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Title: Regulation of neurotransmitter release by amyloid precursor protein through synapsin phosphorylation 37

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Abstract:

Abnormal processing of amyloid precursor protein (APP) and aggregation of the Aβ peptide are known to play a key role in the pathogenesis of Alzheimer disease (AD), but the in vivo function of APP under normal physiological conditions remains poorly understood. In this study, we investigated presynaptic changes in APP knockout (KO) mice. We demonstrate that both sucrose-induced neurotransmission and synaptic depletion in response to high frequency stimulation are significantly enhanced in APP KO compared to wild type (WT) littermates. In addition, the level of phosphorylated forms of synapsins, but not total synapsins, is elevated in the KO mice. Furthermore, we show that the inhibition of L-type calcium channels normalizes phosphorylated synapsins and slows down the high frequency induced synaptic depletion in APP KO mice. These results suggest a new mechanism by which APP regulates synaptic vesicle dynamics through synapsin-dependent phosphorylation.

Keywords: Alzheimer disease, Amyloid precursor protein, Synaptic depletion, Synapsin, Ca channel

Introduction

Alzheimer disease (AD) is the most common form of dementia that affects millions worldwide and imposes enormous economic and social burden on the affected individuals and our society. However, our ability to treat this disease is limited due to incomplete understanding of the fundamental mechanisms underlying the pathogenic process of this disorder. One of the key theories is the amyloid-β (Aβ) hypothesis that posits that the accumulation of Aβ and the formation of Aβ oligomers impairs neuronal function, including synaptic regulation, leading to memory loss and, ultimately, to dementia [1-3]. Aβ peptide is a proteolytic fragment of amyloid precursor protein (APP), whose mutations are linked to AD patients [4-6]. Although it is agreed that the abnormal processing of APP and thus aggregation of the Aβ peptide is a key player in the pathogenesis of AD, the normal function of APP remains poorly defined.

Several studies have shown that APP plays important roles in neuronal development. *In vitro* studies indicate that APP is expressed in the lamellipodia of neuronal growth cones [7, 8] and affects axonal outgrowth through Rac1, a key mediator of actin reorganization [9]. Accordingly, axonal connectivity in APP knockout (KO) mice is impaired, abeit mildly, in forebrain commissures [10] and the retinotectal system [11, 12]. APP also regulates dendritic complexity and spine density. Lack of APP or engineered APP mutations within the C terminus decrease the dendritic complexity and spines in the hippocampal CA1 neurons *in vitro* [13-15] and *in vivo* [13, 16]. APP KO cortical or hippocampal neurons also have reduced spine densities [13, 14, 17, 18]. It is important to note that some of these changes in APP KO mice are age-dependent.

In neurons APP is also localized at the synapse suggesting a role in synaptic transmission and plasticity. In patients with AD, synaptic dysfunction is highly correlated with cognitive decline [19], and Aβ oligomers from patients can directly impair synaptic plasticity and memory in mice [1, 20].

Indeed, APP KO mice exhibited age-dependent impairments in long-term potentiation (LTP) and hippocampus-dependent behaviour, including spatial learning in the Morris water maze [21, 22], consistent with age-dependent reductions in spine defects in these mice [23]. In conditional double KO mice lacking both APP and APLP2, another member of the APP family, strong deficits in both spines and LTP as well as memory are present even in young mice, suggesting an overlapping and compensatory interactions among APP and its family members [17].

In addition to postsynaptic regulation, APP is implicated in presynaptic function. In particular, APP and APLP2 double conditional KO mice show impairments in paired-pulse facilitation (PPF) and the early phase of post-tetanic potentiation, both of which are thought to be of presynaptic origin [17]. In addition, responses to repetitive stimulation of the Schaffer collaterals are altered in neonatal the double KO mice [24]. However, underlying molecular mechanisms responsible for these presynaptic alterations remain unknown.

In this study, we investigated the role of APP in presynaptic function using APP KO mice. We showed that APP KO mice (4-5 weeks-old) were altered in sucrose induced release as well as synaptic depression in response to sustained high frequency stimulation. In addition, we showed that the level of phosphorylated synapsin, a key presynaptic regulator, was significantly elevated in APP KO mice and this elevation was reduced by the L-type calcium channel blocker nifedipine. Similarly, the enhanced synaptic depletion in APP KO mice was rescued by nifedipine. These results suggest that APP regulates neurotransmitter release through a synapsin-dependent mechanism.

