Prevention of Alzheimer’s Disease Pathology by Cannabinoids: Neuroprotection Mediated by Blockade of Microglial Activation

Belen G. Ramirez,1 Cristina Blazquez,2 Teresa Gomez del Pulgar,2 Manuel Guzman,2 and Maria L. de Ceballos1
1Neurodegeneration Group, Cajal Institute, Consejo Superior de Investigaciones Cientificas, 28002 Madrid, Spain, and 2Department of Biochemistry and Molecular Biology I, School of Biology, Complutense University, 28040 Madrid, Spain

Alzheimer’s disease (AD) is characterized by enhanced β-amyloid peptide (βA) deposition along with glial activation in senile plaques, selective neuronal loss, and cognitive deficits. Cannabinoids are neuroprotective agents against excitotoxicity in vitro and acute brain damage in vivo. This background prompted us to study the localization, expression, and function of cannabinoid receptors in AD and the possible protective role of cannabinoids after βA treatment, both in vivo and in vitro. Here, we show that senile plaques in AD patients express cannabinoid receptors CB1 and CB2, together with markers of microglial activation, and that CB1-positive neurons, present in high numbers in control cases, are greatly reduced in areas of microglial activation. In pharmacological experiments, we found that G-protein coupling and CB1 receptor protein expression are markedly decreased in AD brains. Additionally, in AD brains, protein nitration is increased, and, more specifically, CB1 and CB2 proteins show enhanced nitration. Intracerebroventricular administration of the synthetic cannabinoid WIN55,212-2 to rats prevents βA-induced microglial activation, cognitive impairment, and loss of neuronal markers. Cannabinoids (HU-210, WIN55,212-2, and JWH-133) block βA-induced activation of cultured microglial cells, as judged by mitochondrial activity, cell morphology, and tumor necrosis factor-α release; these effects are independent of the antioxidant action of cannabinoid compounds and are also exerted by a CB2-selective agonist. Moreover, cannabinoids abrogate microglia-mediated neurotoxicity after βA addition to rat cortical cocultures. Our results indicate that cannabinoid receptors are important in the pathology of AD and that cannabinoids succeed in preventing the neurodegenerative process occurring in the disease.

Key words: Alzheimer’s disease; β-amyloid; cannabinoids; microglia; neurotoxicity; neuroprotection

Introduction

Alzheimer’s disease (AD), the most common form of dementia, is characterized by the deposition of β-amyloid peptide (βA) within one of its pathological hallmarks: the senile plaque. Activated microglia cluster at senile plaques (McGeer et al., 1987; Dickson et al., 1988), and this seems to be responsible for the ongoing inflammatory process in the disease. Transgenic mouse models of AD also develop plaques in which βA deposits and activated microglia exist (Masliah et al., 1996; Frautschy et al., 1998; Jantzen et al., 2002). Furthermore, microglial activation results in neurodegeneration both in vitro (Meda et al., 1995; Gao et al., 2002; Xie et al., 2002) and in vivo (Weldon et al., 1998; Herrera et al., 2000; Irvani et al., 2002) paradigms. In this context, recent studies have focused on the therapeutic interest of limiting microglial activation and inflammation in AD and other neurological disorders.

Cannabinoids, the active components of marijuana and their analogs, exert a wide spectrum of central and peripheral effects by activating specific cannabinoid receptors, two of which have been well characterized to date: CB1 and CB2 (Howlett et al., 2002; Piemelli, 2003). CB1 receptors are found in high density in the nervous system (Herkenham et al., 1990), in which they mediate cannabinoid psychoactivity, and all types of neural cells express them. Thus, in addition to being present in neurons, CB1 receptors exist in astrocytes (Bouaboula et al., 1995; Sánchez et al., 1998), microglia (Waksman et al., 1999; Walter et al., 2003), and oligodendrocytes (Molina-Holgado et al., 2002). In contrast, the CB2 receptor is considered to be expressed solely in cells and organs of the immune system and is unrelated to cannabinoid psychoactivity. There are also recent reports on the existence of CB2 receptors in microglia (Walter et al., 2003) and on cannabinoids affecting migration (Walter et al., 2003), as well as nitric oxide (NO) and cytokine production (Waksman et al., 1999; Puffenbarger et al., 2000; Facchinetti et al., 2003) in microglial cell cultures in vitro.

