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Calpain inhibition prevents amyloid-β-induced neurodegeneration and associated behavioral dysfunction in rats

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1. Introduction

According to the amyloid-β-hypothesis of Alzheimer’s disease (AD) accumulation of Aβ in brain parenchyma – possibly in its soluble form – causes a degeneration of neurons and their processes in brain areas involved in memory formation (Selkoe, 2008). Among the first regions to be affected are the hippocampus and the nucleus basalis of Meynert. The latter provides the majority of cholinergic input to neocortical structures and plays an essential role in attention and information storage (Blokland, 1995; Van der Zee and Luiten, 1999). Damage and the selective degeneration of the nucleus basalis of Meynert provide the morphological correlate of the cortical cholinergic deficiency in AD. The loss of this discrete cholinergic neuronal population leads to an impairment of higher cortical functions, which is directly related to the progressive deterioration of memory and attention, and cognitive processes in affected patients.

A number of studies suggest that Aβ-induced toxicity in AD is caused by excessive glutamate stimulation, over activation of the NMDA receptor, and subsequent calcium accumulation in the postsynaptic neuron (Harkany et al., 2000; Molnár et al., 2004; Mattson et al., 2000). Recently, the pathology of Aβ has been
correlated to oligomeric forms of the peptide (for review see Walsh and Selkoe, 2007), and studies indicate an involvement of the NMDA receptor also in oligomer toxicity (Shankar et al., 2007). Although the exact mechanism of this process is not fully understood, there is evidence that calpains, Ca2+-dependent cystein proteases, are components of the downstream cascade. Inhibition of calpains prevents excitotoxic neuronal cell death in vitro (Caba et al., 2002; Ray et al., 2006) and in vivo (Chiu et al., 2005; Takano et al., 2005), and there is evidence that calpain cleaves several downstream targets that are critical for the progression of excitotoxic neurodegeneration (Hou et al., 2006; Wu et al., 2004). Calpains have therefore been discussed as a target for interference in the neurodegenerative diseases that are associated with neuronal loss (for review see Huang and Wang, 2001; Goll et al., 2003; Zatz and Starling, 2005).

Using a specific low molecular weight inhibitor, A-705253 (Lubisch et al., 2003), we have recently shown that inhibition of calpain completely prevents NMDA-induced excitotoxic lesions of the nucleus basalis magnocellularis (NBM), the rat analog of the nucleus basalis of Meynert in humans. A-705253 also fully protected from behavioral deficits that accompany such lesions (Nimmrich et al., 2008). Although excitotoxicity is likely to contribute to the pathology of AD, this study did not reveal whether neuronal decline could also be prevented, if the insult was induced by Aβ. To provide this missing link we assessed whether calpain inhibition would protect from Aβ-induced degeneration of the NBM, and whether such treatment would protect from associated cognitive decline of the rats.

As oligomeric Aβ is now thought to underlie the pathology of the disease, we generated Aβ-oligomers in vitro and used such oligomer preparation – rather than the monomeric peptide – to induce NBM degeneration in rats. Lesioning of the NBM causes a decline of cholinergic projections, mimicking the characteristic loss of forebrain cholinergic innervation in AD (Bartus et al., 1982; Gaykema et al., 1992).

Here we present data showing that calpain inhibition prevents Aβ-oligomer-induced neurodegeneration of NBM and associated decrease of cortical cholinergic innervation. Furthermore, calpain inhibition attenuates cognitive deficits that occur as a result of such neurodegeneration.

NMDA receptor activation is an early step in the excitotoxic cascade, and compounds targeting the NMDA receptor have to be administered in close time proximity of the toxic stimulus. Calpain activation lies further downstream in this cascade, thus offering an opportunity to interfere with cell death signaling at later time points. We therefore added to this study an in vitro analysis of the time course of the calpain application relative to the point of insult. Calpain inhibition is also neuroprotective when initiation of the toxic insult has already been initiated.