Materials and Methods

Mice

APP KO mice were obtained from Model Animal Research Center of Nanjing University and genotyped using PCR techniques as previously described [25]. All mice were maintained and used according to experimental protocols approved by the Animal Care Committee at the Hospital for Sick Children (Toronto, Canada) and Southeast University (Nanjing, China).

Antibodies, Chemicals and Other Reagents

Primary and secondary antibodies include: Rabbit polyclonal anti-Synapsin1 (Bioworld, Cat#BS4116), Rabbit polyclonal anti-p-Synapsin1 (Cell signaling technology, Cat#2311), Rabbit polyclonal anti-Actin (Proteintech, Cat#20536-1-AP), Goat polyclonal anti-NRXN1α (LifeSpan BioSciences, Cat#LS-C61771), Goat anti-rabbit (Genscript, Cat#A00098), Alexa Fluor 488 donkey anti-goat IgG (Jackson ImmunoResearch, Cat#705-546-147), Alexa Fluor 555 donkey anti-rabbit IgG (Thermo-Fisher, Cat#A-31570). Drugs include: Picrotoxin (Sigma-Aldrich, Cat#R284556), D-APV (Tocris, Cat#0106), NBQX (Sigma-Aldrich, Cat#N183), Diamond Antifade Mountant (Thermo-Fisher, Cat#P36965), Nifedipine (Sigma-Aldrich, Cat#N7634).

Slice Electrophysiology

All the electrophysiological recordings were carried out as previously described [26-28]. Briefly, the mouse brains from wild type (WT) and APP KO mice were quickly removed, and sagittal 360 μm hippocampal slices were prepared in ice-cold artificial cerebrospinal fluid (ACSF) saturated with 95% O_2/5% CO_2. ACSF contained (in mM): 120.0 NaCl, 3.0 KCl, 1.2 $MgSO_4$, 1.0 NaH_2PO_4, 26.0 $NaHCO_3$, 2.0 $CaCl_2$, and 11.0 D-glucose. The slices were recovered at 28 ^oC for at least 2 hrs before a single slice was transferred to a submersion chamber perfused with 95% O_2 / 5% CO_2 saturated ACSF. For EPSC recording, 100 μM picrotoxin were used to block inhibitory response, and 50 μM D-APV&10 μM NBQX were used to record IPSC response. Hippocampal CA1 neurons were visualized using an infrared differential interference contrast microscope (Zeiss Axioscope or

Olympus X51). Synaptic response was evoked at 0.1 Hz for whole-cell currents, and recorded with glass pipettes (3-4 MΩ) filled with the intracellular solution containing (in mM) 130.0 $CsMeSO_4$, 5.0 NaCl, 1 $MgCl_2$, 0.05 EGTA, 10.0 HEPES, 3.0 Mg-ATP, 0.3 Na_3GTP, and 5.0 QX-314 (pH 7.5) (280-300 mOsm) at -65mV. The synaptic depletion is evoked by stimulating the Schaffer collateral at 5Hz for 180s. For the sucrose puff experiments, after the CA1 neuron was clamped at -65 mV, sucrose-induced current was evoked by a fast puff (70 seconds) delivered through a pipette (3-5 MΩ) filled with ACSF containing 100 μM picrotoxin and500 mM sucrose by using the PV830 Pneumatic Picopump (WPI). All recording data acquisition and analysis were done using the pCLAMP 10.2 (Axon Instruments). n in all recording figures represents the number of slices/neurons and normally only one or two slices from each animal were used.

Immunohistochemistry of Brain Sections

The procedures for brain processing and immunohistochemistry were described previously [28]. Mice were anesthetized by 10% chloral hydrate and subjected to cardiac perfusion with 0.1 M phosphate-buffered saline (PBS) followed by 4% paraformaldehyde . The brain was then dissected and further fixed in 4% PFA/PBS for 24 h, and then transferred to 30% sucrose/PBS solution for another 24 h. The brain was embedded in O.C.T. compound, frozen in liquid nitrogen and stored at -80 °C, before being sliced to 25 μm coronal crystat sections at -20 °C (Leica CM1950). Sections were washed with PBS, permeabilized by 0.1% Triton X-100 in PBS for 2 h, blocked with 10% fetal bovine serum for 1 h, and incubated with the NRX1α/p-Synapsin1 antibodies overnight at 4□ followed by appropriate secondary antibodies at 37 °C for 2 h. After washing, the stained coverslips were mounted with the ProLong Diamond Antifade mounting medium for image collections. Confocal images were obtained at room temperature on Zeiss LSM 700 at 2048 ×2048 pixels using Zeiss 5× (NA 0.15, dry) objective with the same settings and configurations for all samples within each experiment. All images were initially acquired through the Zen 2010 software (Zeiss).

