at day 7 post-hatching, there was no difference between vehicle and thapsigargin treatments in animals expressing GFP alone (DA1240; P>0.9999), while thapsigargin reduced Aβ-mediated neurodegeneration (UA198; P<0.0002). Thapsigargin treatment had no effect on neurodegeneration in Aβ+ApoEε2 (UA351; P=0.9976) or Aβ+ApoEε3 (UA353; P>0.9999), and failed to attenuate neurodegeneration significantly with ApoEε4 co-expression (UA355; P=0.0544). When treated with thapsigargin, Aβ+ApoEε4 was not different from Aβ+ApoEε2 with vehicle (P>0.9999). n=90 for each strain; two-way ANOVA with Tukey’s post hoc test. These data are reported as mean animals±s.d. All nematodes were grown at 20°C. (B) At days 3 and 7 post-hatching, thapsigargin had no effect on synchronized hermaphrodite populations expressing GFP alone in the glutamatergic neurons (DA1240; day 3, P>0.9999; day 7, P>0.9999), but thapsigargin (T) attenuates neurodegeneration with Aβ compared with vehicle (V) control (UA198; day 3, P=0.0015). The effect of thapsigargin on UA198 at day 7 was not statistically significant (P=0.0605). Without Aβ expression, thapsigargin has no statistically significant effect on neurodegeneration in Aβε2 (UA356; day 3, P=0.9999; day 7, P>0.9999), ApoEε2 (UA357; day 3, P>0.9999; day 7, P>0.9999) or ApoEε4 animals (UA358; day 3, P=0.9999; day 7, P>0.9999). These data are reported as mean animals±s.d. n=90 for each strain; two-way ANOVA with Sidak’s post hoc test. All nematodes were grown at 20°C. * denotes statistical significance.
Table 1. Summary of all the strains utilized in this study

<table>
<thead>
<tr>
<th>Strain (Bristol) background</th>
<th>Genotype</th>
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<tr>
<td>UA350</td>
<td>bain5[P::Aβ;ApoE2, P unc-54:tdTomato]</td>
</tr>
<tr>
<td>UA352</td>
<td>bain5[P::Aβ;ApoE3, P unc-54:tdTomato]</td>
</tr>
<tr>
<td>UA354</td>
<td>bain5[P::Aβ;ApoE4, P unc-54:tdTomato]</td>
</tr>
</tbody>
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GFP and ApoE expression

DA1240 adis1240[P cpl-4::GFP+lin-15(+)]; bain5[P::ApoE2, P unc-54:tdTomato] |
DA1241 adis1240[P cpl-4::GFP+lin-15(+)]; bain5[P::ApoE3, P unc-54:tdTomato] |
DA1242 adis1240[P cpl-4::GFP+lin-15(+)]; bain5[P::ApoE4, P unc-54:tdTomato] |

GFP, ApoE and Aβ co-expression

UA198 bain34[P::Aβ;P myo-2::mCherry]; adis124[P::GFP] |
UA351 bain50[P::Aβ;P unc-54:tdTomato]; bain34[P::Aβ;P myo-2::mCherry] |
UA353 bain51[P::ApoE3, P unc-54:tdTomato]; bain34[P::Aβ;P myo-2::mCherry] |
UA355 bain52[P::ApoE4, P unc-54:tdTomato]; bain34[P::Aβ;P myo-2::mCherry] |

Conditional RNAi strains

UA311 bain53[P sid-1::GFP] |
UA359 sid-1[pk3231]; bain53[P sid-1::GFP] |
UA360 sid-1[pk3231]; bain53[P sid-1::GFP] |
UA364 sid-1[pk3231]; bain53[P sid-1::GFP] |
UA365 sid-1[pk3231]; bain53[P sid-1::GFP] |
UA366 sid-1[pk3231]; bain53[P sid-1::GFP] |

