Nicotinic Acetylcholine Receptor-Mediated Neuroprotection by Donepezil Against Glutamate Neurotoxicity in Rat Cortical Neurons

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ABSTRACT

Donepezil is a potent and selective acetylcholinesterase (AChE) inhibitor developed for the treatment of Alzheimer’s disease. To elucidate whether donepezil shows neuroprotective action in addition to amelioration of cognitive deficits, we examined the effects of donepezil on glutamate-induced neurotoxicity using primary cultures of rat cortical neurons. A 10-min exposure of cultures to glutamate followed by a 1-h incubation with glutamate-free medium caused a marked loss of viability, as determined by Trypan blue exclusion. Glutamate neurotoxicity was prevented by 24-h pretreatment of donepezil in a concentration-dependent manner. Among AChE inhibitors examined, donepezil and certain AChE inhibitors such as tacrine and galanthamine showed potent neuroprotective action, although physostigmine did not affect glutamate neurotoxicity. Neuroprotective action of donepezil was antagonized by mecamylamine, a nicotinic acetylcholine receptor (nAChR) antagonist, but not by scopolamine, a muscarinic acetylcholine receptor antagonist. Furthermore, both dihydro-β-erythroidine, an α4β2-neuronal nAChR antagonist, and methyllycaconitine, an α7-nAChR antagonist, each also significantly antagonized the effect of donepezil. Next, we examined the effects of donepezil on glutamate-induced apoptosis. Exposure of 100 μM glutamate to cortical neurons for 24 h induced apoptotic neuronal death and nuclear fragmentation. Donepezil for 24 h before and 24 h during glutamate exposure prevented nuclear fragmentation and glutamate-induced apoptosis. These results suggest that donepezil not only protects cortical neurons against glutamate neurotoxicity via α4β2- and α7-nAChRs but also prevents apoptotic neuronal death.

Alzheimer’s disease (AD) is a progressive neurodegenerative disease. AD is characterized by the presence of two types of abnormal deposit, senile plaques and neurofibrillary tangles, and by extensive neuronal loss (Giannakopoulos et al., 1996). Although the pathogenesis of AD remains unknown, recent studies suggested that amyloid-β protein (Aβ) plays an important role in the neurodegeneration by the progress of the disease (Hardy and Selkoe, 2002). Involvement of glutamate cytotoxicity in various neurodegenerative diseases was suggested in previous studies (Choi et al., 1987; Bresnick, 1989). It was reported that Aβ increases the vulnerability of the cultured cortical neurons to glutamate cytotoxicity (Koh et al., 1990; Mattson et al., 1992). Thus, glutamate may play an important role in Aβ-induced cytotoxicity in the cerebral cortex.

Marked loss of the central cholinergic neurons is one of the hallmarks of the pathogenesis of AD brain (Whitehouse et al., 1982). Moreover, loss or down-regulation of the neuronal nicotinic acetylcholine receptors (nAChRs) has also been observed (Shimohama et al., 1986; Perry et al., 1995). Remarkably, nicotine was reported to inhibit Aβ toxicity (Kihara et al., 1997). Based on those findings, we previously examined the effects of nicotine and related compounds on neurotoxicity induced by glutamate. Nicotine protected cortical neurons against glutamate neurotoxicity via neuronal nAChRs including α4β2- and α7-nAChRs (Shimohama et al., 1996; Kaneko et al., 1997). These findings suggest that activation of neuronal nAChRs is effective in preventing neuronal loss in AD brain.

This study was carried out to examine the neuroprotective effects of acetyl cholinesterase (AChE) inhibitors developed for the treatment of AD. Donepezil is a potent inhibitor of AChE and the first agent used in the treatment of AD be-

ABBREVIATIONS: AD, Alzheimer’s disease; Aβ, amyloid-β protein; nAChR, nicotinic acetylcholine receptor; AChE, acetylcholinesterase; MEM, minimal essential medium; DHβE, dihydro-β-erythroidine; MLA, methyllycaconitine
cause donepezil shows modest improvement with minimal side-effects among other drugs enhancing central cholinergic functions (Kosasa et al., 1999, 2000; Ogura et al., 2000; Sugimoto et al., 2000). Thus, special attention was paid to investigate the effect of donepezil on glutamate neurotoxicity, and we found that donepezil protected cultured cortical neurons against not only neurotoxicity induced by brief exposure to glutamate but also apoptosis induced by long exposure.