Cannabinoids exert neuroprotection under different experi-
mental conditions. Thus, cannabinoid receptor activation protects hippocampal or granule cerebellar neurons from excitotoxicity (Skaper et al., 1996; Shen and Thayer, 1998; Hampson and Grimaldi, 2001) and from hypoxia and glucose deprivation (Nagayama et al., 1999). In vivo, cannabinoids decrease hippocampal neuronal loss and infarct volume after cerebral ischemia (Nagayama et al., 1999), acute brain trauma (Panikashvili et al., 2001), and ouabain-induced excitotoxicity (van der Stelt et al., 2001). These effects have been ascribed to inhibition of glutamate transmission, reduction of calcium influx, and subsequent inhibition of noxious cascades, such as tumor necrosis factor-α (TNF-α) generation and oxidative stress.

This background prompted us to study the characteristics and localization of cannabinoid receptors in AD brain, with particular emphasis on any relationship with microglial activation. Furthermore, the effects of cannabinoid receptor activation were studied in an animal model of AD in vivo and in a model of βA-induced microglial activation in vitro.

Materials and Methods

Materials. βA25–35 and a peptide containing the same 11 amino acids but with a scrambled (SCR) sequence (NeoMPS) were used throughout. βA25–35, and the scrambled peptide were dissolved in distilled water at a concentration of 2.5 mg/ml to allow self-aggregation of the peptide and stored at –80°C until used. βA25–35 (NeoMPS) was dissolved in PBS (1.72 mg/ml), aged at 37°C for 24 h (“fibrillar” peptide), and was vortexed several times during that period, and aliquots were stored at –80°C until used. The control (C) peptide was not subjected to aging (“soluble” peptide). Aggregation of all of the peptides was confirmed by 1H-NMR and 1H-13C NMR. Distilled water at a concentration of 2.5 mg/ml to allow self-aggregation.

Materials. Cell culture reagents were from Sigma unless otherwise stated. Salts and DMSO never exceeded 0.1% in pharmacological or cell culture experiments. Acidic and basic reagents were from Merck (Darmstadt, Germany), with the exception of WIN55,212-2, which was initially dissolved in chloroform.

Immunocytochemistry. Immunostaining of cell cultures, either neuronal or microglial, were similarly performed after fixation with paraformaldehyde (4% in 0.1 M phosphate buffer) for 30 min, followed by rinses with PBS. In addition, rat microglia was immunostained with monoclonal anti-rat CD11 (OX42; 1:100; Serotec, Oxford, UK).

Omission of primary or secondary antibodies resulted in no immunostaining. Specificity of anti-CB1 and anti-CB2 staining was performed by preabsorption of the antibodies with the antigenic peptides (kindly given by Dr. K. Mackie), which completely abolished labeling.

3H-WIN55,212-2 and 35S-GTPyS binding. 3H-WIN55,212-2 binding was conducted as described previously (Breivogel et al., 2001). Briefly, P2 membrane fractions (80 μg of protein) were incubated in assay buffer (Tris 50 mM, pH 7.4, containing 3 mM MgCl2, 1 mM EDTA, and 1 mg/ml fatty acid-free BSA) with 3 nM 3H-WIN55,212-2 (specific activity, 41.0 Ci/mmol; PerkinElmer Life Sciences, Boston, MA) at 30°C for 60 min. Nonspecific binding was determined in the presence of 1 μM SR141716. Saturation curves were constructed with increasing concentrations of 3H-WIN55,212-2 (0.25–10 nM), and, in competition curves, several concentrations of the agonists or antagonists (10–10 to 10–7 M) were assayed. The binding was terminated by filtering through GF/C Whatman filters (0.45 μm), incubated previously with 0.5% polyethyleneimine for at least 2 h, using a Brandel (Gaithersburg, MD) harvester, washed three times with ice-cold 5 mM Tris HCl, pH 7.4, containing 1 mg/ml BSA, and the radioactivity was counted using an LKB-Wallac (Gaithersburg, MD) scintillation counter. 35S-GTPyS binding was performed as described previously (Breivogel et al., 2001). P2 membrane fractions (30 μg of protein) were incubated in assay buffer (Tris 50 mM, pH 7.4, containing 3 mM MgCl2, 1 mM EDTA, and 0.5 mg/ml fatty acid-free BSA) with 0.04 nM 35S-GTPyS (specific activity, 1250 Ci/mmol; PerkinElmer Life Sciences, 30 μM GDP, and 5 μM WIN55,212-2 at 30°C for 60 min. Binding was terminated by rapid filtration as above. Basal activity was determined in the absence of agonist and nonspecific binding in the presence of 10 μM of unlabeled GTPyS. Net stimulation was the difference of the binding in the presence and in the absence (basal binding) of WIN55,212-2. Data were expressed in femtomoles per milligram of protein. All of the procedures for both assays were conducted in plasticware and dilutions of radioligands and cold reagents in plastic tubes coated with 50 mM Tris HCl, pH 7.4, containing 1 mg/ml BSA.