2. Materials and methods
2.1. Calpain inhibitor

Calpain inhibitor A-705253 was solubilized in DMSO (Sigma–Aldrich, St. Louis, USA) and stored as 1 M stock at -20 °C. Working stock solutions with different concentrations of A-705253 were prepared in ultrapure water containing 0.02% sodium chloride with a pH between 5 and 5.5. The solution was prepared freshly before use.

2.2. Preparation of Aβ-oligomers

Oligomeric Aβ1–42 was prepared as was described by Dahlgren et al. (2002). In short, solid Aβ1–42 peptide (EZBiolabs, Carmel, USA) was dissolved in 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP) (Sigma–Aldrich, St. Louis, USA) to a concentration of 1 mM. The peptide solution was aliquoted and the HFIP removed by evaporation in a SpeedVac (Savant Instruments, Hyderabad, India). The dry peptide films were stored at -20 °C until further processing. Before use Aβ1–42 films were dissolved in anhydrous DMSO to 5 mM and subsequently diluted in neurobasal medium to a final concentration of 100 μM (stock solution). The stock solution was incubated at 4°C for 24 h to enable Aβ1–42 oligomerization.

2.3. Animals

All animals were purchased from Harlan (Horst, The Netherlands). For the in vitro experiments, we used male Wistar rats of 3.5 months of age. For the in vitro experiments we used female C57BL/6J mice (12 weeks old). During the experiment animals were kept under normal laboratory conditions in an air-conditioned room (21 ± 2 °C) with a 12/12 h light dark cycle (lights on at 07:00 h) with food and tap water ad libitum. All care and treatments were carried out in accordance with the European Communities Council Directive on the use of experimental animals.

2.4. Nucleus basalis lesion

Surgery was performed as described in Luiten et al. (1995). The animals were anaesthetized with Nembutal (sodiumpentobarbital, 60 mg/kg i.p.). The coordinates for the injection in the nucleus basalis magnocellularis (NBM) were 1.5 mm posterior to bregma, 3.2 mm lateral to midline as defined by the atlas of Paxinos and Watson (1986). A 5 μl Hamilton syringe was lowered into the brain, followed over 10 min by two injections of 0.5 μL of the freshly prepared solution of Aβ1–42 oligomers (250 pmol each) diluted in 0.01 mM phosphate buffer pH 7.4 unilaterally at two dorsoventral positions, 6.0 mm and 6.7 mm ventral to the dura. The final injection amount of the peptide therefore was amounted to 500 pmol per animal. For sham-operated animals two times 0.5 μl phosphate buffered physiological saline solution were infused (0.01 mM pH 7.4 PBS) containing equivalent amount of DMSO, which served for sham-injection. After each injection the needle was left in situ for another 10 min to allow for diffusion and to limit spread of the solution during withdrawal of the needle. Brain injections were performed only in the right hemisphere and the left hemisphere was left undisturbed and served for the self-control side for the histological examinations.

The animals received the calpain inhibitor A-705253 intraperitoneally in doses of 1, 3, and 10 mg/kg of body weight, 1 h before, 12 h after and twice a day for two consecutive days after surgery (for experimental design see Fig. 1).

2.5. Small open-field behavior

A moderate novelty-induced behavioral activation and habituation to a dimly lit home-cage like novel environment was tested in this paradigm (Nimmrich et al., 2008). The test also reflected the general behavioral condition after experimental manipulations, since it was performed 3 days after the surgery. Every 10 s the following behaviors were scored by behavioral sampling technique: a) rearing, b) sniffing with head turning, c) walking, d) grooming, and e) immobility (resting).

Exploration was expressed by a combined score of rearing, sniffing and walking (exploration = 3 × rearing + 1 × sniffing + 2 × walking scores). The representative scores of each behavioral component were summed up in 5 min blocks and analyzed statistically.

2.6. Novel object recognition

Testing the ability of rats to recognize a novel object in an otherwise familiar environment represents a sensitive and discriminating test to assess memory performance. Novel object recognition was measured in a conventional cylindrical environment.