**Materials and Methods**

**Materials.** Eagle’s minimal essential medium (MEM) was purchased from Nissui Pharmaceutical (Tokyo, Japan). Drugs and sources were as follows: L-glutamic acid monosodium salt was from Nacalai Tesque (Kyoto, Japan); dihydro-β-erythroidine-HBr and methyllycaconitine citrate were from Research Biochemicals International (Natick, MA); galanithamine-HBr, tacrine, metrifonate, neostigmine bromide, physostigmine (eserin sulfate), pyridostigmine bromide, mecamylamine-HCl, (-)-scopolamine-HBr, and (+)-diazocilpine maleate ([+]-MK-801) were from Sigma-Aldrich (Saint Louis, MO); DEVD-CHO, 2-[2-(4-hydroxyphenyl)-6-benzimidazoyl]-6-(1-methyl-4-piperazyl)-benzimidazole-3HCl (Hoechst 33258) was from Carbiochem (Darmstadt, Germany); and donepezil hydrochloride ([-]-2-[1-benzylpiperidin-4-yl]methyl)-5,6-dimethoxy-indan-1-one monohydrochloride; E2020] was supplied by Eisai Co. Ltd. (Tsukuba-shi, Japan).

**Cell Culture.** Primary cultures were obtained from the cerebral cortex of fetal Wistar rats (17–19 days of gestation) according to the procedures described previously (Kume et al., 1997, 2000). Briefly, single cells dissociated from the whole cerebral cortex of fetal rats were plated on plastic coverslips placed in Falcon 60-mm dishes and 12-well plates (5.1 × 10⁶ cells/dish).

Cultures were incubated in Eagle’s MEM supplemented with 10% heat-inactivated fetal bovine serum (1–7 days after plating) or 10% heat-inactivated horse serum (8–13 days after plating), glutamine (2 mM), glucose (total 11 mM), NaHCO₃ (24 mM), and HEPES (10 mM). Cultures were maintained at 37°C in a humidified 5% CO₂ atmosphere. Six days after plating, non-neuronal cells were removed by adding cytosine arabinoside (10 μM). Only mature cultures (10–13 days in vitro) were used for experiments.

**Measurement of Neurotoxicity.** Neurotoxicity induced by glutamate was quantitatively assessed by examining cultures under Hoffman modulation microscopy according to the methods described previously (Kume et al., 1997, 2000). All experiments were performed in Eagle’s MEM at 37°C. Cell viability was assessed by Trypan blue solution for 10 min at room temperature, fixed with isonic formalin (pH 7.0, 2–4°C), and rinsed with physiological saline. In each experiment, the cells on five coverslips were counted to obtain the means ± S.E.M. of cell viability.

**Hoechst Staining.** To reveal the nuclear morphological changes in cultured neurons, cells were stained with a nuclear dye Hoechst 33258 according to the methods described previously (Osakada et al., 2003). Briefly, after glutamate treatment, cultures were fixed with neutral formaldehyde for 30 min and incubated with 1 mg/ml Hoechst 33258 for 30 min at room temperature. Cells were visualized and photographed under ultraviolet illumination using fluorescent microscopy (Olympus, Tokyo, Japan).

**Statistics.** Values are shown as means ± S.E.M. The statistical significance was evaluated by Dunnett’s two-tailed test and defined as a probability value of less than 5%.

**Results**

**Effects of Donepezil on Glutamate Neurotoxicity.** The exposure of cultured cortical neurons to glutamate markedly reduced cell viability (Fig. 1). Trypan blue exclusion revealed that the cell viability was decreased by 10-min treatment with 1 mM glutamate, whereas most of the cells without drug treatment had nonstained, bright cell bodies. We examined the effects of donepezil on this glutamate neurotoxicity. Treatment of cultures with donepezil (1 μM) for 24 h before glutamate treatment. Scale bar = 50 μm.