βA and cannabinoid administration to rats. All of the experiments were performed according to ethical regulations on the use and welfare of experimental animals of the European Union and the Spanish Ministry of Agriculture, and the procedures were approved by the ethical committee of the CSIC. βA administration to male Wistar rats was performed essentially as described previously (Pavía et al., 2000). βA25–35, or a peptide with a scrambled sequence (NeoMPS), which was used as control, were injected intracerebroventricularly daily for 7 d (20 μg in 10 μl of saline per day), and the animals were tested at different times after the first injection. Other animals received a cannabinoid (WIN55,212-2, 10 μg in 10 μl of 20% DMSO/80% saline per day) together with the peptides. The Hamilton syringe used for intracerebroventricular injections
were switched to MEM with N2 additives (Sigma), and treatments (6 d shown). For cocultures, 15
vitro
and a shrunken cell body were considered nonviable. Whereas neurons with fragmented neurites
staining under phase-contrast microscopy by an observer unaware of the
platform were placed on it and left there for 15 s. Data acquisition was performed with a video camera (Noldus Information Technology, Wageningen, The Netherlands).

Cell cultures and treatments. Primary mixed glial cultures were prepared from neonatal rat cortex as described previously (McCarthy and de Vellis, 1980). Mechanically dissociated cortices were seeded onto 75 cm
flasks in DMEM/Ham’s F-12, supplemented with 10% fetal calf serum (FCS) and 40
flasks in DMEM/Ham’s F-12, supplemented with 10% fetal calf serum
atmosphere of 5% CO2/95% air at 37°C, and the medium was changed
every 2 or 3 d. After being cultured for 3 weeks, flasks were shaken for 2–3 h at 230 rpm, and floating cells were pelletted, seeded onto a plastic dish, and incubated at 37°C for 4 h, and loosely bound cells were aspirated. Adherent cells were detached (PBS plus 1 mm EDTA) and 3 × 10
cells were seeded onto poly-Orn-coated 96-well plates in DMEM/Ham’s F-12 supplemented with 0.5% FCS. The cultures were at least 99% pure, as judged by immunocytochemical criteria. Mitochondrial activity (redox state) was assessed by the MTT assay. Neuron cultures from rat cortices were prepared as described previously (Fernández-Tomé et al., 2004) with some modifications. Briefly, cerebral cortices were mechanically dissociated in trypsin (1 mg/ml; Worthington, Freehold, NJ) at 37°C for 10 min, followed by DNase addition (50 μl; Roche Products, Welwyn Garden City, UK). Cells were collected after centrifugation and seeded further in Neurobasal (Invitrogen, San Diego, CA), containing B27 additives (Invitrogen), onto gelatin/poly-Lys-coated P24 plates (Falcon, Franklin Lakes, NJ) at a density of 25 × 10
. After 4 d in culture, they were switched to MEM with N2 additives (Sigma), and treatments (6 d in vitro) were performed in MEM. Neuron cultures were completely devoid of microglia as determined by TL or OX42 immunostaining (data not shown). For cocultures, 15 × 10
microglial cells were seeded in inserts (membrane pore size, 0.4 μm; diameter, 9 mm; Costar, Cambridge, MA) in DMEM containing 0.5% FCS and, at 24 h, were treated with βA42, for 4 h. After being cultured for 3 weeks, microglia, neurons, and the medium was aspirated and placed over neuron cultures (25 × 10
; 24-well plates, Costar) for an additional 20 h. Drugs were added in 1/10 of the final volume to maintain aggregation of peptides. Cell counts were performed by Coomassie brilliant blue (0.2% in 10% acetic acid/40% methanol) staining under phase-contrast microscopy by an observer unaware of the treatments (four fields per condition in triplicate) in a Zeiss (Oberkochen, Germany) Axioscope microscope. Neurons showing intact neurites with uniform diameter and soma with a smooth round appearance were considered viable, whereas neurons with fragmented neurites and a shrunken cell body were considered nonviable.