AimImageBrowser software (Zeiss) was used to adjust the image brightness/contrast and extract a subregion. All measurements were performed using the ImageJ software (NIH).

Western Blot Analysis

Whole brain protein lysates were prepared from 4 to 5 week-old APP KO and WT littermates as previously described [26, 29]. One mouse brain was homogenized in a Dounce homogenizer with 1.5 ml ice-cold lysis buffer containing (in mM): 20 Tris-HCl (pH 7.5), 150 NaCl, 1 EDTA, 1 EGTA, 1% Triton X-100, 2.5 sodium pyrophosphate, 1 β-glycerophosphate, 1 Na3VO4, 20 NaF, and 1% protease inhibitor cocktail and phosphatase inhibitor (Roach) and kept at 4 ℃ for 40 min before debris was removed by centrifugation at 14,000g for 10 min. Synaptosomal protein lysate was prepared by using an extraction kit for synaptic proteins (87793, Pierce). For Nifedipine treatment experiments, brain slices (prepared as the slice electrophysiology section) were incubated with 10 μM Nifedipine in the oxygen saturated ACSF for 1 hour, then were homogenized with the above lysis buffer. The protein samples were mixed with 25% volume of 5×SDS loading buffer (250 mM Tris-HCl, 10% SDS, 0.5% bromophenol blue, 50% glycerol, 5% beta-mercaptoethanol, pH 7.4) for electrophoresis on a SDS-PAGE ployacrylamide gel and electrotransfered to a PVDF filter. The filter was then blocked with 5% dry milk in TBST (20 mM Tris-HCl, 9% NaCl, 1% Tween-20, pH 7.6) and incubated overnight at 4 ℃ with primary antibodies in TBST. Following washing and incubation with appropriate secondary antibodies, the filter was washed extensively and developed using an enhanced chemiluminescence (Thermo) method of detection and analyzed using the AlphaEaseFC software as per manufacturer's instruction. The amount of total protein loaded was controlled by normalizing each tested protein with anti-actin immunoreactivity on the same blot.

Statistical Methods

All the data in the graphs were presented as mean ± SEM and statistically evaluated by independent-samples t-tests. $p < 0.05$ was considered as significant (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

Results and Discussion

Increased Presynaptic RRP Size in APP KO Mice

Previous studies using cultured neurons showed that the readily releasable pool (RRP) size is increased in APP KO mice compared to wild type (WT) littermates [30]. To determine whether this alteration occurs in hippocampal slices, we used high concentration (500 mM) sucrose puffs to the Schaffer collateral area of acute hippocampal slices and recorded excitatory postsynaptic current (EPSC) in the CA1 pyramidal neurons (Fig. 1A). As shown in Fig. 1B, the application of sucrose evoked a significantly greater postsynaptic responses in APP KO compared to WT slices. These results suggest that the size of the RRP is greater in APP KO mice and that APP normally acts as a negative regulator of the RRP.

Elevated Synaptic Depletion in Response to High Frequency Stimulation in APP KO Mice

At presynaptic terminals, the reserve pool (RP) is thought to be important to replenish the RRP under intense neuronal activities [31, 32]. Therefore, we examined whether the size of the RP is altered in APP KO mice using high frequency stimulation. We recorded evoked EPSC from CA1 pyramidal neuron in response to a 5 Hz stimulation (lasting 180 s). As shown in Fig. 2A and 2B, both WT and APP KO mice showed initial facilitation followed by gradual depression of EPSCs. However, in APP KO slices, the depression was significantly faster and stabilized to a lower level compared to WT control (Fig. 2C and 2D). These results suggest that the size of the RP is reduced and/or its

trafficking to the RRP is impaired in APP KO mice. Thus APP deletion has opposing effects on the RRP and RP, suggesting that APP may play a key role in dynamic regulation between these two pools of synaptic vesicles at the excitatory synapse.