![Fig. 1. Microphotographs showing effects of donepezil on glutamate neurotoxicity. Culture fields were photographed after Trypan blue staining followed by formalin fixation. A, shows the cells with sham treatment. B, shows the cells treated with glutamate (1 mM) for 10 min and further incubated with glutamate-free medium for 1 h. C, shows the cells exposed to donepezil (1 μM) for 24 h before glutamate treatment. Scale bar = 50 μm.](https://doi.org/10.1091/0021-9525.1999.137.773)
suggest that the long-term exposure of donepezil is necessary to exhibit a protective action against glutamate neurotoxicity.

The magnitude of the protective effect of donepezil against glutamate neurotoxicity increased in a concentration-dependent manner when the long-term exposure was employed (Fig. 3). Cultures were treated with donepezil at concentrations ranging from 0.001 to 10 μM. Donepezil at concentrations greater than 0.1 μM significantly protected cortical neurons against glutamate neurotoxicity.

**Effects of AChE Inhibitors on Glutamate Neurotoxicity.** Table 1 summarizes IC50 values of AChE inhibitors in previous studies (Arnal et al., 1990; Tang et al., 1996; Rakonczay et al., 1998; Ogura et al., 2000). IC50 values of donepezil for AChE were reported to be 6.7 to 13.6 nM (Tang, 1996; Ogura et al., 2000). That the neuroprotective effect of donepezil was observed at higher concentrations than IC50 values for AChE suggested that donepezil protected cortical neurons against glutamate neurotoxicity through mechanisms other than AChE inhibition.

Among other drugs enhancing central cholinergic functions, donepezil is one of the most potent and selective anti-dementia drugs, which show modest improvement with minimal side-effects (Ogura et al., 2000; Sugimoto et al., 2000). We compared the effect of donepezil with that of various AChE inhibitors. We tested the effects of four groups of AChE inhibitors at the same concentration (1 μM). The first group includes tacrine and galanthamine, which are approved for AD treatment. The second group was physostigmine, a potent AChE inhibitor, but is not approved for AD treatment. The third includes neostigmine and pyridostigmine, quaternary ammonium compounds unable to pass through the membrane. The fourth group was metrifonate, an irreversible AChE inhibitor. As shown in Fig. 4, all drugs, except for physostigmine, showed significant protective effects against glutamate neurotoxicity. Statistical analysis revealed that donepezil and galanthamine of the first group showed more potent neuroprotective effects than the drugs of the other groups. By contrast, tacrine showed more potent effect than

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<th>Drug</th>
<th>IC50a (nM)</th>
<th>IC50b (nM)</th>
<th>IC50c (nM)</th>
<th>IC50d (nM)</th>
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<tr>
<td>Donepezil</td>
<td>6.7 ± 0.35</td>
<td>13.6</td>
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<tr>
<td>Tacrine</td>
<td>77 ± 1.4</td>
<td>450</td>
<td>93.0</td>
<td>80</td>
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<td>Galanthamine</td>
<td></td>
<td>1995</td>
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<tr>
<td>Physostigmine</td>
<td>0.67 ± 0.015</td>
<td>18</td>
<td>251</td>
<td>60</td>
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<tr>
<td>Neostigmine</td>
<td>25</td>
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<tr>
<td>Pyridostigmine</td>
<td></td>
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<td>Metrifonate</td>
<td>1080</td>
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**a** IC50 values for AChE in the rat brain are taken from Ogura et al. (2000).
**b** IC50 values for AChE in human cortex are taken from Rakonczay et al. (1998).
**c** IC50 values for AChE in the rat cerebral cortex are taken from Tang (1996).
**d** IC50 values for AChE in the mouse brain are taken from Arnal et al. (1990).
phystostigmine but not other drugs of the third and fourth groups.

**Effects of Nicotinic Receptor Antagonists on the Neuroprotection by Donepezil.** Previously, we reported that nicotine protected cortical neurons against Aβ- or glutamate-induced neurotoxicity via nAChRs (Shimohama et al., 1996; Kaneko et al., 1997; Kihara et al., 1997). To determine the involvement of nAChRs in the neuroprotective effects of donepezil, we examined the effects of mecamylamine, an nAChR antagonist, and scopolamine, a muscarinic acetylcholine receptor antagonist, on the neuroprotective action of donepezil. Each antagonist was added to donepezil-containing medium. As a result, mecamylamine (10 μM) but not scopolamine (10 μM) significantly antagonized the protection by 24-h pretreatment with 10 μM donepezil (Fig. 5), suggesting that nAChRs play a crucial role in the neuroprotective effect of donepezil.