TNF-α analysis. Cell-free supernatants from microglial cultures were collected, microfiltered, stored at −80°C, and assayed by a TNF-α commercial sandwich ELISA (Biosource, Camarillo, CA) in strict accordance with instructions of the manufacturer. The sensitivity was 10 pg/ml.

Western blot analysis. Western blot was performed as described previ
ously (Molina-Holgado et al., 2002). Tissues were sonicated in lysis buffer, samples were centrifuged at high speed for 10 min, and superna
tants were collected. Total protein was assayed by the Bio-Rad (Hercules, CA) protein assay. An aliquot of each sample (30 μg of protein) was separated by SDS-PAGE (10%), and proteins were transferred from the gels onto nitrocellulose membranes. The blots were blocked with 1% defatted dry milk for 1 h at room temperature and incubated overnight at 4°C with the following antibodies: anti-CB1 (1:5000), anti-CB2 (1:2000), anti-N-Tyr (1:3000), polyclonal anti-calbindin D-28K (1:5000; Swant, Bellinzona, Switzerland), and monoclonal anti-α-tubulin (1:20,000; Sigma). Finaly, samples were subjected to enhanced chemiluminescence and densitometric analysis. Densitometric analysis of bands was performed by Quantity One quantitation software (version 4.2; Bio-Rad) from film exposures; the background was always subtracted, and the percentage of optical density was obtained considering 100% of that of control samples within the same film. Immunoprecipitations were performed by incubating overnight at 4°C lysozyme aliquots (100 μg of protein) with the anti-N-Tyr antibody (1 μg/mg protein lysate) prebound to pro
tein A-agarose (Sigma). After washing, the immunoprecipitates were resolved by 10% SDS-PAGE and Western blotted with anti-CB1, and anti-CB2 antibodies as above.

Statistical analysis. Statistical significance analysis was assessed by using two-way or one-way ANOVA, followed by Bonferroni’s post hoc test or by unpaired Student’s t test (Prism software, version 4.0; GraphPad Software, San Diego, CA). A value of p < 0.05 was considered significant. Binding saturation and inhibition curves were plotted by nonlinear regression, and IC50 values were determined using the one-site competition model (Prism software).

Results
Cannabinoid receptors in AD brain

We studied by immunolabeling the localization of cannabinoid receptors in relation to senile plaques and microglial activation. All of the AD cases studied (six of six) showed CB1 and CB2 immunoreactivity in frontal cortical senile plaques (Fig. 1a), along with markers of microglial activation, such as the histo-
compatibility glycoprotein HLA-DR (McGeer et al., 1987) (Fig. 1a) and protein nitration (Fig. 1a, N-Tyr). Double-immunolabeling studies addressed the question of whether CB1 neurons are vulnerable in AD, and microglial activation accounted for it. In agreement with previous immunohistochemi
cal studies in nonhuman primates (Ong and Mackie, 1999), high numbers of CB1 neurons and fibers, surrounded by resting micro
glia, were observed in all layers of the frontal cortex in controls (Fig. 1b). CB2-positive neuron density was greatly reduced in AD. Thus, although in some AD cases (two of six) CB2-positive neu
rons were still present in areas of microglial activation (Fig. 1b), they were completely absent in others (four of six) (Fig. 1b). Likewise, no coexistence of CB2-positive plaques and neurons was evident in these cases. In addition to CB2 expression in AD plaques, we also found labeling in tangle-like neurons and dystro
fic neurites (four of six cases) (Fig. 1c), whereas normal brain was devoid of any signal (five of five cases). Labeling speci
ficity was demonstrated by antigenic peptide preabsorption of the anti-CB antibodies used (Fig. 1c), which completely blocked immunoreactivity.