Enhanced Synaptic depletion at Inhibitory Synapses in APP KO Mice

In addition to excitatory synapses, APP has also been implicated in presynaptic release at inhibitory synapses [33]. Therefore, we also examined inhibitory postsynaptic currents (IPSC) in response to 5 Hz stimulation in APP KO mice. As shown in Fig. 3A and 3B, the IPSC amplitude decreased gradually in both WT and KO groups, but the depression was significantly greater in APP KO compared to WT mice (Fig. 3B and 3C). This result suggests that APP may play a general role in modulating vesicle dynamics at both excitatory and inhibitory synapses.

Increased Phosphorylated Synapsins in APP KO Mice

Synapsins (Syn) are a family of presynaptic proteins known to be involved in the regulation of dynamic transition of synaptic vesicles between RP to RRP via a phosphorylation-dependent pathway [32, 34]. They are also implicated in vesicles priming and fusion at the presynaptic membrane [35, 36]. To investigate whether the effect of APP deletion is related to synapsins, we examined the level of phosphorylated synapsin 1 in APP KO mice. As shown in Fig. 4A and 4B, while the total synapsin 1 was not altered, the amount of phosphorylated synapsin 1 at serine 9 [p-Syn (Ser9)] was significantly increased in APP KO compared to WT mice. To determine whether this change occurred at the synapse, we analyzed p-Syn1 (Ser9) using synaptosomal protein lysates and found that the level of p-Syn1 (Ser9) was also significantly higher in APP KO compared to WT mice (Fig. 4C and 4D). Immunostaining experiments of hippocampal sections generated similar results (Fig. 4E). These results indicate that APP deletion enhances synapsin 1 phosphorylation

and/or inhibits synapsin 1 dephosphorylation, suggesting that the effect of APP on vesicle dynamics may be mediated through phosphorylation/dephosphorylation of synapsins.

Rescue of p-Syn (Ser9) and Synaptic depletion by Inhibiting L-Type Calcium Channels

Previous studies have shown that synapsin 1 at Ser9 can be phosphorylated by Ca^{2+}/calmodulin - dependent protein kinase II (CaMKII) [37, 38] and that the level of L type calcium channel (LTCC) was increased in APP KO mice [39]. Therefore, it is possible that the increased p-Syn1 (Ser9) in APP KO mice was caused by the increased LTCC and subsequent Ca^{2+} influx. To test this hypothesis, we treated brain slices with the LTCC blocker nifedipine and then analyzed p-Syn1 (Ser9). As the shown in Fig. 4F, the level of p-Syn1 (Ser9) became similar between WT and APP KO slices. We then tested whether the elevated synaptic depletion in APP KO mice was also caused by altered LTCC function by treating brain slices with nifedipine followed by recording EPSC or IPSC in response to 5 Hz stimulation. As shown in Fig. 5, the APP KO and WT slices now exhibited similar depletion. Taken together, these results suggest that the effect of APP on synaptic depletion during high frequency stimulation is mediated by LTCC and subsequent Ca^{2+}-dependent phosphorylation of synapsins.

In summary, by using a combination electrophysiological recordings and biochemical analyses, we have demonstrated that APP KO mice have a larger RRP and faster synaptic depletion during high frequency stimulation. These synaptic changes are associated with elevated phosphorylated forms of synapsins. In addition, both changes in synapsins and synaptic deletions can be rescued by inhibiting LTCC. Our results are consistent with the idea that APP normally functions to suppress L type calcium channels, inhibit synapsin phosphorylation (or enhance dephosphorylation) and maintain a proper RP/RRP size. Future studies would be to determine exactly what kinases and phosphatases are responsible for synapsin phosphorylation/dephsophorylation that are regulated by APP and

whether manipulations of synapsins can rescue the deficits in APP KO mice. Elucidation of the APP-synapsin pathway would open a new avenue of investigation that may ultimately help understand the role of APP at the synapse and provide potential targets to treat AD.

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Figure Legend:

Fig. 1. Enhanced EPSC induced by high concentration sucrose in APP KO mice. (**A**) Sucrose application and whole-cell recordings in acute hippocampal slices. (**B**) Sample traces of 500 mM sucrose-induced EPSC responses recorded from CA1 neurons in WT (black) and APP KO (red)

mice. (**C**) Summary graph of the sucrose-induced EPSC peak values (WT: 41.975 ± 7.787 pA, n = 8; APP KO: 78.300 ± 10.658 pA, n = 10, p = 0.018).