Attenuation of neurodegeneration by starvation is independent of ApoE function

Starvation and caloric restriction increase health and lifespan through multiple pathways that overlap with significant conservation among yeast, *C. elegans*, Drosophila, rodents and primates (Fontana et al., 2010). Furthermore, dietary restriction reduces Aβ toxicity (Stein Kraus et al., 2008). We therefore hypothesized that starvation would attenuate Aβ-mediated neurodegeneration and tested its effect in the context of the three distinct *ApoE* alleles. To test this, synchronized embryos were hatched onto unseeded plates and incubated for 24 h, after which time they were transferred to normal (nematode growth medium; NGM) nematode plates seeded with *Escherichia coli*. Although early-L1-stage larval starvation attenuated neurodegeneration as expected in worms expressing Aβ alone, this protective effect was also shared indiscriminately with animals co-expressing any of the *ApoE* alleles (Fig. 4A). These data suggest that, in modulating its effects on neuron survival, ApoE operates outside of this starvation-induced rescue response, thus excluding this mechanism of dietary restriction as an *ApoE*-allele-specific means of modulating neurotoxicity. However, alternative dietary restriction regimens in *C. elegans* have been found to extend lifespan through parallel or overlapping pathways (Greer and Brunet, 2009). The extension of lifespan by dietary deprivation was dependent on heat shock factor 1 (*hsf-1*), while AMP-activated protein kinase 2 (*aak-2*) and FOXO/daf-16 were required for lifespan extension by the absence of peptone. Because the dietary deprivation regimen begins dietary restriction at day 2 of adulthood (day 5 post-hatching), animals were washed off food at day 5 post-hatching and moved to unseeded plates until analysis at day 7. Although dietary deprivation reduced neurodegeneration in the background expressing Aβ alone (Fig. 4B), dietary deprivation provided no statistically significant rescue in the Aβ+ApoE2, Aβ+ApoE3 or Aβ+ApoE4 backgrounds, suggesting that the ApoE protein, irrespective of allelic variation, might generally interfere with *hsf-1*-associated protective mechanisms. In contrast, there was no statistically significant change in neurodegeneration in animals subjected to the absence of peptone regimen at either days 3 or 7 (Fig. 4C).

Survival shortened by Aβ is rescued by ApoE2 and ApoE3, but not ApoE4

Because AD is an age-related disease and *ApoE4* homozygosity is associated with earlier onset of AD (Bu, 2009; Corder et al., 1993; Liu et al., 2013a), we examined how the relationship between Aβ and ApoE in the glutamatergic neurons affected survival with aging. Additionally, the Mantel–Cox/log-rank method was used for statistical analyses, as it assigns equal weights in statistical calculations for the entire pattern or path of the curve, not just the median or maximum values displayed. Both wild type (Bristol N2) and animals expressing GFP alone exhibited similar survival curves that were not significantly different from each other (Fig. 5A). In animals expressing Aβ, survival was significantly reduced (Fig. 5A), suggesting a relationship between glutamatergic neurodegeneration and aging in the *C. elegans* neuronal model. In animals expressing *APOE* alleles alone (encoding ApoE2, ApoE3 or ApoE4), the survival curves were similar to the N2 control (Fig. 5B-D). However, co-expression of Aβ+ApoE2 or Aβ+ApoE3 increased survival (Fig. 5E,F), compared with Aβ alone (Fig. 5A). In contrast, co-expression of Aβ+ApoE4 had no significant effect compared with Aβ alone (Fig. 5G). These data suggest that integrity of the glutamatergic neurons through the aging process, as differentially modulated by the *APOE* alleles in the presence of Aβ, affects whole-animal survival.

DISCUSSION

The *APOE4* allele is the strongest risk factor associated with late-onset AD, yet determining precisely how the *APOE* alleles differentially modulate Aβ toxicity and neuronal behavior remains unresolved. An expedient examination of the relationship between the *APOE* alleles and Aβ requires a model system in which neuronal dysfunction and loss are amenable to both genetics and tractable neuronal outputs. Our *C. elegans* model of Aβ-induced neurodegeneration in glutamatergic neurons recapitulates mammalian and cell culture models for AD-associated gene analyses (Griffin et al., 2017; Matlack et al., 2014; Treusch et al., 2011). Furthermore, genes associated with AD have *C. elegans* orthologs (Mukherjee et al., 2017; Vahdati Nia et al., 2017). Here, we debut a model of ApoE activity in our established neuronal model of Aβ-induced neurodegeneration in glutamatergic neurons that provides a protective effect against Aβ-mediated neurodegeneration, while the most prevalent allele, *ApoE3*, provides none (Bu, 2009; Corder et al., 1993; Huang and Mucke, 2012; Liu et al., 2013a). *APOE4* is associated with enhanced susceptibility and earlier onset of AD, as well as exacerbated neurodegeneration. Studies have shown that the *APOE2* allele may be neuroprotective through a mechanism that consists of more than simply the absence of the *APOE4* allele (Corder et al., 1994; Talbot et al., 1994). It is noteworthy that in...
several of our assays, we identified contrasting phenotypes from *C. elegans* with either Aβ+Apoe2 or Aβ+Apoe4. As an illustration, overexpression of human ApoE2 in *C. elegans* vitiates Aβ-mediated neurodegeneration, whereas ApoE3 only appears to have a rescuing phenotype later in life (Fig. 1B). However, the neuroprotective effect observed was not recapitulated by the ApoE4 variant (Fig. 1B). These data, which are functionally reflective of the well-established clinical susceptibility profile associated with ApoE, highlight the conservation of the neurodegenerative consequences that arise with the allelic distribution associated with AD. While loss of neuroprotective function in the Aβ+Apoe4 background represents a mechanically relevant observation, additional avenues of ApoE4-associated alterations in cell biology remain to be explored. For example, although the ε4 allele is typically associated with increased Aβ toxicity and disruption of homeostatic pathways *per se*, we observe no increase in neurodegeneration by the *APOE*ε4 allele. This may be due to a C-terminal proteolytic product of *APOE*ε4 that more strongly induces cellular responses associated with neurodegeneration (Bien-Ly et al., 2011; Brecht et al., 2004; Harris et al., 2003; Tolar et al., 1999). However, the effectors of this cleavage are unknown. Yet, full-length ApoE4 has been observed to alter expression of sirtuin, which could affect observable phenotypes under additional stress (Lattanzio et al., 2014; Theendakara et al., 2013, 2016). Thus, *C. elegans* might be an effective model for examining how full-length ApoE4 and its truncate modify Aβ toxicity *in vivo*.