Fig. 1. Schematic outline of the experimental setup for the in vivo experiments. Rats received in total 6 intraperitoneal injections of the calpain inhibitor A-705253 or saline. The first injection was given 1 h prior to unilateral Aβ lesions into the nucleus basalis magnocellularis, the other 5 injections followed within two consecutive days after the lesion. From the fourth day on (after the lesion) the rats were subjected to different behavioral tests. Ten days after the lesion the animals were transcardially perfused and the brains removed for immunohistochemical analysis.
open-field box of 80 cm diameter, in which the floor was divided into 20 sectors and surrounded by a 60 cm high reflective aluminum wall (Nyakas et al., 2009).

During the first day the rats were allowed to habituate to the apparatus and their open-field behavior was recorded for 3 min (conventional open field). The test was carried out the day following to the 3 min open-field test and consisted of 2 sessions. During the 1st session the rats were allowed to explore in the open-field apparatus for 5 min while two identical objects (A + A) were placed into the arena. During the 2nd session, carried out 2.5 h after the 1st session, one of the two objects was replaced by a novel one (B + A). The ratio of visiting the novel versus known objects indicated the object recognition ability, i.e. attention behavior. The number and the period in sec spent with exploration of the objects during the 1st and 2nd sessions were recorded. The recognition ability of the novel object at the 2nd session was calculated in the following way: duration of exploration of the novel (B) object was divided by the duration of exploration of both novel (B) and familiar (A) objects and expressed in percentage. The criterion to pass the test was that both objects had to be visited at least 5 times during the first session representing sufficient interest for object exploration. From the 57 animals only one failed to perform the test, thus statistical analysis was conducted on 56 animals.

2.7. Brain tissue processing

At postoperative day 10 the animals were transcardially perfused under deep pentobarbital anesthesia with a fixative solution of 4% paraformaldehyde in 0.1 M phosphate buffer pH 7.4 after a short pre-rinse with heparinized saline. The brains were removed, post fixed for 2 days in the same fixative and stored in phosphate buffer at 0 °C. cryoprotected by 30% sucrose for 4 days and sectioned on a cryostat microtome at a thickness of 20 μm. Vials processed for immunostaining contained every 10th section at the level of NBM, i.e. the serial sections positioned 200 μm apart. Free floating brain sections were processed for immunocytochemical staining.

2.8. ChAT staining of cholinergic fibers

Immunostaining procedure was applied to visualize choline-acetyltransferase (ChAT) positive cholinergic neurons in NBM and their axon ramifications in the target brain areas selecting parietal neocortex. Goat anti ChAT primary antibody (AB144P; Lot: LV1359401; Chemicon International, Temecula, CA, USA) was used in a dilution rate of 1:1500 to recognize activated microglia. The biotinylated second antibody and the ABC kit were obtained from Vector Labs (CA, USA, see above). DAB reaction was enhanced by nickel enhanced diaminobenzidine (DAB) reaction in the presence of H2O2.

2.9. Microglial activation

Mouse anti rat integrin αM (CD11b) monoclonal antibody (CLB1512; Lot: 0604026553; Chemicon International, Temecula, CA, USA) was used as first antibody in a dilution rate of 1:1500 to recognize activated microglia. The biotinylated secondary antibody and the ABC kit were obtained from Vector Laboratories (CA, USA). The staining was completed with nickel-enhanced diaminobenzidine (DAB) reaction in the presence of H2O2.

