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Impaired β-Amyloid Secretion in Alzheimer’s Disease Pathogenesis

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A central question in Alzheimer’s disease (AD) research is what role β-amyloid peptide (Aβ) plays in synaptic dysfunction. Synaptic activity increases Aβ secretion, potentially inhibiting synapses, but also decreases intraneuronal Aβ, protecting synapses. We now show that levels of secreted Aβ fall with time in culture in neurons of AD-transgenic mice, but not wild-type mice. Moreover, the ability of synaptic activity to elevate secreted Aβ and reduce intraneuronal Aβ becomes impaired in AD-transgenic but not wild-type neurons with time in culture. We demonstrate that synaptic activity promotes an increase in the Aβ-degrading protease neprilysin at the cell surface and a concomitant increase in colocalization with Aβ42. Remarkably, AD-transgenic but not wild-type neurons show reduced levels of neprilysin with time in culture. This impaired ability to secrete Aβ and reduce intraneuronal Aβ has important implications for the pathogenesis and treatment of AD.

Introduction
A defining neuropathological feature of Alzheimer’s disease (AD) is the aberrant accumulation of β-amyloid peptide (Aβ). Aβ accumulation can lead to alterations in synapses and memory (Selkoe, 2002; Almeida et al., 2005; Hsieh et al., 2006). The site(s) and mechanism(s) whereby Aβ initiates dysfunction of synapses in AD are of major interest. Secreted, extracellular Aβ has traditionally been viewed as the source of Aβ-induced toxicity to synapses in AD, since addition of Aβ1–42 impairs synaptic function (Cleary et al., 2005; Shankar et al., 2008). In contrast, picomolar levels of extracellular Aβ were recently shown to enhance synaptic plasticity (Puzio et al., 2008). Remarkably, synaptic activity increases levels of secreted, extracellular Aβ (Kamenetz et al., 2003; Cirrito et al., 2005). Since the default network of the brain is particularly prone to the development of AD, it has been hypothesized that brain regions with the highest baseline metabolic activity are prone to AD because of high amounts of secreted Aβ (Cirrito et al., 2008; Palop and Mucke, 2010). However, it is unclear why such elevated levels of secreted Aβ from default network activity cause problems only with aging. Moreover, at-risk individuals for AD show reduced brain activity decades before clinical symptoms (Reiman et al., 2004), which might predict reduced Aβ secretion. There is increasing support for an alternative scenario focusing on aberrant intracellular accumulation of Aβ within vulnerable neurons (Gouras et al., 2010). In fact, we recently demonstrated that Aβ-related synapse damage and memory impairment in AD-transgenic mice correlated with this intracellular pool of Aβ but not with plaques (Tampellini et al., 2010).

We now provide evidence for reduced Aβ secretion with time in culture in AD-transgenic but not wild-type neurons. Furthermore, we show that synaptic activity is able to reduce levels of intracellular Aβ in AD-transgenic neurons at 12 but not at 19 days in vitro (DIV). We demonstrate that levels of neprilysin are reduced in AD-transgenic but not wild-type neurons with time in culture. Finally, we provide mechanistic evidence consistent with neprilysin leading to degradation of Aβ42 at the cell surface with synaptic activity.

Materials and Methods
Neuronal cultures. Primary neuronal cultures were prepared from cortices and hippocampi of embryonic day 15 Tg2576 (AD-transgenic) (Hsiao et al., 1996) and wild-type littermate mouse embryos, as described previously (Tampellini et al., 2009). Tg2576 male and wild-type female mice (Jackson Laboratories) were bred to generate the embryos. Mice were used in accordance with the NIH Guide for the Care and Use of Laboratory Animals.

Antibodies. For immunofluorescence, the following antibodies were used: neprilysin (H-321; Santa Cruz Biotechnology), amyloid precursor protein (APP) intracellular domain (AICD; Covance), postsynaptic density-95 (PSD-95; Millipore), Aβ42 (C terminus; Covance). For Western blot, the following antibodies were used: human-specific Aβ/APP 6E10 (Covance), murine and human Aβ/APP 4G8 (Covance), rabbit polyclonal APP (C terminus) 369, phospho-CaMKII (Millipore), total CaMKII (Millipore). Secondary antibodies were conjugated to Alexa Fluor-488 or -546 (Invitrogen) or horseradish peroxidase (GE Healthcare).