AD brain protein nitration (Smith et al., 1996) is thought to be a consequence of the reaction of NO and superoxide to form the toxic peroxynitrite radical. In control brain, N-Tyr immunoreac
tivity was present in astrocytes and in neuronal nuclei (Fig. 2a). N-Tyr-positive astrocytes were present in AD brain as well (data not shown), but now many pyramidal neurons showed cytoplasmic labeling in all of the cases studied (six of six) (Fig. 2a). Protein nitration was significantly increased in AD compared with control brain (Fig. 2b). Moreover, nitration of CB1 and CB2 protein was markedly increased in AD, as shown by immunoprecipita
tion studies (Fig. 2c).

Subsequently, we examined the pharmacological characteris
tics of cannabinoid receptors by using the synthetic cannabinoid agonist WIN55,212-2. "H-WIN55,212-2-specific binding, as de
fined by the selective CB2 antagonist SR141716 (Rinaldi-Carmona et al., 1994) at 1 μM, was similar in control and AD cases (Fig. 3a), as were the saturation curves for the binding process.
to 5 μM), and completely blocked by SR141716 and AM251 (pEC50, 7.87 ± 0.13 and 7.87 ± 0.10, respectively). Together, these results indicate that, in human brain, WIN55,212-2 interacts with CB1 or CB2-like receptors.

Cannabinoid treatment prevents βA-induced toxic effects in vivo

βA overexpression or administration to rodents models AD by activating microglia (Masliah et al., 1996; Frautschy et al., 1998; Netland et al., 1998) and inducing cognitive impairment (Müller et al., 1994; Deloebte et al., 1997). We administered βA (20 μg/d, i.c.v) or the control peptide (SCR) alone or in combination with WIN55,212-2 (10 μg/d) and studied microglia staining at the end of the treatment (8 d). Resting microglia were observed in rats injected with SCR and/or the cannabinoid (Fig. 4). Interestingly, there was an intense microglial activation in the cortex of βA-treated rats, which was prevented by WIN55,212-2 treatment (Fig. 4).

We next examined whether cannabinoid administration affected cognitive function. In contrast to control rats that learned the spatial navigation task over 5 d of training, βA-treated rats failed to do so. More important, WIN55,212-2 treatment prevented βA-induced cognitive impairment (Fig. 5a), whereas it did not alter the learning process when combined with SCR. This cannabinoid effect was not attributable to changes in the locomotor activity of the animals. Thus, WIN55,212-2 produced its typical hypolocomotor action on the first day of treatment, but this effect was not evident at the seventh day of administration and 2 months later (data not shown), when the navigation task was performed. As expected, intracerebroventricular administration of the cannabinoid agonist did not induce adverse effects. Indeed, just after the cessation of the treatment, the general hematological profiles of the WIN55,212-2-treated rats were normal. Likewise, neither the biochemical parameters nor markers for tissue damage changed at the end of the 7 d administration period.

Interestingly, the changes in neuronal protein expression observed in AD patients were mimicked by repeated administration of βA to rats. Thus, the expression of the neuronal markers calbindin (Fig. 5b,c) and α-tubulin (Fig. 5c,f) was significantly reduced in both situations. Of importance, this reduction was attenuated by cannabinoid administration to rats (Fig. 5c,f). CB1 expression was also decreased in βA-treated rats (Fig. 5d), as was the case in AD brain (Fig. 3e).