2.10. Quantification of cortical cholinergic innervation

2.10.1. Reduction in cholinergic fiber density and cholinergic neurons

The quantification procedure for cholinergic fiber density in the parietal neocortex was established in our laboratory and described in detail in a series of previous publications (Horváth et al., 2000; Harkany et al., 2001; Dolga et al., 2009). Briefly, parietal neocortex which is topographically the target of different cholinergic pathway from the NBM sites where the Aβ(42) oligomers were injected, was analyzed for ChAT positive fiber density with a Quantimet 600HR (Leica, Germany) image analysis program. The exact measurement took place in the superficial sublayer of the layer V cortica area representing the densest zone of cortical cholinergic innervation. In addition we determined the number of ChAT positive neurons in the NBM. Three brain sections were analyzed for each experimental animal and the results were averaged. Percent surface area of positively stained fibers against zero background and number of positively stained neurons were computed in both sides of the brain section. The ChAT positive fiber density and NBM cell count ipsilaterally to the lesion was compared to the intact contralateral side and the percent decrement was calculated as an indicator of cholinergic degeneration.

2.10.2. Magnitude of microglial reaction

The magnitude of microglial activation was quantified with by image analysis measuring the extent of CD11b-immunoreactive microglia in a specific volume at the level of the lesion site (total infiltration volume). Therefore, a series of positively stained sections were used to reconstruct the extent of activation area. At each section the surface area of core structure around the injection channel and the size of infiltration area were measured with the Quantimet 600 system (Leica, Germany) by means of manual delineation of the affected area. Based on these measurements the total volume of the infiltrated brain area was computed: \((x_1 + x_2 + \ldots + x_n) \times 200 \, \mu m^2\), where \(x\) was the cross-sectioned stained area in \(\mu m^2\) and 200 μm was the distance between two consecutive sections. The volume of affected brain area was expressed in \(\mu m^3\).

2.10.3. Primary cortical neuron culture

Primary cortical neurons were prepared from embryonic brains (E14 of C57BL/6j mice. The cortices were carefully dissected, mesenges were removed and the neurons separated by trituration. Cells were plated on poly-D-lysine pre-coated plates at a density of \(1.2 \times 10^5\) cells/well (96 well plates). Neurobasal medium supplemented with 2% (v/v) B27-supplement, 0.5 mM glutamine, 1% (v/v) penicillin/streptomycin was used as a culture medium. After 48 h neurons were treated with 10 μM cytosine arabinoside for another 48 h to inhibit non-neuronal cell growth. Subsequently, the medium was completely exchanged with fresh medium and after 6 days of in vitro culture, the neurons were used for experiments.

2.10.4. Treatment of cells

The neuroprotective effect of A-705253 was assessed by incubating neurons (cultured in 96 well plates) for 24 h with 25 μM or 50 μM oligomeric Aβ in the presence or absence of different concentrations of A-705253. After the treatment the cell viability was determined by an MTT-assay. All treatments were performed in triplicates and the experiments were repeated at least two times.

2.10.5. Determination of cell viability by MTT-assay

Neuronal viability was determined by the colorimetric MTT [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide] assay as described previously (Mosmann, 1983). 1.25 mg/ml MTT solution was added to each well of a 96 well plate. After 2 h of incubation, cells were lysed in DMSO. The absorbance of each well was measured with an automated ELISA plate reader (Bio-Rad, Munich, Germany) at 595 nm with a reference filter at 630 nm.

2.10.6. Statistics

The Statistica 8 package was applied for one-way ANOVA evaluation of the results of independent groups which was followed by Dunnett post hoc t-test to reveal differences between two selected groups. The level of \(p < 0.05\) was accepted as significant. Data are presented as means ± S.E.M.

3. Results

3.1. A-705253 protects neurons against Aβ42-induced toxicity in vitro

To investigate the neuroprotective properties of A-705253 against Aβ42-induced toxicity, we treated primary cortical neurons with different concentrations (0.04–5 μM) of the calpain inhibitor and challenged with 25 μM or 50 μM of oligomeric Aβ42 for 24 h. Our results show that the calpain inhibitor A-705253 in the present condition protects primary cortical neurons against oligomeric Aβ42. Moreover, we found that concentrations in the range of 1 μM of A-705253 in the current experimental setup are most effective (Fig. 2A).