To elucidate the nicotinic receptor subtypes mediating the neuroprotective action of donepezil, we used the following antagonists: dihydro-β-erythroidine (DHβE), an α4β2-nAChR antagonist, and methyllycaconitine (MLA), an α7-nAChR antagonist. Each antagonist was added to donepezil-containing medium. Both DHβE (10 nM) and MLA (10 nM) significantly antagonized the protective effect of donepezil (Fig. 6).

**Effects of Donepezil on Glutamate-Induced Apoptosis.** Next, we investigated whether donepezil could prevent apoptosis. Exposure of 100 μM glutamate to cortical neurons for 24 h induced nuclear fragmentation (Fig. 7) and neuronal death (Fig. 8). To address whether caspase-3 activation contributes to 24 h glutamate neurotoxicity, we used DEVD, a caspase-3 inhibitor. Treatment of cultures with DEVD (1 μM) for 24 h before and 24 h during glutamate exposure prevented nuclear fragmentation (Fig. 7) and neuronal death (Fig. 8). Cycloheximide, a protein synthesis inhibitor, and actinomycin D, an RNA synthesis inhibitor, also prevented 24 h glutamate neurotoxicity (data not shown). Taken together with these results, we considered 24 h glutamate neurotoxicity was mediated through apoptosis. Donepezil (1 μM) for 24 h before and 24 h during glutamate exposure prevented nuclear fragmentation (Fig. 7) and glutamate-induced apoptosis (Fig. 8).

**Discussion**

In the present study, we demonstrated that donepezil protected cultured cortical neurons against glutamate neurotoxicity. The neuroprotective action of donepezil was prominent among various types of AChE inhibitors examined. In addition, the neuroprotective effect of donepezil was inhibited by selective antagonists for α4β2- and α7-nAChRs. Furthermore, donepezil prevented glutamate-induced apoptosis.

Donepezil prevented glutamate neurotoxicity when the cultures were treated with glutamate 24 h before, 10 min during, and 1 h following glutamate exposure. In contrast, concomitant addition of donepezil and glutamate did not exhibit a protective action. This suggests that a prolonged donepezil treatment before glutamate exposure is necessary to elicit a neuroprotective effect. Since the effect of donepezil was antagonized by nAChR antagonists, some possible hypotheses could be proposed. First, donepezil may induce neuroprotective factors by stimulating nAChRs. Greenberg et al. (1986) demonstrated the regulation of c-fos transcript levels following nAChRs activation in PC12 cells. The regulation of gene expression by nAChRs stimulation suggests that donepezil can induce the transcription factor-regulated synthesis of neuroprotective factors via nAChRs. Second, long-time exposure of donepezil may up-regulate the expression of nAChRs, which would potentiate nAChR-mediated neuroprotective effects. In addition to nicotine, donepezil or certain AChE inhibitors approved for AD treatment were reported to up-regulate the expression of nAChRs (Barnes et al., 2000; Svensson, 2000; Woodruff-Pak et al., 2001). Although it was known that α7-nAChRs were inactivated by nicotine, Kawai and Berg (2001) recently showed that the expression of nAChRs containing the α7-subunit was up-regulated by nic-
otine exposure without undergoing inactivation. These previous findings suggest that the long-term exposure of donepezil at higher concentration than IC50 value of AChE would elicit up-regulation of neuronal nAChRs, which may lead to potentiate neuroprotective effects against glutamate neurotoxicity.

Among AChE inhibitors examined in the present study, donepezil and galanthamine, which are currently available for AD treatment (Stahl, 2000), showed more potent neuroprotective effects than physostigmine, neostigmine, pyridostigmine, and metrifonate. Donepezil and galanthamine have similar neuroprotective effects on glutamate neurotoxicity, although the IC50 value of these inhibitors for AChE were very different (Table 1). Thus, it is likely that donepezil and galanthamine protect cortical neurons against glutamate neurotoxicity through mechanisms other than AChE inhibition. Interestingly, galanthamine was reported to interact with nAChRs directly and sensitize nAChRs by increasing the probability of channel opening and by slowing down receptor desensitization (Coyle and Kershaw, 2001; Maelicke et al., 2001). These allosterically potentiating ligand actions of galanthamine were observed in both α4β2- and α7-nAChRs (Maelicke, 2000; Samochocki et al., 2000). Nevertheless, a recent study showed that galanthamine, but not donepezil, acting primarily as an allosteric potentiating ligand at presynaptically located nAChRs, potentiated glutamatergic transmission in rat hippocampal slice (Santos et al., 2002). As various experimental conditions including culture preparation and drug administration are different, however, further investigations are required to explain the nAChRs-mediated neuroprotection by donepezil.