Calcium homeostasis is found to be perturbed in AD, particularly by ApoE through glutamatergic (NMDA) receptor function (Chen et al., 2010; Hartmann et al., 1994; Qiu et al., 2003; Tolar et al., 1999). Thapsigargin treatment increases cytosolic calcium levels by inhibiting calcium uptake into the ER and we find that it mitigates Aβ toxicity, but not in the presence of either ApoE2 or ApoE3 (Fig. 2A), suggesting that ApoE has a function within calcium homeostasis that is selectively lost by the *APOE*ε4 allele. Whether this is dependent on glutamatergic receptors in our model is not yet clear. However, it appears that ER-derived calcium also contributes to ApoE4-associated calcium defects (Tolar et al., 1999). Notably, autophagy has also been shown to be impaired in AD. Although it

Fig. 3. See next page for legend.
Thapsigargin treatment (T) did not affect the phenotype in the GFP background (UA359; P = 0.9999 for each). Thapsigargin treatment provided no additional protection with Aβ+|ApoEε2 co-expression (day 3, P = 0.9999; day 7, P = 0.9999) and no additional benefit of thapsigargin treatment with Apoeε2ε4 background increased neurodegeneration at both days 3 (P = 0.0001) and 7 (P = 0.0001), but Apoeε2ε4 still provided rescue with Aβ-7 depletion when compared with Aβ alone with Aβ-7 RNAi (day 3, P = 0.0001; day 7, P = 0.0007). Similar effects were observed in the Aβ+Apoe3 background, including no additional protection with thapsigargin treatment compared with vehicle (V) (UA365; day 3, P = 0.9999; day 7, P = 0.9999), depletion of Aβ-1 providing no additional protection with Aβ+ Apoeε2ε4 co-expression (day 3, P = 0.9368; day 7, P = 0.9999), and no additive protection with thapsigargin treatment and sca-1 RNAi (day 3, P = 0.5193; day 7, P = 0.9999). Similarly, 2RNAi significantly increased neurodegeneration compared with EV control (day 3, P = 0.0001; day 7, P = 0.0001), but it was still statistically significantly neuroprotective compared with Aβ alone with Aβ-7 RNAi (day 3, P = 0.0001; day 7, P = 0.0002). Thapsigargin treatment did not reduce neurodegeneration with Aβ-7 RNAi in the Aβ+Apoe3 background (day 3, P = 0.9999; day 7, P = 0.9999). In contrast, as previously observed, thapsigargin was protective in the Aβ+Apoe4 background at both days 3 (UA366: P = 0.0001) and 7 (P = 0.0001). Although sca-1 RNAi conferred no additional protection with co-expression of Aβ+Apoe3 or Aβ+Apoe4 ε4. At day 3 and 7 post-hatching, neither Aβ-7 nor sca-7 RNAi depletion had an effect on animals expressing GFP alone (UA359; P = 0.9999 for each).

Yeast and mammalian models have provided insights into the relationship between neurodegenerative disease, calcium and mitochondria that have been further recapitulated in C. elegans (Bornhorst et al., 2014; Caraveo et al., 2014; Kim et al., 2018; Martinez et al., 2017b; Ray et al., 2014). Given the decline of the mitochondrial unfolded protein response (UPRmt) with aging (Baker and Haynes, 2011), and that Apoeε4ε2 makes Apoeε4 ε2 far less likely to be retained at the ER. Perhaps the additional cysteine residues in Apoeε2 compared with Apoeε3 or Apoeε4 makes Apoeε4 an agent of redox stabilization at mitochondria during stress (Yamauchi et al., 2017). Additionally, variations in the translocase of outer mitochondrial membrane 40 (TOMM40) and Apoe are associated with differences in longevity (Lin et al., 2016). Notwithstanding, the interaction between Apoe and the ER stress pathway is poorly understood and deserves to be more explicitly delineated.

Induction of autophagy by thapsigargin is reported to occur through stimulation of ER stress (Bernales et al., 2006; Ding et al., 2007; Høyer-Hansen et al., 2007; Kouroku et al., 2007). Although our data suggest divergent participation in protection between autophagy and Apoe, they do not preclude the possibility of ER stress. Whether Apoeε4 yields protection by inducing ER stress is unclear. It is, however, unlikely, considering that Apoeε4 has been shown to significantly increase ER stress compared with Apoeε3 in mice (Verghese et al., 2013; Zhong et al., 2009). In such a paradigm, increased ER stress by Apoeε2 would presumably recapitulate Apoeε4-associated phenotypes. Further, the protective effect of Apoeε4 might not be attributed to differences in ER stress induction, as Apoeε2 and Apoeε3 have been reported to have no difference in the expression of ER stress targets IRE1 (also known as ERN1), BiP (also known as HSPA5) and CHOP (also known as DDIT3), which increase, instead, with Apoeε4 expression (Verghese et al., 2013). Rather, stress and injury typically increase the expression of Apoe in brains (Xu et al., 2006). The effect of increased Apoe expression during stress might be due to mitochondrial interactions, because RNA sequencing of mouse brains revealed Apoe-allele-specific responses in mitochondrial gene expression (Babenko et al., 2017; Xu et al., 2006). Indeed, Apoeε3 is less likely to be retained at the ER (Brodbeck et al., 2011), and although the retention of Apoeε4 in the ER has not been reported, the effect of RET retention is due to the S61R present in Apoeε3 and Apoeε4, but not present in Apoeε2, thus making Apoeε2 far less likely to be retained at the ER. Perhaps the additional cysteine residues in Apoeε2 compared with Apoeε3 or Apoeε4 makes Apoeε2 an agent of redox stabilization at mitochondria during stress (Yamauchi et al., 2017). Additionally, variations in the translocase of outer mitochondrial membrane 40 (TOMM40) and Apoe are associated with differences in longevity (Lin et al., 2016). Notwithstanding, the interaction between Apoe and the ER stress pathway is poorly understood and deserves to be more explicitly delineated.

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may be induced by thapsigargin treatment, these data suggest that autophagy and Apoe participate with Apoe toxicity through separate mechanisms. Despite this, the relationship between autophagy and calcium is not entirely clear (Sun et al., 2016). Future analyses using the Apoeε4 transgenic worm models could include autophagy, as its component proteins are highly conserved in C. elegans (Chang et al., 2017; Martinez et al., 2015; Stavoe et al., 2016).
stress conditions to modulate MAMs and protect against cell death (Sreekumar et al., 2017). Supplementation of a humanin derivative reduced cognitive defects in a transgenic AD mouse model (Niihara et al., 2011). Future work would include measuring changes in intracellular calcium with expression of the different APOE alleles, to determine whether these changes are dependent on the mitochondrial calcium unipporter or ER stress, and how this affect mitochondrial stability towards neuronal integrity. As such, this model provides a potent medium with which to further understand and probe these interactions for therapeutic targets.