Furthermore, we were interested if the temporal dynamics of the treatment is important for the neuroprotective effect. Therefore we applied 1 μM A-705253 2 h and 1 h before, 1 h and 2 h after, or together with the Aβ42 challenge. We found that pre-treatment, or simultaneous treatment of A-705253 with Aβ42 was fully protective against Aβ induced toxicity (Fig. 2B). Interestingly, when neurons were treated 1 h after the insult, calpain inhibition still exerted a significant neuroprotective effect. However, application of the compound could not prevent neuronal damage when applied 2 h after the insult.

3.2. Calpain inhibition prevents Aβ42-induced degeneration of cholinergic fibers and neurons after lesion of the nucleus basalis magnocellularis

Recently, we demonstrated that the inhibition of calpain can protect cholinergic neurons against an NMDA-initiated excitotoxic insult (Nimmrich et al., 2008). Although excitotoxicity is likely to contribute to the pathology of AD, this study did not reveal whether neuronal decline could also be prevented, if the insult was induced by Aβ. To assess the sensitivity of cholinergic neurons to Aβ-induced toxicity we injected oligomeric Aβ42 into the NBM and quantified the loss of cholinergic neurons and their cortical innervations that originate from the NBM (Fig. 3) (Gaykema et al., 1992). Cholinergic neurons and fibers were visualized with the cholinergic marker ...
choline-acetyl transferase (ChAT, EC3.2.1.6) (Harkany et al., 2000). The fiber density was measured in the superficial sublayer of the layer V as described earlier (Horváth et al., 2000). The cholinergic fiber density (Fig. 3A and B) and the number of neurons (Fig. 3C and D) ipsilaterally to the lesion was compared with the intact contralateral side respectively. The percentage of fiber and neuronal loss in the various experimental groups is summarized in Fig. 4. Injection of oligomerized Aβ42 into the NBM led to a loss of 40.6 ± 2.3% in cholinergic neurons, which is a 26.78% higher depletion compared to the lesioned control, and that over activation of the NMDA receptor should be considered in part, on proper neocortical information processing. In a previous study we could show that a lesion of the NBM in rats leads to pathological effect of Aβ-42-lesioned group showed less attention towards the novel object as compared to the controls treated with vehicle. The amyloid-injected and drug treated groups performed all better than the lesioned control, and even the dose of 1 mg/kg A-705253 was effective in preventing Aβ42-induced memory deficits (see Fig. 6D).

3.5. A-705253 prevents Aβ-induced memory deficits in a novel object recognition paradigm

Cholinergic neuronal projections from the NBM are well known to directly modulate neocortical attentional and memory functions. The novel object recognition task is a learning task which depends, in part, on proper neocortical information processing. In a previous study we could show that Aβ-42-lesioned group showed less attention towards the novel object as compared to the controls treated with vehicle. The amyloid-injected and drug treated groups performed all better than the lesioned control, and even the dose of 1 mg/kg A-705253 was effective in preventing Aβ42-induced memory deficits (see Fig. 6D).

4. Discussion

Soluble, oligomeric forms of Aβ42 are increasingly associated with the neuropathological mechanisms of AD. Whereas the toxicity of Aβ-42 oligomers has been demonstrated in multiple studies, mainly in vitro, the mode of action of those peptide aggregates remains largely unknown. However, a greater understanding of the underlying process of amyloid toxicity is pressing in order to develop medication that specifically interferes with the Aβ-induced disease cascade. A number of authors reporting in vitro studies have suggested that the pathological effect of Aβ oligomers is mediated by the NMDA receptor (Shankar et al., 2007; Kelly and Ferreira, 2006; De Felice et al., 2007), and that over activation of the NMDA receptor should be considered as a common principle for some major neurological diseases, including AD (Lipton and Rosenberg, 1994; Harkany et al., 2000; Shankar et al., 2007; Kelly and Ferreira, 2006; De Felice et al., 2007).
Stimulation of the NMDA receptor leads to excessive entry of calcium into the cell, which activates proteases that are involved in cell death signaling. Calpain is a calcium-activated cysteine protease that has been implicated to contribute to NMDA-mediated excitotoxic cell death in various studies. For example, inhibition of calpain is neuroprotective after NMDA-exposure in hippocampal slice cultures (Caba et al., 2002). In vivo, calpain inhibition reduces neurodegeneration in the rat retina after NMDA-injection (Chiu et al., 2005). Calpain has therefore been discussed as target for neurodegenerative disorders (Huang and Wang, 2001; Zatz and Starling, 2005; Saez et al., 2006). Using the specific calpain inhibitor A-705253 we recently reported that inhibition of calpain prevents NMDA-induced lesioning of the NBM in rats, whereas physiological NMDA-cascades remained unaffected (Nimmrich et al., 2008). However, although these studies suggested that calpain inhibition can prevent excitotoxic neurodegeneration in various in vitro and animal models, evidence that calpain inhibition could be protective against Aβ oligomer-induced neuronal deterioration remained elusive.