α4β2- and α7-nAChRs are involved in cognitive processes in the brain in addition to neuroprotection (Changeux et al., 1998). α7-nAChRs were reported to bind Aβ 1-42 (Wang et al., 2000), and this binding might inhibit α7-nAChR-dependent learning and memory. The reduction of α7-nAChRs activation would cause neurons vulnerable to various toxic insults such as glutamate. Recent findings suggested that α7-nAChRs activation led to the neuroprotection against glutamate neurotoxicity via the Ca2+-dependent phosphatidylinositol 3-kinase pathway, and that nicotine protected neurons by activating phosphatidylinositol 3-kinase, which activated Akt and up-regulated Bcl-2 (Kihara et al., 2001). Furthermore, Ca2+ influx through α7-nAChRs could activate Ca2+/calmodulin-dependent protein kinase-2 in PC12 cells (MacNicol and Schulman, 1992), resulting in nitric-oxide synthase-1 inactivation by its phosphorylation (Nakane et

Fig. 6. Effects of α4β2- and α7-nAChRs antagonists on donepezil-induced neuroprotection against glutamate neurotoxicity. We used DHβE (10 nM) as an α4β2-nAChR antagonist and MLA (10 nM) as an α7-nAChR antagonist. Donepezil and antagonists were added for 24 h before application of glutamate. **, P < 0.01 compared with glutamate alone; ##, P < 0.01. Data represent the means ± S.E.M. of n = 5 independent observations.

Fig. 7. Microphotographs showing effects of donepezil and caspase-3 inhibitor on glutamate-induced apoptosis. We used DEVD as a caspase-3 inhibitor. Culture fields were photographed after Hoechst 33258 staining followed by formalin fixation. A, shows the cells with sham treatment. B, shows the cells treated with glutamate (100 μM) for 24 h. C, shows the cells exposed to donepezil (1 μM) for 24 h before glutamate treatment. D, shows the cells exposed to DEVD (1 μM) for 24 h before glutamate treatment. Arrowheads indicate nuclear fragmentation. Scale bar = 10 μm.

Fig. 8. Effects of donepezil and caspase-3 inhibitor on glutamate-induced apoptosis. Cultures were pretreated by donepezil (1 μM), DEVD (1 μM), and (+)-MK-801 (1 μM) for 24 h before 100 μM glutamate application for 24 h. **, P < 0.01, compared with glutamate alone. Data represent the means ± S.E.M. of n = 5 independent observations.
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al., 1991). We previously reported that the neuroprotective effect of nicotine via α4β2- and α7-nAChRs was effective against glutamate neurotoxicity (Kaneko et al., 1997). Thus, these findings suggest that the neuroprotective action of donepezil via α4β2- and α7-nAChRs may be mediated by the same mechanisms to nicotine.

Finally, we investigated the effects of donepezil on apoptotic neuronal death. Twenty-four hours exposure of glutamate induced apoptotic neuronal death. Donepezil prevented glutamate-induced apoptosis when the cultures were treated with donepezil for 24 h before and 24 h during glutamate exposure. A recent study showed that donepezil did not prevent apoptosis induced by staurosporine in NG108-15 and HeLa cell lines (Zhang et al., 2002). However, effects of donepezil on apoptosis in neuronal cells did not understood. In the present study, we showed donepezil prevented glutamate-induced apoptosis in cortical neurons. To our knowledge, this is the first report that donepezil prevented neuronal apoptosis.

In conclusion, it was shown that donepezil protected cortical neurons against glutamate neurotoxicity via neuronal α4β2- and α7-nAChRs. In addition, donepezil prevented glutamate-induced apoptosis. The present findings suggest that donepezil shows neuroprotective action in addition to amelioration of cognitive deficits.

References


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