Loss or depletion of the insulin signaling receptor, daf-2, doubles lifespan in C. elegans (Kenyon et al., 1993) in a manner that is independent of autophagy (Greer and Brunet, 2009). In C. elegans models of proteotoxicity, loss of daf-2 reduces α-synuclein-mediated neurodegeneration (Knight et al., 2014; Ray et al., 2014), paralysis-induced poly-Q toxicity (Steinkraus et al., 2008) and paralysis-induced Aβ toxicity (Cohen et al., 2006; Florez-McClure et al., 2007; Steinkraus et al., 2008). Furthermore, loss of daf-2 decreases Aβ toxicity (Steinkraus et al., 2008) by increasing the autophagic clearance of Aβ (Florez-McClure et al., 2007). However, different longevity association pathways are activated in response to diverse dietary restriction regimens (Greer and Brunet, 2009). Peptone absence extends lifespan through aak-2 and FOXO/daf-16, but yielded no change in neurodegeneration, suggesting that daf-2-mediated protection observed in other Aβ models (Cohen et al., 2006) might be engaged through downstream mechanisms in parallel with AAK-2 activation of FOXO/β. For example, reduced insulin-like signaling decreased Aβ accumulation by elevating autophagy and lysosome populations (Florez-McClure et al., 2007). In the dietary deprivation model, the extension of lifespan requires hsf-1. In such a model, it is feasible that the complete absence of food during the first larval stage could activate responses controlled by HSF-1 activity independently of expression of any APOE allele (Steinkraus et al., 2008). However, this would stand in opposition to the hsf-1-dependent dietary deprivation model that begins starvation 2 days into adulthood (Greer and Brunet, 2009; Steinkraus et al., 2008), but was only protective with Aβ alone (Fig. 4B), suggesting an interaction between ApoE in the dietary deprivation model that does not take place in the L1 starvation model. We show a potent neuroprotective effect of two different dietary restriction regimens that interact differently with ApoE in Aβ toxicity in vivo (Fig. 4A, B). Considering the robust understanding and utility of C. elegans in aging research, this model opens avenues for more thorough examination of the relationships between longevity pathways, ApoE and Aβ.
Although ApoE is associated with longevity (Fuku et al., 2017; Lin et al., 2016; Schächter et al., 1994; Skillbäck et al., 2018), it is not clear how ApoE interacts with other longevity-associated pathways, especially when challenged by Aβ-induced proteostatic stress. A more thorough understanding of transcriptional changes with ApoE expression would shed light on the neuronal effect of ApoE that drives the differences between L1 starvation and dietary deprivation models. ApoE ε4 has been observed to translocate to the nucleus and alter gene expression by altering transcriptional regulation (Lattanzio et al., 2014; Theendakara et al., 2013, 2016). Many of these genes appear conserved from *C. elegans* to humans and might have similar implications for metabolism, stress response and aging (Arey and Murphy, 2017; Vahdati Nia et al., 2017). Thus, future studies combining transcriptional profiling of the ApoE-Aβ transgenics with RNAi or genetic depletion of up- or downregulated target genes would be informative.

Aging remains the most definitive risk factor for AD. Therefore, it is significant to note that, in the absence Aβ, none of the *APOE* alleles had an effect on survival (Fig. 5B-D). Survival curves comparing N2 with ApoEε2 (UA350; *P*=0.6679), N2 and ApoEε3 (UA352; *P*=0.0845), or N2 and ApoEε4 (UA354; *P*=0.8255). (E-G) Survival curves comparing Aβ with Aβ+ApoEε2 (E), Aβ+ApoEε3 (F) and Aβ+ApoEε4 (G). (E) The presence of ApoEε2 with Aβ (UA351) significantly increases survival compared with Aβ alone (*P*=0.0119). (F) Survival was also significantly increased in Aβ+ApoEε3 (UA353) compared with Aβ alone (*P*=0.0026). (G) In contrast, Aβ+ApoEε4 (UA355) did not significantly alter survival (*P*=0.0906). *n*=200 for each line. The log-rank (Mantel–Cox) method to account for differences in survival was applied for statistical analysis of all strains.

![Fig. 5. Effects of apolipoprotein E isoforms and Aβ expression on *C. elegans* survival. Animal populations were synchronized by a 2-h egg lay and maintained at 20°C. The L4 molt was defined as t=0, and survival was assessed by scoring response to mechanical probing. (A) Aβ expression (UA198) significantly reduced survival, compared with the survival curves for both wild-type (WT) N2 nematodes (*P*<0.0001) and nematodes expressing GFP alone in glutamatergic neurons (DA1240; *P*<0.0001). There was no significant difference between N2 and expression of GFP alone (DA1240; *P*=0.2669). (B-D) Survival curves comparing N2 with ApoEε2 (UA350; *P*=0.6679), N2 and ApoEε3 (UA352; *P*=0.0845), or N2 and ApoEε4 (UA354; *P*=0.8255). (E-G) Survival curves comparing Aβ with Aβ+ApoEε2 (E), Aβ+ApoEε3 (F) and Aβ+ApoEε4 (G). (E) The presence of ApoEε2 with Aβ (UA351) significantly increases survival compared with Aβ alone (*P*=0.0119). (F) Survival was also significantly increased in Aβ+ApoEε3 (UA353) compared with Aβ alone (*P*=0.0026). (G) In contrast, Aβ+ApoEε4 (UA355) did not significantly alter survival (*P*=0.0906). *n*=200 for each line. The log-rank (Mantel–Cox) method to account for differences in survival was applied for statistical analysis of all strains.](dmm037218_fig5.png)
behaviors and fat storage (Chun et al., 2015; Hamilton et al., 2005; Lee and Ashrafi, 2008; Greer and Brunet, 2009; Greer et al., 2008; Hills et al., 2004; Kindt et al., 2007; Lee et al., 2008; Zheng et al., 1999). Because the glutamatergic neuronal circuitry modulates feeding behaviors, Aβ might possibly depress survival through dysfunctional feeding, which is hitherto repressed by the protection of neuronal structure observed with APOEε2 co-expression. The ability of the APOEε2 allele to reduce survival depression by Aβ would therefore be due to restored glutamatergic connectivity through the associated neuroprotective phenotypes. Uninhibited feeding, in combination with the utilization of fat storage from loss of glutamatergic signaling, potentially incites insulin signaling responses that influence longevity (Greer et al., 2008; Gusarov et al., 2017). The connection between insulin signaling and longevity was first realized in C. elegans (Kenyon et al., 1993). Clinical research shows a complex relationship between diabetes, AD and ApoE4 (Arnold et al., 2018). Administration of insulin facilitated memory recall in patients carrying APOEε2 or APOEε3, but further impaired recollection in APOEε4 patients (Regier et al., 2006). Considering the history and utility of C. elegans in the study of aging, we propose this model would be an effective tool to study the relationship between aging, insulin signaling and ApoE variants in Aβ-induced neurodegeneration.