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neurons failed to enhance secretion of both Aβ/H9262. Right, Levels of Aβ secreted comparable amounts of Aβ peptides at 12 and 19 DIV (n = 6; left), AD-transgenic neurons showed decreased levels of Aβ1–40 and Aβ1–42 in media at 19 compared with 12 DIV (n = 10; *p < 0.05, **p < 0.01; right). B, Levels of intraneuronal Aβ42 were increased by 46 ± 17% in AD-transgenic neurites at 19 compared with 12 DIV (n = 4; p < 0.05). C, D, Levels of intraneuronal Aβ42 were unchanged in wild-type neurites at 19 compared with 12 DIV, as quantified by confocal immunofluorescence (C) and ELISA (D) (n = 4). E, Left, Levels of αCTFs were decreased by 52 ± 2%, while levels of βCTFs and full-length APP were unchanged in AD-transgenic neurites at 19 compared with 12 DIV (n = 4; p < 0.01). Right, Levels of αCTFs were decreased by 32 ± 9% (n = 5; p < 0.05), while levels of βCTFs (longer exposure) showed a trend for a 49 ± 16% decrease (p = 0.074) in wild-type neurites at 19 compared with 12 DIV. F, At 19 DIV, AD-transgenic neurons failed to enhance secretion of both Aβ1–40 and Aβ1–42 during g-LTP (n = 6; right). In contrast, wild-type neurons were still able to increase Aβ1–40 and Aβ1–42 secretion during g-LTP (n = 4; *p < 0.05, left). Conc., Concentration. Scale bars, 50 μm.

Figure 1. Decreased Aβ secretion in AD-transgenic (Tg) but not wild-type (WT) neurons with time in culture. A, Levels of Aβ1–40 and Aβ1–42 were assayed by ELISA in media of AD-transgenic or wild-type neurons. While wild-type neurons secrete comparable amounts of Aβ peptides at 12 and 19 DIV (n = 6; left), AD-transgenic neurons showed decreased levels of Aβ1–40 and Aβ1–42 in media at 19 compared with 12 DIV (n = 10; *p < 0.05, **p < 0.01; right). B, Levels of intraneuronal Aβ42 were increased by 46 ± 17% in AD-transgenic neurites at 19 compared with 12 DIV (n = 4; p < 0.05). C, D, Levels of intraneuronal Aβ42 were unchanged in wild-type neurites at 19 compared with 12 DIV, as quantified by confocal immunofluorescence (C) and ELISA (D) (n = 4). E, Left, Levels of αCTFs were decreased by 52 ± 2%, while levels of βCTFs and full-length APP were unchanged in AD-transgenic neurites at 19 compared with 12 DIV (n = 4; p < 0.01). Right, Levels of αCTFs were decreased by 32 ± 9% (n = 5; p < 0.05), while levels of βCTFs (longer exposure) showed a trend for a 49 ± 16% decrease (p = 0.074) in wild-type neurites at 19 compared with 12 DIV. F, At 19 DIV, AD-transgenic neurons failed to enhance secretion of both Aβ1–40 and Aβ1–42 during g-LTP (n = 6; right). In contrast, wild-type neurons were still able to increase Aβ1–40 and Aβ1–42 secretion during g-LTP (n = 4; *p < 0.05, left). Conc., Concentration. Scale bars, 50 μm.

Results

We previously reported progressive intraneuronal Aβ42 accumulation, alterations in endosomal trafficking, and AD-like synapse alterations in AD-transgenic neurons with time in culture, analogous to changes seen in vivo in AD-transgenic mouse brains with aging (Takahashi et al., 2004; Almeida et al., 2005, 2006). In this study, we examined whether time in culture affects Aβ secretion in AD-transgenic neurons. In wild-type neurons, levels of secreted Aβ1–40 and Aβ1–42 remained unchanged between 12 and 19 DIV (Fig. 1A, left). In contrast, in AD-transgenic neurons, levels of secreted Aβ1–40 and Aβ1–42 fell by 33 ± 4% and 39 ± 9%, respectively, between 12 and 19 DIV (Fig. 1A, right). We next examined levels of intraneuronal Aβ with time in culture. There was a 46 ± 17% increase in levels of intraneuronal Aβ42 in AD-transgenic neurites at 19 compared with 12 DIV, as quantified by confocal immunofluorescence microscopy (Fig. 1B). In contrast, levels of intraneuronal Aβ42 were unchanged in wild-type neurons at 19 compared with 12 DIV (Fig. 1C,D).
Interestingly, the levels of APPα C-terminal fragments (αCTFs) fell by 52 ± 2% between 12 and 19 DIV in AD-transgenic neurons, whereas levels of APPβ C-terminal fragments (βCTFs) and full-length APP remained unchanged (Fig. 1E, left). Thus, amyloidogenic processing of APP, as reflected by the βCTF/αCTF ratio, increased approximately twofold from 12 to 19 DIV in AD-transgenic neurons. Levels of αCTFs and βCTFs were both comparably decreased in wild-type neurons at 19 compared with 12 DIV (Fig. 1E, right), and therefore the βCTF/αCTF ratio did not change.