Fig. 2. Faster synaptic depletion in response to high frequency stimulation in APP KO mice. (**A**) Sample traces of EPSC responses during 5 Hz stimulation (180 seconds) in WT and APP KO CA1 neurons. (**B**) Summary graph of normalized EPSC responses during the course of 180 seconds of 5 Hz stimulation. (**C**) Descending liner fitting curves of EPSC in WT and APP KO during the first 2 – 50 seconds of 5 Hz stimulation period (WT: y = 249.970 - 3.053x, APP KO: y = 271.721 - 4.503x). (**D**) Summary graph of ΔEPSC values during the first 4 – 20 seconds of 5 Hz stimulation (the 16^{th} second: WT: -40.208 ± 16.077, n = 10, APP KO: -87.488 ± 8.505, n = 7, p = 0.037; the 20^{th} second: WT: -50.344 ± 17.268, n = 10, APP KO: -107.051 ± 9.838, n=7, p = 0.023).

Fig. 3. Faster synaptic depletion during high frequency stimulation at inhibitory synapses in APP KO mice. (A) Sample traces of IPSC responses in response to 5 Hz stimulation (180 seconds) in WT and APP KO CA1 neurons. (**B**) Summary graph of normalized IPSC responses during the course of 180 seconds of 5 Hz stimulation. (**C**) Summary graph of ΔIPSC values during the first 4 – 20 seconds of 5 Hz stimulation (the 16^{th} second: WT: -13.599 ± 5.238, n = 7, APP KO: -34.023 ± 5.127, n = 9, p = 0.016).

Fig. 4. Elevated level of phosphorylated synapsin 1in APP KO mice. (**A**) Sample Western blots of total brain lysates and summary graph of p-Syn1 (Ser9) level (WT: 1.000 ± 0.000, n = 6, APP KO: 1.929 ± 0.269, n = 6, p = 0.006). (**B**) Sample Western blots of total brain lysates and summary graph of total synapsin 1 (WT: 1.000 ± 0.000, n = 5, APP KO: 1.031 ± 0.142, n = 5, p = 0.833). (**C**) Sample Western blots of synaptosomal protein lysate and summary graph of p-Syn1 (Ser9) (WT: 1.000 ± 0.000, n = 4, APP KO: 1.360 ± 0.160, n = 4, p = 0.004). (**D**) Sample Western blots of synaptosomal protein lysate and summary graph of total Syn1 (WT: 1.000 ± 0.000, n = 3, APP KO: 1.003 ± 0.079,

n = 3, p = 0.968). (**E**) Sample images of immunostained hippocampal sections (CA1 area) and summary graph of p-Syn1 (Ser9) immunofluorescence intensity (WT: 1.000 ± 0.187, n = 9, APP KO: 1.620 ± 0.203, n = 9, p = 0.009). (**F**) Sample Western blots of total protein lysates prepared from brain slices treated with nifedipine (WT: 1.000 ± 0.000, n = 4, APP KO: 1.113 ± 0.085, n = 4, p = 0.233).

Fig. 5. Nifedipine slows down synaptic depletion in APP KO mice. (**A**, **D**) Sample traces of EPSC (**A**) and IPSC (**D**) responses during 5 Hz stimulation in nifedipine-treated WT and APP KO CA1 neurons. (**B**, **E**) Summary graphs of normalized EPSC (**B**) and IPSC (**E**) response during the course of 180 seconds of 5 Hz stimulation in nifedipine-treated slices. (**C**, **F**) Summary graphs of ΔEPSC (**C**) and ΔIPSC (**F**) values during the first 4 – 20 seconds of 5 Hz stimulation (**C**; 16^{th} second: WT: -62.567 ± 11.703, n = 6; APP KO: -73.771 ± 7.026, n = 6, p = 0.431; 20^{th} second: WT: -80.705 ± 11.120, n = 6; APP KO: -97.753 ± 8.372, n = 6, p = 0.249. **F**; 16^{th} second: WT: -22.907 ± 9.700, n = 5; APP KO: -18.043 ± 8.826, n = 5, p = 0.720).