Cannabinoid treatment prevents βA-induced microglial activation and neurotoxicity in vitro

First, we examined the effects of cannabinoids on βA-induced alterations in pure microglial cell cultures. As expected, microglia in culture expressed both CB1 and CB2 receptors (Walter et al., 2003) (Fig. 6a). Microglial activation after fibrillar βA challenge (0.5 μM) included morphological changes at 24 h (Fig. 6b), as well as increased mitochondrial activity (in the absence of cell prolif-
when neurons were exposed for 20 h to microglial cells pretreated with 0.5 \textmu M fibrillar \( \beta A \) for 4 h (Fig. 7a,b), whereas, at this time point and concentration, the peptide did not significantly alter neuron survival in the absence of microglial cells (Fig. 7a) (Barger et al., 1995; Fernández-Tome et al., 2004). Both WIN55,212-2 and JWH-133 (100 nM) prevented microglia-mediated neurotoxicity after \( \beta A \) treatment (Fig. 7a,b). The neuroprotective effect of WIN55,212-2 on \( \beta A \) neurotoxicity in cocultures was prevented by the selective antagonists SR141716 and SR144528, whereas the effect of JWH-133 was only counteracted by the latter (Fig. 7a). These results support that the neuroprotective effect of cannabinoids relies on the prevention of \( \beta A \)-induced microglial activation.

### Discussion

One of the key features of AD is microglial activation, a process that may serve dual functions. For a long time, it was thought to be responsible for the ongoing inflammatory process occurring in the neurological condition (for review, see Akiyama et al., 2000). However, it has been recognized recently that removal of \( \beta A \) by activated microglia may be beneficial (Bard et al., 2000; Wyss-Coray et al., 2001; Janzen et al., 2002). These cells are part of the senile plaques in cerebral cortex and hippocampus of the afflicted patients. We have shown that \( \text{CB}_1 \) and \( \text{CB}_2 \) receptors are colocalized in plaques, in line with a recent report (Benito et al., 2003). Upregulation of inducible nitric oxide synthase occurs in senile plaques in AD (Lee et al., 1999) and in microglia after \( \beta A \) administration \emph{in vivo} (Weldon et al., 1998). Furthermore, N-Tyr immunoreactivity has been observed in plaques in AD (Vodovoz et al., 1996) and in mice carrying amyloid precursor protein plus presenilin-1 mutations (Matsuoka et al., 2001). Protein nitration therefore appears to be a marker of the effects of the peroxynitrite radical and a consequence of microglial activation. In normal human brain, we observed a high density of \( \beta A \)-positive neurons (Ong and Mackie, 1999; Benito et al., 2003), mostly pyramidal cells, which are lost in AD brain, in particular in areas bearing plaques, pointing to the vulnerability of such neurons to the toxic species generated by microglia (e.g., NO and cytokines). Given that \( \beta A \)-positive neurons were segregated from plaques, their possible contribution to \( \beta A \) receptors in plaques may be ruled out, and this points to microglial cells as the unique source.

Previous works in human brain have mapped \( \beta A \) receptors by autoradiographic techniques (Westlake et al., 1994; Glass et al., 1997, 2000), but their pharmacological characteristics were not determined. Furthermore, it is widely accepted that \( \text{CB}_2 \) receptors are not present in normal brain, but we wondered whether, by using an appropriate selection of cold ligands to define specific binding, we would be able to show \( \text{CB}_2 \) receptors, at least in pathological brain, such as AD. In human cortical membranes, \( ^3\text{H-WIN55,212-2} \) binding to \( \beta A \) receptors, as defined by the \( \text{CB}_2 \)-selective antagonist SR141716, was saturable and of high affinity. The apparent affinity is similar to that observed in rat brain (Breivogel et al., 1997), albeit the density of binding sites \( (B_{\text{max}}) \) is much lower. Rather than a species trait, aging (Maiellou and Vanderhaeghen, 1992; Romero et al., 1998; Mato and Pazos, 2004) may account for the difference in density, given that our controls were nonpathological aged subjects. WIN55,212-2 is a mixed \( \text{CB}_1/\text{CB}_2 \) cannabinoid receptor agonist that activates, with similar affinities, \( \text{CB}_1 \) and \( \text{CB}_2 \) receptors (Howlett et al., 2002) and may also interact with other, as yet uncharacterized, receptor subtypes (Breivogel et al., 2001). The relative potencies of the drugs in our pharmacological studies are in general agreement with previous studies (Rinaldi-Carmona et al., 1994, 1998;
Breivogel et al., 1997), including those in cells transfected with the cloned human cannabinoid receptors (Felder et al., 1995; MacLennan et al., 1998). Together, these results indicate that, in human brain, WIN55,212-2 interacts with CB1 or CB1-like receptors. CB1 receptors outnumber other characterized cannabinoid receptors, and such a high density may have masked CB2 receptors, which were observed by immunohistochemistry, with a very restricted localization in AD brain.