It has been shown that Aβ secretion is enhanced by synaptic activation (Kamenetz et al., 2003; Cirrito et al., 2005; Tampellini et al., 2009). Given the fall in steady-state secretion of Aβ in AD-transgenic neurons with time in culture, we investigated whether Aβ secretion was impaired during synaptic activity in AD-transgenic neurons with time in culture. g-LTP was used to stimulate neurons (Ehlers, 2003) at 12 and 19 DIV followed by Aβ ELISA of the conditioned media. We previously demonstrated that g-LTP increases Aβ secretion in AD-transgenic neurons at 12 DIV (Tampellini et al., 2009). We now show that, although g-LTP increases Aβ secretion in wild-type neurons at 19 DIV, it failed to increase Aβ secretion in AD-transgenic neurons at 19 DIV (Fig. 1F).

We reported that synaptic activation reduced intracellular Aβ42 and restored levels of PSD-95 back to wild-type levels in AD-transgenic neurons at 12 DIV (Tampellini et al., 2009). To investigate whether these effects are modulated by aging in vitro, we induced g-LTP in 19 DIV AD-transgenic neurons and quantified levels of intraneuronal Aβ and PSD-95. At 19 DIV, g-LTP reduced levels of intraneuronal Aβ42 by 23 ± 4% in wild-type (WT; left) but not AD-transgenic (Tg; right) neurons at 19 DIV, as determined by confocal immunofluorescence (n = 4; p < 0.01). A. Aβ1–42 ELISA of lysates from g-LTP compared with untreated neurons at 19 DIV revealed reduced levels of Aβ1–42 in wild-type but not in AD-transgenic neurons (n = 4; *p < 0.05). B. Western blot of cell lysates demonstrated reduced levels of intraneuronal Aβ in g-LTP-treated compared with -untreated AD-transgenic neurons at 12 (lanes 1 and 2, longer exposure) but not 19 (lanes 3 and 4) DIV (n = 3). D, C, E, PSD-95 puncta increased in g-LTP-activated AD-transgenic neurons at 19 DIV, although they failed to reach wild-type levels (n = 5; **p < 0.01). E, Wild-type neurons (12 DIV) showed a 74 ± 21% greater relative colocalization of nephrilysin with the MVB/late endosomal marker tumor susceptibility gene 101 (TSG101) than the early endosomal marker early endosomal antigen-1 (EEA1) (n = 3; p < 0.01). Conc., Concentration. Scale bars: A, D, E, 50 μm; E, inset, 10 μm.

Figure 2. Impaired ability for synaptic activity to reduce intraneuronal Aβ42 and protect synapses in AD-transgenic neurons with time in culture. A, g-LTP reduced levels of intraneuronal Aβ42 by 23 ± 4% in wild-type (WT, left) but not AD-transgenic (Tg, right) neurons at 19 DIV, as determined by confocal immunofluorescence (n = 4; p < 0.01). B, Aβ1–42 ELISA of lysates from g-LTP compared with untreated neurons at 19 DIV revealed reduced levels of Aβ1–42 in wild-type but not in AD-transgenic neurons (n = 4; *p < 0.05). C, Western blot of cell lysates demonstrated reduced levels of intraneuronal Aβ in g-LTP-treated compared with -untreated AD-transgenic neurons at 12 (lanes 1 and 2, longer exposure) but not 19 (lanes 3 and 4) DIV (n = 3). D, E, PSD-95 puncta increased in g-LTP-activated AD-transgenic neurons at 19 DIV, although they failed to reach wild-type levels (n = 5; **p < 0.01). E, Wild-type neurons (12 DIV) showed a 74 ± 21% greater relative colocalization of nephrilysin with the MVB/late endosomal marker tumor susceptibility gene 101 (TSG101) than the early endosomal marker early endosomal antigen-1 (EEA1) (n = 3; p < 0.01). Conc., Concentration. Scale bars: A, D, E, 50 μm; E, inset, 10 μm.
Activity-induced reduction in intraneuronal Aβ promoted recovery of PSD-95 puncta to wild-type levels in AD-transgenic neurons at 12 DIV (Tampellini et al., 2009). In contrast, levels of PSD-95 did not recover back to wild-type levels in g-LTP-treated compared with -untreated 19 DIV AD-transgenic neurons (Fig. 2D), although there was still an increase compared with untreated AD-transgenic neurons.