It should be noted that known functions of ApoE are not limited to the nervous system (McNeill et al., 2010; Rosenson et al., 2017; Zhang et al., 2010). By restricting the expression of alleles to a single cell type, as in our model, the cellular and subcellular effects can be isolated from the emergent effects of endogenous expression that would otherwise compound the complexity underlying Aβ-mediated neurodegeneration. Furthermore, C. elegans has no endogenous ApoE ortholog allowing use of this model for dissection of the interactions between ApoE and evolutionarily conserved pathways without obfuscation from other perturbations, such as immunological and hepatic responses typically associated with ApoE. Because of the genetic and pharmacological amenability of C. elegans, screening for modifiers of ApoE-Aβ activity is tenable. Additional phenotypic outputs might provide further insight into nuances of ApoE-induced effects. Because the glutamatergic signaling that regulates fat storage in response to food also modulates pharyngeal pumping rate (Greer and Brunet, 2009), both fat storage (Yen et al., 2010) and pharyngeal pumping (Sanders et al., 2017) are potential quantifiable outputs of glutamatergic signaling. Likewise, the olfactory circuit is modulated by glutamatergic signaling (Chalasani et al., 2007), exhibiting quantifiable changes in turning and reversals (Bhattacharya et al., 2014; Xiao et al., 2015) in response to specific odors (Chalasani et al., 2010). Furthermore, the C. elegans olfactory circuitry is a workshop for research in the neurobiological basis of learning (Cho et al., 2016). Consequently, candidate compounds can be tested for their effects on neurodegeneration, and also how they affect neuron function and animal health. Thus, this model provides a new medium through which neuronal mechanisms of ApoE can be distinctly probed to expedite the identification of therapeutic targets and risk factors to better address the urgent and unmet societal burden represented by AD.

**MATERIALS AND METHODS**

**Plasmid construction**

The cDNAs of the human APOE alleles were a generous gift from Susan Lindquist. The cDNAs were cloned by Gateway Technology (Invitrogen) according to the manufacturer’s protocol. Briefly, primers 5'-GGGGACA-AGTTTTGACAAGAAGCGGCTCCCTGACGATGGTGTGTGCACTGATCA-3' and 5'-GGGGACAAGCTTGTACACGAAACCACTTTGAGCTCA-3' were used to amplify the APOE alleles and amplics were recombined with pDONR221 by BP reaction to generate entry clones. Entry clones were confirmed by sequencing and recombined with Pemat::expression vectors by LR reaction. Expression clones were confirmed by sequencing.