The present study provides now evidence that calpain inhibition is neuroprotective against Aβ oligomer-induced cholinergic cell lesion. Injection of oligomeric Aβ to the nucleus basalis caused a strong deterioration of cortical cholinergic projections leading to deficits in learning behavior. Behavioral decline was prevented by application of the calpain inhibitor A-705253. The neuroprotective effect of calpain inhibition was also shown by morphological analysis. Cholinergic denervation in the parietal cortex and the extent of microglia activation around the injection in the NBM were greatly attenuated by A-705253. The present findings expand previous findings in animal models of excitotoxicity, and allow the conclusion that inhibition of calpain is effective in vivo against neurodegeneration triggered by oligomeric Aβ. Interestingly, our in vitro studies indicate that calpain inhibition is not only effective when the compound is applied prior to the insult. Efficacy of A-705253 against Aβ-induced cell damage was demonstrated -- albeit less pronounced -- up to 1 h after administration of Aβ. This indicates that the Aβ-induced cell death cascade -- once initiated -- may not instantly kill the neuron, but requires some time until degeneration is irreversible. If this holds true also for other acute forms of neurodegeneration, this could offer a promising avenue for the treatment of acute neurodegenerative disorders. It is likely that drugs targeting the NMDA receptor may only be effective up to the...
time of the insult. At least from studies on long-term potentiation (LTP), a neurophysiological paradigm considered to mimic neuronal memory processing, it is known that NMDA receptor-related cascades cannot be reversed by NMDAR blockers once the cascade is initiated. This could be the reason why patients suffering from acute neurodegenerative processes do not benefit from current pharmacological treatment: the drug is administered once the NMDAR-dependent cell death cascade has already started. Future studies need to reveal whether inhibition of calpain is also effective in vivo after NBM-lesioning, which is currently hampered by the fact that the time of Aβ diffusion to target cells cannot exactly be determined. The time point of treatment, however, may be less relevant for more chronic neurodegenerative diseases, like those accompanying amyloidoses. In any case, calpain inhibition might be superior to drugs targeting the NMDA receptor for another reason: calpain inhibition does not affect physiological processes like LTP (Nimmrich et al., 2008). It should be noted that A-705253 also inhibits other molecules like cathepsin B to some extend. We therefore cannot fully exclude that at least some of the observed protective effects may be attributed to mechanisms other than calpain inhibition. In reverse, it is also possible that the reduction of efficacy at higher concentration is caused by inhibition of other proteins. Future synthesis of more selective compounds is highly desirable for dissecting the molecular components of neuroprotection.

The model presented here reflects some essential hallmarks of the AD pathology. The NBM is one of the early regions to be affected during AD and the overall neuropathology in this model, including cholinergic denervation and microglial activation, features much of the pathology found in AD patients.