We showed that activity-dependent reduction in intraneuronal Aβ is dependent on the Aβ-degrading protease neprilysin (Tampellini et al., 2009). Data on the subcellular localization of neprilysin showed marked relative colocalization of neprilysin predominantly with late endosomes (Fig. 2E). To investigate the mechanism of neprilysin-dependent Aβ42 clearance with synaptic activity, levels of neprilysin were quantified as a function of synaptic activation. g-LTP did not change total levels of neprilysin (data not shown); however, it did increase levels of surface neprilysin by 37 ± 7% in stimulated compared with unstimulated wild-type neurons (Fig. 3A). Surface neprilysin also increased in stimulated compared with nonstimulated AD-transgenic neurons (Fig. 3B). We next explored whether the increased localization of neprilysin to the cell surface could be responsible for the augmented neprilysin-dependent Aβ42 degradation. To test this hypothesis, g-LTP was induced in AD-transgenic neurons in the presence of the neprilysin inhibitor thiorphan to prevent loss of Aβ42 labeling from degradation. g-LTP increased the relative colocalization of neprilysin with Aβ42 at the cell surface by 54 ± 21% (Fig. 3C).

Since synaptic activation failed to reduce levels of intraneuronal Aβ in AD-transgenic neurons at 19 DIV, we next investigated whether levels of neprilysin were altered in AD-transgenic neurons with time in culture. Remarkably, levels of neprilysin were decreased by 18 ± 8% in 19 compared with 12 DIV AD-transgenic but not wild-type neurons, as quantified by confocal immunofluorescence (Fig. 4A). Previous work reported that neprilysin is regulated by the AICD (Pardossi-Piquard et al., 2005). To investigate whether reduction of neprilysin might be related to reduced levels of AICD in the nucleus with time in culture, we double-labeled nuclei of 12 and 19 DIV AD-transgenic neurons with Hoechst stain and an AICD-specific antibody. Remarkably, the number of AICD-positive nuclei was decreased by 27 ± 6% in 19 compared with 12 DIV AD-transgenic neurons (Fig. 4B), suggesting reduced synthesis of neprilysin with time in culture.

Figure 3. Synaptic activation increases neprilysin surface levels and colocalization with Aβ42. A, g-LTP increased levels of surface neprilysin by 37 ± 7% in g-LTP-treated compared with -untreated wild-type neurons at 12 DIV (n = 6; p < 0.01). B, g-LTP also increased levels of surface neprilysin in g-LTP-treated compared with untreated AD-transgenic neurons at 12 DIV (n = 3; p < 0.01). C, g-LTP increased the relative colocalization of neprilysin with Aβ42 by 54 ± 21% at the cell surface in AD-transgenic neurons at 12 DIV (n = 3; p < 0.01). Scale bars: A–C, 50 μm; C, insets, 10 μm.
Discussion

The data presented here provide evidence for an impaired ability of familial AD-transgenic neurons to efficiently modulate levels of secreted and intraneuronal Ab with time in culture. We demonstrate that the ability to secrete Ab falls with time in culture in AD-transgenic but not wild-type neurons. Activity-induced Ab secretion also falls with time in culture in AD-transgenic but not wild-type neurons. Moreover, with time in culture, AD-transgenic neurons become impaired in their ability to reduce intracellular Ab and protect synapses in response to synaptic activity. We provide evidence that the mechanism by which synaptic activity reduces intracellular Ab42 is dependent on the Ab-degrading protease neprilysin. Synaptic activity leads to recruitment of neprilysin to the cell surface and increased colocalization with Ab42. Finally, we show that neprilysin levels fall with time in culture in AD-transgenic but not wild-type neurons, providing a mechanism for the failure of synaptic activation to reduce intracellular Ab in aged AD-transgenic neurons (Fig. 4C,D).