**C. elegans strains**

C. elegans were maintained following standard procedures (Brenner, 1974) to generate the worm ApoE models (Table 1), expression constructs were injected into Bristol N2 animals at 50 ng/μl with the co-injection marker transgene (Punc-53::tdTomato) at 50 ng/μl. At least three stable independent lines were generated, crossod with UA198 (baln5[Peat-::Aβ, Pmyo-2::mCherry]; adls1240[Peat-::GFP]) and analyzed for each C. elegans transgenic construct. Representative transgenic lines were selected and the corresponding transgenic lines in the N2 background were integrated using a Spectrolinker XL-1500 (Spectronics Corporation, Westbury, NY, USA). Integrated strains were outcrossed three times to N2 worms to generate the following strains: UA350 (baln5[Peat-::APOE2, Punc-53::tdTomato]), UA352 (baln5[Peat-::APOE3, Punc-53::tdTomato]) and UA354 (baln5[Peat-::APOE4, Punc-53::tdTomato]) (Table 1). These were crossed with UA198 to generate the following strains: UA351 (baln5[Peat-::APOE2, Punc-53::tdTomato]; baln5[Peat-::Aβ, Pmyo-2::mCherry]; adls1240[Peat-::GFP]), UA353 (baln5[Peat-::APOE3, Punc-53::tdTomato]; baln5[Peat-::Aβ, Pmyo-2::mCherry]; adls1240[Peat-::GFP]) and UA355 (baln5[Peat-::APOE4, Punc-53::tdTomato]; baln5[Peat-::Aβ, Pmyo-2::mCherry]; adls1240[Peat-::GFP]) (Table 1). They were also crossed with UA198 to generate strains UA356 (adls1240[Peat-::GFP::lin-13+]; baln5[Peat-::APOE2, Punc-53::tdTomato]); UA357 (adls1240[Peat-::GFP::lin-13+]; baln5[Peat-::APOE3, Punc-53::tdTomato]) and UA358 (adls1240[Peat-::GFP::lin-13+]; baln5[Peat-::APOE4, Punc-53::tdTomato]).

To generate conditional RNAi-sensitive strains, N2 animals were injected with the glutamatergic neuron promoter-sid-1 construct (Psid-1::sid-1::Aβ) with the co-injection marker (Pdat-1::GFP), integrated and outcrossed as previously described, to produce strain UA311 (baln5[Pdat-1::sid-1::sid-1, Pdat-1::GFP]). This strain was then crossed with the sid-1(pk3321) mutant strain to generate strain UA359 (sid-1(pk3321); baln5[Pdat-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]), which was subsequently crossed with UA198 to produce strain UA360 (sid-1(pk3321); baln5[Pdat-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]; baln3[Pdat-1::sid-1::Aβ, Pmyo-2::mCherry]). The RNAi-sensitive UA198 was then crossed with each of the Aβ-ApoE strains to produce strain UA364 (sid-1(pk3321); baln5[Pdat-1::sid-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]; baln3[Pdat-1::sid-1::Aβ, Pmyo-2::mCherry]; UA365 (sid-1(pk3321); baln5[Pdat-1::sid-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]; baln3[Pdat-1::sid-1::Aβ, Pmyo-2::mCherry]; UA366 (sid-1(pk3321); baln5[Pdat-1::sid-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]; baln5[Pdat-1::sid-1::sid-1::Aβ, Pmyo-2::mCherry]; UA367 (sid-1(pk3321); baln5[Pdat-1::sid-1::sid-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]; baln5[Pdat-1::sid-1::sid-1::sid-1::Aβ, Pmyo-2::mCherry]; UA368 (sid-1(pk3321); baln5[Pdat-1::sid-1::sid-1::sid-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]; baln5[Pdat-1::sid-1::sid-1::sid-1::sid-1::Aβ, Pmyo-2::mCherry]; UA369 (sid-1(pk3321); baln5[Pdat-1::sid-1::sid-1::sid-1::sid-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]; baln5[Pdat-1::sid-1::sid-1::sid-1::sid-1::sid-1::Aβ, Pmyo-2::mCherry]; UA370 (sid-1(pk3321); baln5[Pdat-1::sid-1::sid-1::sid-1::sid-1::sid-1::sid-1, Pdat-1::GFP]; adls1240[Pdat-1::GFP]; baln5[Pdat-1::sid-1::sid-1::sid-1::sid-1::sid-1::sid-1::Aβ, Pmyo-2::mCherry].

**Neurodegeneration analysis**

Animals for analysis were synchronized with a 3-h egg lay using gravid hermaphrodites and incubated at 20°C, unless otherwise specified. To examine the neurons, hermaphrodites at indicated post-hatching time points were immobilized using 3 mM levamisole on glass cover slides and inverted onto 2% agarose pads on microscope slides. Each analysis was replicated at least three times with 30 animals per condition (30 animals × 3 trials = 90). C. elegans glutamatergic neurons were analyzed for neurodegeneration as previously described (Matlack et al., 2014; Tardiff et al., 2012, 2017; Treusch et al., 2011). Briefly, animals were scored for glutamatergic neurodegeneration at days 3 and 7 post-hatching, as reported in the Results and in figure legends. An animal was scored as normal if all five tail neurons were present and without malformities such as distention, apoptotic swelling, axon breaks, separation of the soma or loss of fluorescence.

**Mechanosensation assay**

Assays were performed as previously described (Chalfie and Sulston, 1981; Chalfie et al., 1985). Briefly, animal populations were synchronized by a 3-h egg lay and progeny were incubated at 20°C until day 4 post-hatching.
C. elegans sensitivity to soft touch was assayed by gently stroking hermaphrodite animals on the posterior and anterior with an eyelash hair glued to the end of a Pasteur pipette. Backward locomotion was induced by gently stroking the head of the animal with the eyelash followed by stroking the tail just below the anus. A positive result for soft touch sensitivity was recorded if the animal ceased backward locomotion or began moving forward. This process was repeated five times per animal, and the number of positive responses to posterior soft touch out of five was recorded. A total of 30 worms per strain were scored per biological replicate and percentage posterior touch response was calculated as the percentage average response within the population. The experiment was repeated at least three times (n=3×30=90) and data represent the average of all three biological replicates with s.e.m., as previously reported (Zhang et al., 2004).

**Peptone absence**

Animals and media were prepared as previously described (Greer and Brunet, 2009). Briefly, age-synchronized populations of animals were obtained by allowing gravid adults to lay eggs for 3 h at 20°C on NGM plates containing either the standard quantity of peptone (2.5 g/l), as our control, or no peptone, and seeded with OP50 at a concentration of 5×10^{12} CFU/ml. Animals were maintained at 20°C and transferred as necessary until scoring for neurodegeneration.

**Dietary deprivation**

Animals and media were prepared as previously described (Lee et al., 2006). Briefly, age-synchronized populations of animals were obtained by allowing gravid adults to lay eggs for 3 h at 20°C on seeded NGM plates. Animals were transferred to fresh seeded plates as necessary until day 2 of adulthood (day 5 post-hatching), at which point they were either transferred to seeded plates as they had been previously (ad libitum condition) or transferred to unseeded plates (dietary deprivation). Animals were maintained for neurodegeneration analysis at day 7 post-hatching.

**Survival assays**

Survival assays were performed as previously described (Hsin and Kenyon, 1999). Briefly, strains were allowed to grow at 20°C in optimal growth conditions for at least two generations before the experiment began. Synchronized animal populations for survival analysis were generated by a 1-h egg laying using gravid hermaphrodites and incubated at 20°C. The L4 molt was defined as t=0, at which time animals were transferred to experimental plates. A total of 200 animals for each of nine strains were examined and all strains were assigned five initial plates with 40 worms each. Animals were then transferred to new plates every day, until the worms’ reproductive stage had passed, after which point animals were then transferred every other day to ensure that appropriate amounts of food remained on the plate. Survival was assessed immediately after each transfer, as previously described (Hsin and Kenyon, 1999). To score for death, animals were examined for locomotive response to prodding with a platinum wire. Briefly, animals were touched five times on the head and the tail and assessed for reverse or forward locomotion in response. Animals were classified as dead if they ceased moving and failed to respond to this stimulation. A third category, censored, was utilized for animals that did not die of the natural aging process. Worms were classified as censored if they crawled off the plate, burrowed, or displayed vulval rupture or internal hatching, as previously described (Hsin and Kenyon, 1999). Seeded plates were stored at 20°C until completion. In GraphPad Prism software, the log-rank (Mantel-Cox) method was used to account for differences between survival curves. Specifically, all time points are assigned equal weights in statistical calculations whereby the entire pattern or path of the curve is being analyzed in testing for significance, not just the maximum value displayed (Hansen et al., 2008).

**Pharmacological treatments**

Thapsigargin (Acros Organics) was dissolved in dimethyl sulfoxide (DMSO) and added to NGM plates to a final concentration of 3 μg/ml, as reported previously (Zwaal et al., 2001), with the modification that thapsigargin was added directly to the medium rather than supplemented on the surface.

**Experimental design and statistical analysis**

Hermaphrodites were analyzed, which is standard in the C. elegans field, and all animals were incubated at 20°C, unless otherwise specified. In all cases, sample sizes (typically 30 animals per condition; for a total of 90 animals) were standardized within each experiment and examined in a uniform fashion. All experiments used at least three independent replicates per experiment per variable to generate a mean and s.d. In experiments using one independent variable across multiple tested effects (e.g. neuron cell death as a function of construct type), a one-way ANOVA series was used with a multiple-comparisons post hoc test (Tukey’s). For grouped analyses, a two-way ANOVA series was used with Sidak’s post hoc test. Survival was analyzed by the log-rank (Mantel-Cox) method, as previously described in
the survival assay section. P<0.05 was the absolute minimum threshold for statistical significance. Statistics were performed using GraphPad Prism software.

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Competing interests

The authors declare no competing or financial interests.

Author contributions


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