Beyond this, Aβ oligomers — rather than amyloid plaques or monomeric amyloid-β — are thought to underlie the neurotoxic initiator of the disease. They occur in patients prior to plaque formation and correlate much better with cognitive deficits than amyloid plaques. Aβ oligomers are therefore — to the best of our knowledge — currently the most appropriate conformation of β-amyloid to induce pathology. The oligomer preparation used here has been introduced by Stine and colleagues (Stine et al., 2003) and was shown to contribute to neurodegeneration, and a discrimination from these targets mandatory. It is likely that A-705253 has fully reached the target in our experiments as it rapidly penetrates tissues, affecting its cellular target within minutes after perfusion (Neuhof et al., 2003, 2004). It also effectively prevented Aβ-induced toxicity at doses previously shown to inhibit calpain (Nimmrich et al., 2008). Aβ oligomers have been extracted from brains of AD patients and correlate well with the severity of the disease. Aβ oligomers are therefore — to the best of our knowledge — currently the most appropriate conformation of β-amyloid to induce pathology. The oligomer preparation used here has been introduced by Stine and colleagues (Stine et al., 2003) and was shown to...
be toxic to neurons (Lambert et al., 1998). They also impair LTP (Lambert et al., 1998; Trommer et al., 2005) and have been demonstrated to exhibit their pathogenic action via the NMDA receptor (Lacor et al., 2007). The preparation is similar in their biophysical properties to brain derived Aβ oligomers, underlining their physiological relevance (Gong et al., 2003). In spite of all similarities to AD it must be noted, however, that the experimental model presented here involves a rather rapid decline of neurons and thus differs from the slowly progressive neurodegeneration observed in AD. It would be challenging to examine whether calpain inhibition also prevents more chronic neurodegeneration processes, which is currently only feasible in transgenic mouse models. Most of these transgenic models, however, suffer from a lack of neurodegeneration and decline of cholinergic fibers. Hence, it may be an adequate approach to combine the effect of calpain inhibition on neurodegeneration in an acute in vivo model, and the prevention of other deficits — like synaptic decline — in chronic mouse models. The latter effects were explored by Battaglia and colleagues using another, less specific calpain inhibitor, E64 (Battaglia et al., 2003), who showed that long-term (5 mo) intraperitoneal application of E64 in APP(K670N/M671L)/PS1(M146L) mice prevented synaptic impairment as measured by LTP. Chronic calpain inhibition also attenuated the development of deficits in spatial behavior of these mice. Thus, it is likely that calpain inhibition serves to protect from acute and chronic neuronal decline, and from a variety of pathological features observed in AD.

Interestingly, protection from behavioral deficits in our study is more sensitive to calpain inhibition than the prevention of cholinergic denervation and microglia activation. A significant improvement in cognitive function measured by novel object recognition was already accomplished with 1 mg/kg of A-705253 whereas the best protection from Aβ-induced cholinergic denervation was achieved with a dose of 3 mg/kg. This did not further improve with the highest dose of 10 mg/kg (data not shown). This suggests that the efficacy of calpain inhibitor A-705253 reaches a plateau at 3 mg/kg in our in vivo model.

In addition, the highest dose (10 mg/kg) A-705253 did not significantly prevent microglia activation. This could indicate that neither cholinergic denervation nor microglia activation do fully contribute to the behavioral outcome measured by the novel object recognition test. It is very likely that the microglia reaction might follow a different dose—response course, which might facilitate other molecular pathways, specific for microglia independent from functional changes behind the behavioral effects.

Whether the effect on behavior at 1 mg/kg may be due to an improvement of physiological function (and hence remain undetected by neuroanatomical analysis) should be assessed in further studies. Recent data showing the involvement of calpain in Aβ-mediated dysfunction of the synaptic vesicle machinery (Kelly et al., 2005; Kelly and Ferreira, 2006) could support such view.

In summary, the presented study adds evidence that calpain inhibition signifi- cantly decreases acute Aβ oligomer-induced degeneration of NBM and its associated cholinergic fiber projections, and attenuates behavioral deficits associated with such lesions. Furthermore, in vitro data suggest that inhibition of calpain is still effective when performed shortly after the insult. Our findings indicate that
inhibiting calpain could be a promising strategy for the therapeutic intervention of amyloid-β related neuropathology in AD.

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