These data have important implications for AD. Decreased neuronal secretion of Ab with aging in AD could explain previous data that baseline interstitial Ab42 levels appear to be reduced in older compared with younger AD-transgenic mice (Cirrito et al., 2005). Reduced Ab42 levels are also seen in CSF in human AD, even in subjects who are cognitively normal but later develop AD (Fagan et al., 2009). The traditional explanation for reduced CSF Ab42 with AD is that secreted Ab is decreased by sequestration to extracellular plaques. Decreased secretion would also contribute to reduced Ab42 levels in CSF or interstitial fluid. Of note, other pathological conditions linked with AD, such as brain injury, also show reduced levels of extracellular Ab (Brody et al., 2008) and increased intraneuronal Ab (Gouras et al., 2010).

Reduced Ab secretion fits well with increasing evidence for early intraneuronal Ab accumulation with AD pathogenesis, as reported in human AD, Down syndrome, and in AD-transgenic rodents (Gouras et al., 2000; D’Andrea et al., 2001; Wirths et al., 2001; Takahashi et al., 2002; Oddo et al., 2003; Cataldo et al., 2004; Echeverria et al., 2004; Lord et al., 2006; Oakley et al., 2006; Knobloch et al., 2007; Gandy et al., 2010). Intraneuronal Ab accumulates and oligomerizes preferentially in distal processes even before plaques (Takahashi et al., 2004), and is associated with memory impairment, decreased synaptic plasticity, and subcellular pathology (Mori et al., 2002; Takahashi et al., 2002; Oddo et al., 2003; Almeida et al., 2005; Billings et al., 2005; Tomiyama et al., 2010). Intraneuronal Ab42 localizes and accumulates preferentially in late endosomes, including multivesicular bodies (MVBs) (Takahashi et al., 2002; Langui et al., 2004; Almeida et al., 2006). Interestingly, neprilysin also localizes to late endosomes/
MVBS (Fig. 2E). We show that neprilysin significantly relocates to the cell surface during synaptic activation. Neprilysin is a transmembrane neutral endopeptidase with the catalytic site at the C-terminal side, which can be either extracellular or luminal. Since neprilysin works best at neutral pH, the cell surface would be the optimal location for it to degrade Aβ42. In fact, we observed that colocalization of neprilysin and Aβ42 was increased at the cell surface with synaptic activation. This pool of Aβ42 could derive from amyloidogenic APP processing occurring within synaptic endosomes with synaptic activity (Cirrito et al., 2008; Tampellini et al., 2009), followed by trafficking of Aβ to the cell surface (Rajendran et al., 2006). The finding that neprilysin normally declines with aging in synaptic layers of wild-type mouse brain (Iwata et al., 2002) supports the theory that it plays a critical role in synaptic accumulation of Aβ with aging and AD. We show that neprilysin is reduced in AD-transgenic but not wild-type neurons with time in culture, although it is possible that a decline would eventually occur later in wild-type neurons. Reduced neprilysin in AD-transgenic neurons with time in culture can explain the impaired ability to reduce intraneuronal Aβ, in particular Aβ42, with synaptic activity, since we previously reported the inability of synaptic activity to reduce Aβ42 in neprilysin knock-out neurons or when neprilysin activity was blocked by treatment with thiorphan (Tampellini et al., 2009). In addition, it has been shown that extracellular Aβ can upregulate intracellular Aβ (Yang et al., 1999; Tampellini et al., 2009), which could lead to a vicious cycle of Aβ-induced elevation and synapse damage.

Overall, this study provides novel evidence for reduced Aβ secretion and impaired ability to reduce intraneuronal Aβ with time in culture in AD-transgenic neurons, and further underscores the important role of neprilysin in regulating neuronal Aβ.

References
Brody DL, Magnoni S, Schwetye KE, Spinner ML, Esparza TJ, Stocchetti N, Billings LM, Oddo S, Green KN, McGaugh JL, LaFeaLA FM (2005) Intraneuronal Abeta accumulation and impaired ability to reduce intraneuronal Aβ, with time in culture can explain the impaired ability to reduce intraneuronal Aβ, in particular Aβ42, with synaptic activity, since we previously reported the inability of synaptic activity to reduce Aβ42 in neprilysin knock-out neurons or when neprilysin activity was blocked by treatment with thiorphan (Tampellini et al., 2009). In addition, it has been shown that extracellular Aβ can upregulate intracellular Aβ (Yang et al., 1999; Tampellini et al., 2009), which could lead to a vicious cycle of Aβ-induced elevation and synapse damage.

Overall, this study provides novel evidence for reduced Aβ secretion and impaired ability to reduce intraneuronal Aβ with time in culture in AD-transgenic neurons, and further underscores the important role of neprilysin in regulating neuronal Aβ.