In a previous work, cannabinoid receptor binding in cortical areas of AD brain was unchanged, and the reduction in hippocampal subfields was unrelated to the pathological changes (Westlake et al., 1994). However, in agreement with our histological findings, in biochemical studies, we have shown that CB1 protein expression and function are markedly reduced in AD. Indeed G-protein coupling, as judged by 35S-GTPγS binding, was greatly diminished in samples from AD patients. Given that enhanced protein nitration was observed along CB receptors in plaques, we examined whether they may be a target for such alteration. In AD, total protein nitration is increased compared with controls (Aoyama et al., 2000). More specifically, both CB1 and CB2 receptor proteins show enhanced protein nitration in AD than in controls. It should be noted that protein nitration, known to inactivate other proteins in AD (Aoyama et al., 2000), might interfere with CB receptor function as well. In summary, significant alterations in the localization, expression, and function of cannabinoid receptors occur in AD and may play a role in its physiopathology.

Our present results confirm and extend those of previous works, showing marked alterations in cannabinoid receptors in AD brain. Benito et al. (2003) reported that CB1-positive neurons appeared to be preserved in AD parahippocampal cortex, but frontal cortex was not studied. Therefore, the region of study may account for the difference between their and our results. Autoradiographic studies, used by Westlake et al. (1994), lack cellular resolution, which may explain why decreased binding did not correlate with areas showing pathology (senile plaques and tangles) in hippocampal subfields in AD. In this work, we combined histological, pharmacological, and biochemical techniques to show loss of CB1-positive neurons in frontal cortex of AD brain, as well as decreased CB1 protein expression and G-protein coupling, despite preserved binding.

In the present study, we used rats repeatedly injected intracerebroventricularly with βA to model AD. Indeed, we reported decreased muscarinic receptors in cortex (Pavia et al., 2000) and increased monomeric G1 acetylcholinesterase isofrom (Sáez-Valero et al., 2002), similar to those in AD. These animals show increased microglial reaction at the end of βA administration (Netland et al., 1998; Weldon et al., 1998) and cognitive impairment at 2 months (Delobette et al., 1997) compared with control animals. Interestingly, βA-treated rats reproduced the same reduction in neuronal markers, including CB1 protein, occurring in AD, validating further the experimental model. Cannabinoids induce neuroprotection against excitotoxicity (Shen and Thayer, 1998), ischemia (Nagayama et al., 1999), and glucose deprivation (Nagayama et al., 1999) in vitro. These compounds are also effective against acute brain damage in vivo, including excitotoxic insult (van der Stelt et al., 2001), ischemia (Nagayama et al., 1999), and acute brain trauma (Panikashvili et al., 2001). Furthermore, the involvement of CB1 receptors and their endogenous ligands as neuroprotectants has been demonstrated recently in CB1-null mutants, which are more susceptible to neurodegeneration (Parmentier-Batteur et al., 2002; Marsicano et al., 2003). In this work, we report that microglial activation induced in vivo by βA was completely prevented by cannabinoid administration. We have shown that the loss of neuronal markers induced by βA is attenuated by cannabinoid administration. More importantly, the cognitive deficits occurring in βA-treated rats are also prevented by the cannabinoid. Together, these results constitute the
first evidence that cannabinoids exert neuroprotection in a model of AD.

Cannabinoids prevent microglial activation and decrease NO production (Waksman et al., 1999) and TNF-α expression and release (Puffenberger et al., 2000; Facchinetti et al., 2003) evoked by different agents. In this work, cannabinoids with different pharmacological profiles effectively counteracted the well-known βA-induced microglial activation, in particular TNF-α release, which is potentially neurotoxic. Milton (2002) reported that the toxicity of high concentrations (25 μM) of βA peptides was prevented by endocannabinoids in NT-2 cells, a human teratocarcinoma cell line that can be differentiated into neuronal phenotype, and in myeloma cells. Thus, anandamide and noladin ether protected the cells by a CB1- or a CB1/CB2-mediated effect, respectively, depending on the cell line used. These results were not reproduced in our neuronal cultures. Thus, different synthetic cannabinoids did not prevent direct toxicity of βA on primary neurons in culture. However, a neuroprotective effect of cannabinoids was disclosed using a βA microglia-mediated neurotoxicity paradigm. The selective CB2 agonist JWH-133 was as effective as WIN55,212-2, the mixed CB1/CB2 agonist. As shown in microglia–neuron cocultures and in βA-treated rats, these beneficial effects of cannabinoids may rely on their ability to block βA-induced microglial activation. In line with this notion, cannabinoids are unable to prevent βA-induced death of primary neurons in culture. This may be of particular importance for the possible endorsement of cannabinoids to therapeutic applications because of their psychotropic side effects, which may cast clinical concern. CB2 receptors appear to be exclusively expressed by microglia, and blockade of its activation may be attained by CB2 agonists with no overt psychoactivity.

The search for new and effective treatments for AD is of crucial importance, and limiting ongoing inflammatory responses secondary to microglial activation has been proposed (Akiyama et al., 2000). Furthermore, recent studies on therapeutic strategies for neurodegenerative diseases such as Parkinson’s disease and AD have focused on the neuroprotective properties (e.g., slowing the ongoing neurodegeneration) rather than just on palliating symptoms of the diseases (Dawson and Dawson, 2002). Because cannabinoids combine both anti-inflammatory and neuroprotective actions, our findings

![Figure 5.](image) **Figure 5.** Cannabinoid treatment prevents cognitive impairment and loss of neuronal markers in rats. **a,** Latency (in seconds) to find a hidden platform in the water maze during training. Results are mean of n = 5 in each group; SEM have been omitted for clarity and were always <12% of the mean; *p < 0.05 and **p < 0.01 compared with SCR-treated rats at the same training day; #p < 0.05 and ##p < 0.01 compared with βA-treated rats (ANOVA with Bonferroni’s post hoc test). WIN, WIN55,212-2. **b, c,** Expression of calbindin (b) and α-tubulin (c) in control (C) and AD frontal cortex; results are mean ± SEM of n = 18 control and AD; ***p < 0.001 compared with controls. **d–f,** Expression of CB1 (d), calbindin (e), and α-tubulin (f) in frontal cortex of rats at 2 months after treatment. OD, Optical density. Results are mean ± SEM of n = 5 in each group; *p < 0.05 and **p < 0.01 compared with SCR-treated rats (ANOVA with Bonferroni’s post hoc test); representative blots are shown. Error bars represent SEM.

![Figure 6.](image) **Figure 6.** Cannabinoids prevent βA-induced microglial activation in vitro. **a,** Immunostaining of cultured microglia with anti-OX42 (top), CB1 (middle), and CB2 (bottom) antibodies. **b,** Fibrillar βA1-40 (fib), but not soluble βA1-40 (sol), induced a rod-like morphology, which was prevented by HU-210 (HU). **c,** Cannabinoids (HU-210 (HU), WIN55,212-2 (WIN), and JWH-133 (JWH), at 100 nM for 4 h) prevented TNF-α release and mitochondrial activity, as induced by fibrillar βA1–40 (500 nM). TNF-α release in controls was 26 ± 4.5 pg/ml. Results are mean ± SEM of n = 4–6; *p < 0.05 and **p < 0.01 compared with soluble βA1–40-treated control cultures; *p < 0.05, **p < 0.01 compared with fibrillar βA1–40-treated cultures (ANOVA with Bonferroni’s post hoc test).
may set the basis for the use of these compounds as a therapeutic approach for AD.

References


mine, adiponectin, and GABARs. Oligodendrocyte cell lines were used to study the effects of cannabinoids on oligodendrocyte function.

References:


