

Review

The Role of Endocannabinoid Signaling in the Molecular Mechanisms of Neurodegeneration in Alzheimer's Disease

Gaurav Bedse^{a,b}, Adele Romano^b, Angelo M. Lavecchia^b, Tommaso Cassano^{c,*} and Silvana Gaetani^b

^a*Department of Biochemical Sciences, Sapienza University of Rome, Rome, Italy*

^b*Department of Physiology and Pharmacology "V. Erspamer", Sapienza University of Rome, Rome, Italy*

^c*Department of Clinical and Experimental Medicine, University of Foggia, Foggia, Italy*

Handling Associate Editor: Patrizia Mecocci

Accepted 23 July 2014

Abstract. Alzheimer's disease (AD) is the most common form of progressive neurodegenerative disease characterized by cognitive impairment and mental disorders. The actual cause and cascade of events in the progression of this pathology is not fully determined. AD is multifaceted in nature and is linked to different multiple mechanisms in the brain. This aspect is related to the lack of efficacious therapies that could slow down or hinder the disease onset/progression. The ideal treatment for AD should be able to modulate the disease through multiple mechanisms rather than targeting a single dysregulated pathway. Recently, the endocannabinoid system emerged as a novel potential therapeutic target to treat AD. In fact, exogenous and endogenous cannabinoids seem to be able to modulate multiple processes in AD, although the mechanisms that are involved are not fully elucidated. This review provides an update of this area. In this review, we recapitulate the role of endocannabinoid signaling in AD and the probable mechanisms through which modulators of the endocannabinoid system provide their effects, thus highlighting how this target might provide more advantages over other therapeutic targets.

Keywords: 2-AG, Alzheimer's disease, amyloid- β , anandamide, cannabinoids, CB1, CB2, FAAH, MAGL, tau

INTRODUCTION

Alzheimer's disease (AD) is the most common cause of dementia. About 35.6 million people worldwide are now suffering from AD, and disease prevalence is expected to affect 115 million by 2050 [1]. AD was discovered 100 years ago but the insight into symptoms, etiology, disease progression, pathological mechanism, and treatment has gained a significant progress

over last 30 years. Although we have known about this disease for over a century, to date there is no curative treatment available. Three acetylcholinesterase (AChE) inhibitors (donepezil, rivastigmine, and galantamine), and a non-competitive N-methyl-D-aspartate (NMDA) receptor antagonist, memantine, are the only drugs available and approved by the United States Food and Drug Administration (FDA) for the treatment of AD [2]. The latest (2011) guidance from the National Institute for Health and Clinical Excellence recommends that the three AChE inhibitors are available for managing mild-to-moderate AD, whereas memantine is recommended as an option for treating people

*Correspondence to: Tommaso Cassano, Department of Clinical and Experimental Medicine, University of Foggia, Viale Luigi Pinto 1, Foggia - 71100, Italy. Tel.: +39 0881 588042; Fax: +39 0881 188 0432; E-mail: tommaso.cassano@unifg.it.

with moderate AD who are intolerant to or have a contraindication to AChE inhibitors treatment or with severe AD symptoms.

However, all present pharmacological therapies for AD do not reverse the disease progression and are accompanied by several side effects. Moreover, most AD cases are diagnosed when the disease is already progressed to an advanced level, and this might be due to the lack of early blood-based biomarkers of the disease. Interestingly, a recent study discovered and validated a set of ten lipids from peripheral blood that are proposed to be early biomarkers of AD [3].

Today, worldwide efforts are underway to find new compounds to treat the disease, delay its onset, and prevent it from developing. Unfortunately, not a single new drug has been approved for AD treatment in more than a decade. Therefore, it is necessary to explore novel potential therapeutic targets.

The endocannabinoid (eCB) system appears to be a promising therapeutic target as it has the ability to modulate a range of aspects of AD pathology. At a first glance, it is striking that cannabinoids like delta-9-tetrahydrocannabinol (Δ^9 -THC), known to impair memory, could be beneficial in AD [4]. However, augmentation of eCB signaling could reduce excitotoxicity, oxidative stress, and neuroinflammation and thus could alleviate symptoms of AD [5]. Previous reviews have highlighted the beneficial effects of cannabinoids in AD treatment [5–10], but none of them have focused on the molecular mechanisms through which eCBs exert their beneficial effects. Thus, the present review will extensively cover recent findings on the dysregulation of eCB signaling and the molecular mechanisms involved in beneficial effects of cannabinoids in AD.

ALZHEIMER'S DISEASE PATHOPHYSIOLOGY

AD is a progressive, degenerative, and irreversible neurological disorder that causes deterioration of memory, judgment, and reasoning in the elderly [11]. Patients suffering from AD exhibit cognitive impairment, memory loss, and behavioral changes [11]. The neurodegeneration in AD is characterized by neuronal loss and synaptic injury [12]. Moreover, AD is associated with extracellular insoluble plaques [13], intracellular neurofibrillary tangles (NFTs) [14], astrogliosis [15], and microglial cell proliferation [16]. Extracellular senile plaques are mainly composed of amyloid- β (A β) protein. The deposition of A β is the

first event in the pathogenesis of AD that precedes the formation of phosphorylated tau aggregation [17]. NFTs consist of paired helical filaments resulting from hyperphosphorylation of the microtubule-binding protein tau [11]. Tau plays an important role in the maintenance of microtubule stability. In AD, tau is aberrantly hyperphosphorylated and proteolyzed resulting in impairment of normal functions of tau [11].

AD may be classified in two types based on genetic endowment. The first type is inherited via an autosomal dominant pattern, i.e., familial AD, and the second type is sporadic AD. Familial AD displays early disease onset, whereas sporadic AD cases mostly develop the disorder at an older age [18]. Etiology of AD is multifactorial with genetic, environmental, and developmental components playing a role [2]. A large body of evidence supports the notion that AD pathogenesis is related to a progressive accumulation of A β protein due to an imbalance between A β production, aggregation, and clearance [11, 19]. A β is formed following sequential cleavage of amyloid- β protein precursor (A β PP) by two proteases termed β - and γ -secretases (see Fig. 1). After excessive generation, A β self aggregates into A β oligomer and then it further aggregates into insoluble extracellular senile plaques. Most of the evidence suggests that A β oligomers instead of fibrils are responsible for neurotoxic effects of A β [20–23].

Besides plaques and NFTs, AD is also characterized by neuroinflammation. It is widely accepted that the deposition of A β is one of the main features of AD and seems to trigger a cascade of neuroinflammatory events that ultimately leads to neurodegeneration [24, 25]. Brain inflammation is mediated by the activation of glial cells, microglia, and astrocytes, and expression of inflammatory mediators and neurotoxic free radicals [26]. Microglial cells are the central nervous system (CNS) resident phagocytes of the immune system and produce a wide range of cytokines, such as interleukins [27]. Activated microglia accumulates at the site of A β deposition and, as expected, actively engulfs and clears A β deposits [28]. A β is able to stimulate Src family kinases and Syk tyrosin kinases [29], which further can activate mitogen-activated protein kinase (MAPK) and nuclear factor κ B (NF κ B) cascades that are required for proinflammatory cytokine and reactive oxygen species (ROS) production (see Fig. 1) [27]. It has been also reported that A β can directly activate MAPK and extracellular signal regulated kinase (ERK) pathways [30]. Transient activation of these signaling pathways after A β binding to microglia results in upregulation of proinflammatory cytokines such as interleukin-1 β (IL-1 β) and tissue tumor necrosis factor-alpha

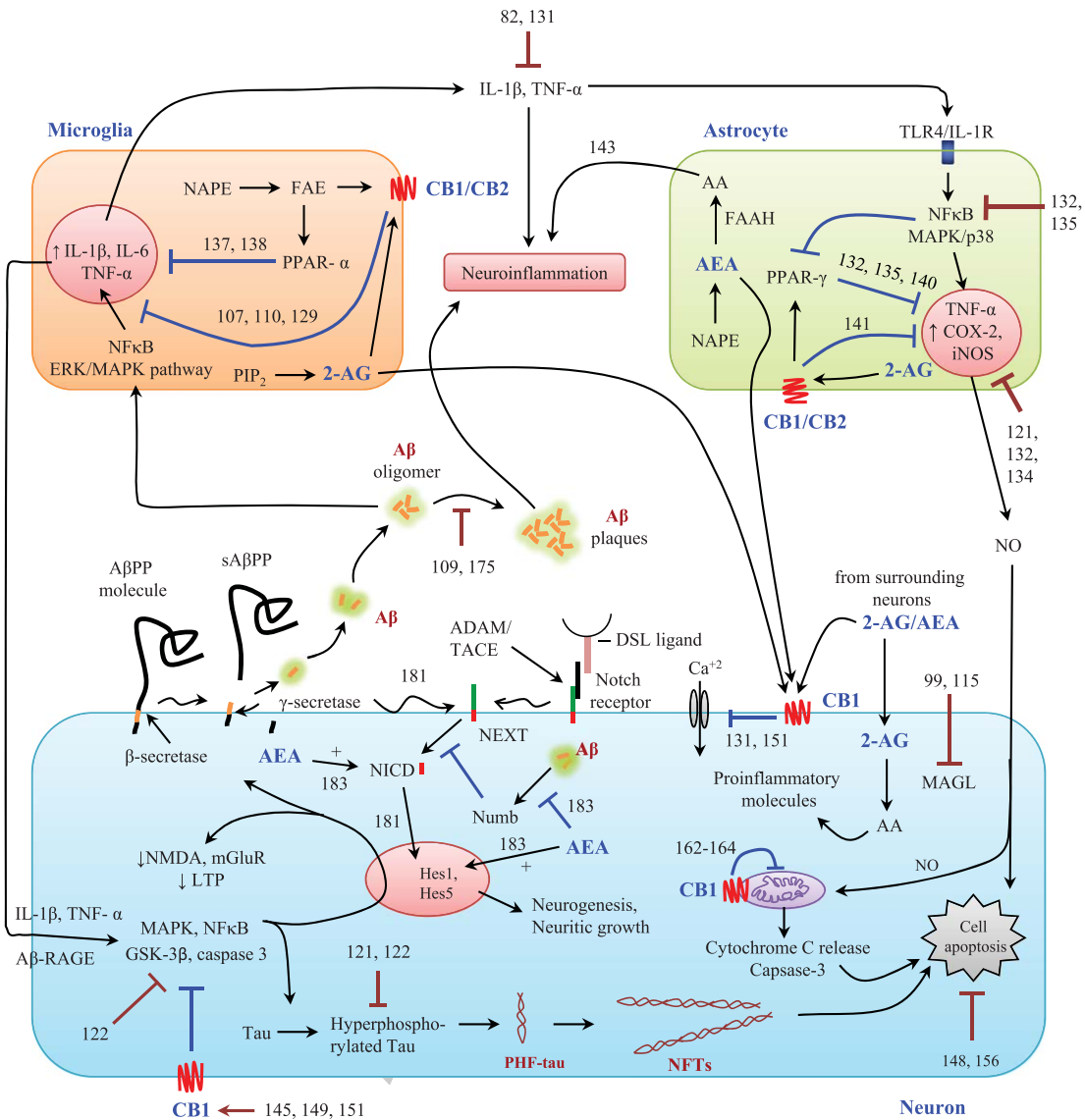


Fig. 1. Endocannabinoid signaling and molecular mechanisms of neurodegeneration in AD. Proteolytic cleavage of amyloid- β protein precursor (A β PP) by β - and γ -secretase results in generation of A β_{42} monomers, which under pathological conditions, assembles into oligomers. A β_{42} oligomers activate microglia and astrocytes. Activated microglia produces inflammatory cytokines through nuclear factor κ B (NF κ B) and mitogen-activated protein kinase (MAPK) pathways. Cytokines released from microglia integrate inflammation process in surrounding astrocytes and neurons through various signaling pathways. Cytokines and A β_{42} , through various mechanisms, activate MAPK, NF κ B, glycogen synthase kinase-3 β (GSK-3 β), and caspase-3 pathways. A β_{42} through MAPK and NF κ B pathways negatively modulates long-term potentiation by controlling NMDA and mGlu receptor expression, and ultimately causing memory impairment. Moreover, A β_{42} through the activation/release of kinases, nitric oxide (NO), and caspase-3 increases phosphorylation of tau, which ends in the formation of neurofibrillary tangles (NFTs) in neurons. Under inflammatory conditions both microglia and astrocytes synthesize endocannabinoids (anandamide; AEA and 2-arachidonoylglycerol; 2AG), which through cannabinoid receptors (CB $_1$ /CB $_2$) and peroxisome proliferator-activated receptors (PPAR) suppress production of cytokines, iNOS and COX-2 expression. Moreover, AEA augments Notch-1 signaling, which is important in neuronal development, neurogenesis, and neuritic growth. Mitochondrial CB $_1$ receptors inhibit the release of cell apoptotic factors and Ca $^{+2}$ influx in response to reactive oxygen species. Thus activation of endocannabinoid signaling exerts antioxidant, anti-inflammatory and anti-apoptotic effects. NAPE, N-acyl-phosphatidyl-ethanolamine; FAE, fatty acid ethanolamides; ERK, extracellular signal regulated kinase; PIP $_2$, phosphatidylinositol-4,5-bisphosphate; AA, arachidonic acid; FAAH, fatty acid amide hydrolase; MAGL, monoacylglycerol lipase; TLR-4, toll-like receptor-4; ADAM, metalloproteinase domain-containing protein; TACE, tumor necrosis factor-converting enzyme; DSL, Delta/Serrate/LAG-2; NICD, notch intracellular domain; NEXT, notch extracellular truncation; RAGE, receptor for advanced glycation end-products.

(TNF- α) [27]. IL-1 β and TNF- α are considered as primary cytokines responsible for chronic inflammation in AD [31]. Furthermore, IL-1 β released from glia activates MAPK and NF κ B signaling cascades in astrocytes and neurons, resulting in excessive inflammation and tau phosphorylation [27, 31] (Fig. 1). Additionally A β oligomers can induce production of inducible nitric oxide synthase (iNOS), nitric oxide (NO), and TNF- α in astrocytes [32]. Activation of toll-like receptor (TLR; e.g., TLR-4), fundamental receptors involved in pathogen recognition and activation of innate immunity, can also activate MAPK and NF κ B pathways [33, 34]. Activation of these signaling cascades in neurons could inhibit synaptic plasticity. p38-MAPK cascade has been recognized as one of the signal transducer downstream of NMDA and metabotropic (mGlu) glutamate receptors and its activation contributes to the inhibition of long term-potential (LTP) [35, 36]. Moreover, MAPK is rapidly activated after interaction of A β with the receptor for advanced glycation end-products, leading to inhibition of LTP and tau phosphorylation (Fig. 1) [27].

THE ENDOCANNABINOID SYSTEM

eCBs are highly lipophilic molecules which are synthesized from lipid membrane precursors and have been shown to modulate neuronal activities [37]. These are elements of the eCB system that also includes the enzymes required for their synthesis and metabolism and the cannabinoid (CB) receptors that serve as their molecular targets. Unlike classical neurotransmitters, eCBs are synthesized and immediately released "on demand" upon neuronal activation and act retrogradely through the synaptic cleft to activate CB receptors located pre-synaptically [37, 38]. By activating CB receptors in the CNS, eCBs suppress neurotransmitter release in a transient or long-lasting manner at both excitatory and inhibitory synapses [38].

The first identified eCB was anandamide (arachidonylethanolamine; AEA) [39], which is the derivative of ethanolamine and arachidonic acid (AA). The existence of a second eCB was postulated and soon identified as 2-arachidonoylglycerol (2-AG) [40, 41]. 2-AG is an ester derivative of AA and glycerol. The synthesis of AEA and 2-AG is believed to be driven by the cleavage of membrane-associated phospholipids. AEA is synthesized from hydrolysis of N-acyl-phosphatidylethanolamine (NAPE) by phospholipase D (PLD) [42, 43]. 2-AG synthesis derives from the hydrolysis of phosphatidylinositol-

4,5-bisphosphate (PIP₂) and is mediated by the generation of diacylglycerol (DAG), via the actions of either phospholipase C (PLC) or phospholipase D (PLD) [44]. DAG is subsequently converted to 2-AG by DAG lipase [44]. eCBs are produced by a variety of cell types including endothelial cells, adipocytes, glial cells, and macrophages [45–47]. 2-AG is more abundant than AEA in the brain and behaves as a full agonist for CB₁ and CB₂ receptors, while AEA acts as a partial agonist for CB₁ receptors [48]. In addition to CB₁ receptors, AEA can also activate peroxisome proliferator-activated- α receptors (PPAR- α) and transient receptor potential vanilloid-1 (TRPV1) channels [49].

CB₁ receptors are widely expressed throughout the brain [50], predominantly in cerebellum, cortex, hippocampus, and basal ganglia [38]. They are mostly found on axon terminals of a variety of neuronal populations and their activation results in inhibition of adenylate cyclase activity and calcium influx into the axon terminal; thus, CB₁ receptor signaling functions to suppress neurotransmitter release into the synapse [38]. CB₁ receptors are also expressed in periphery organs [51]. Following CB₁ receptor identification, peripheral CB-receptor was identified and designated as CB₂ receptor [52]. CB₂ receptors are widely distributed in cells and tissues of immune system. Recently, it has been discovered that CB₂ is also expressed within the CNS and its expression occurs at various stages of inflammation [53–56]. This expression of CB₂ was primarily localized in the microglia and astrocytes [57–59]. Interestingly, CB₂ receptor expression can be detected in these cells in CNS only after various insults, whereas it cannot be detected in resting microglia [60]. The CB₂ exerts its effects through initiation of phospholipase C (PLC) and inositol 1, 4, 5-triphosphate (IP₃) signaling pathways that results in increased levels of intracellular calcium [59]. There is also evidence on other putative CB-receptor subtypes [61], but no new receptor has been fully characterized or cloned yet. Moreover, it has been proposed that G-protein coupled receptor GPR55 may be a novel cannabinoid receptor [62]. Another suggested putative novel CB-receptor is the TRPV1 receptor, a ligand-gated ion channel [63].

eCBs after their actions are rapidly eliminated by cellular uptake and enzymatic hydrolysis. After cellular re-uptake AEA is metabolized by the fatty acid amide hydrolase (FAAH) [64] expressed mostly by postsynaptic neurons. FAAH metabolizes also other N-acyl ethanolamines, like palmitoylethanolamide (PEA) and oleoylethanolamide

(OEA). N-acyl ethanolamine hydrolyzing acid amidase (NAAA) has been identified to take also part in the metabolism of AEA [65]. 2-AG is mainly metabolized by monoacylglycerol lipase (MAGL) in presynaptic neurons [66]. At lesser extent 2-AG is also metabolized by FAAH, serine hydrolase α/β hydrolase 6 (ABDH6), serine hydrolase α/β hydrolase 12 (ABDH12), and cyclooxygenase-2 (COX-2) [65].

The understanding of the eCB system is constantly evolving as new discoveries are progressing. Previously it was thought that retrograde signaling was the principal mode by which eCBs mediate short- and long-term forms of plasticity at both excitatory and inhibitory synapses. However, increasing evidence suggests that eCBs can also signal in a nonretrograde manner [67]. The general physiological actions of non-retrograde signaling eCBs are mediated by TRPV1 in the CNS [68]. The concept of on demand synthesis of eCBs is also challenged now as recent studies have demonstrated intracellular storage of AEA in adiposomes [49]. It has been recently shown that the majority of CB₁ receptors does not reach the cell surface but instead shows intracellular localization. A significant part of intracellular CB₁ receptor is present on endosomes [69, 70]. Moreover, it has been revealed that CB₁ receptors are also present on mitochondrial membranes and regulate activity of mitochondria [71].

ENDOCANNABINOID SIGNALING IN ALZHEIMER'S DISEASE

Multiple data are available showing that the eCB system is implicated in AD progression. Cortex and hippocampus, key structures for learning and memory functions, are the two brain regions that are affected by AD pathology [72], and they express high levels of CB₁ receptors as well as other components of the eCB system [73]. Evidence suggests that microglia and astrocytes also express the enzymes involved in the synthesis and degradation of the eCBs and that the activation of cannabinoid receptors expressed by activated microglia controls immune-related function [59]. Moreover, eCBs are known to exert anti-inflammatory, antioxidant, and neuroprotective effects [7, 74–77].

Therefore, it is not surprising that eCB signaling plays a crucial role in AD. Table 1 compiles all reports addressing the expression levels of eCB signaling components in AD in humans as well as in *in vitro* and *in vivo* preclinical models. The major implications of dysregulated eCB signaling in AD are briefly discussed below.

The relationship of CB₁ receptors and AD is sparse and often contradictory in the literature. Westlake and colleagues evaluated the CB₁ mRNA expression and [³H]CP-55,940 (CB₁ and CB₂ agonist) binding density in postmortem AD human brains [78]. [³H]CP-55,940 binding was reduced but no alterations in CB₁ expression levels were observed in AD brains compared to aged-matched controls. Though [³H]CP-55,940 binding was reduced, it was not selectively associated with the AD-pathology. In accordance to this report, other research groups found that CB₁ receptor levels were unaltered in patients suffering from AD [79–81]. In contrast, significant decrease in CB₁ receptor expression has been reported in the cortex of AD patients [82, 83]. CB₁ expression was greatly reduced and CB₁ protein nitration was enhanced in the areas of microglial activation in AD brains [82]. However, reduced CB₁ levels were correlated to hypophagia but not with any AD molecular marker or cognitive status [83]. Furthermore, CB₁ receptor selective radioligand study revealed that CB₁ receptor density increases in early AD and decreases during later disease stages [84]. In line with these results, two recent papers by our group [85] and by Kalifa and his colleagues [86] reported a decrease in CB₁ protein expression in transgenic mice models of AD. However, we found that in aged triple transgenic mice of AD (3 × Tg-AD) CB₁ mRNA was significantly increased in limbic brain areas. Though we did not find a direct correlation between CB₁ mRNA and CB₁ protein, an inverse correlation between CB₁ protein levels and A β protein were observed in hippocampus and basolateral amygdala [85]. The reduced CB₁ expression in A β PPswe/PS1 Δ E9 mice was associated with astroglial proliferation and elevated expression of cytokines, iNOS and TNF- α [86]. Similarly, pretreatment with A β ₄₂ in rats and C6 rat astrogloma cells can cause a down-regulation of CB₁ receptor [87]. Furthermore, Ahmad and colleagues investigated the availability of CB₁ receptor in AD patients by positron emission tomography. This study neither found any difference in CB₁ receptor availability between AD and healthy volunteers nor found a correlation between CB₁ receptor and A β deposition [88]. Even though CB₁ receptors were unchanged, it has been proposed that the coupling between receptor and G_i protein could underlie the reduced signaling of CB₁ receptor [89]. A recent study further showed that CB₁ receptor activity depends on the AD stages. CB₁ activity was found higher at earlier AD stages in limited hippocampal areas and internal layers of frontal cortex, but a decrease was observed at the advanced stages [90]. The

Table 1
Altered eCB signaling in AD

Subjects	Tissue	Component of eCB system	Observation	Ref.
Human AD patient	Cortex, Hippocampus, Striatum, Anterior cingulate gyrus, Caudate nucleus	CB ₁ protein and binding	Unchanged	[79–81, 88]
Human AD patient	Hippocampus, Neocortex, Basal ganglia, Brainstem	CB ₁ mRNA CB ₁ binding	CB ₁ mRNA- Unchanged CB ₁ binding-reduced in hippocampus, substantia nigra, globus pallidus	[78]
Human AD patient	Cortex	CB ₁ protein	Decreased	[82, 83]
Human AD patient	Blood	CB ₁ mRNA	Increased	[97]
3 × Tg-AD mice	Hippocampus, BLA, Prefrontal cortex	CB ₁ mRNA and protein	CB ₁ mRNA-altered	[85]
Human AD patient	Prefrontal cortex	CB ₁ binding	CB ₁ protein- reduced in dorsal hippocampus and BLA CB ₁ density increases in early AD followed by decreases during later disease stages	[84]
Human AD patient	Prefrontal cortex, Hippocampus	CB ₁ -receptor-dependent Gi protein activation	CB ₁ activity increased at earlier AD stages and decreased at advance stages	[90]
AβPP ^{swe} /PS1ΔE9 mice	Hippocampus	CB ₁ protein	Decreased	[86]
AβPP ^{swe} /PS1ΔE9 mice	Hippocampus, Cortex	CB ₁ -receptor-dependent Gi protein activation	Unchanged	[191]
Rat (Aβ ₄₂ insult)	Brain/Cells	CB ₁ and CB ₂ mRNA/protein	CB ₁ -decreased CB ₂ -increased	[87]
Human AD patient	Cortex, Hippocampus, Blood	CB ₂ protein and mRNA	Increased	[79, 82, 83, 91, 92, 97]
Human DS patient	Cortex	CB ₂ protein and FAAH protein	Increased	[95]
AβPP ^{swe} /PS1ΔE9 mice	Cortex	CB ₂ binding	Increased	[96]
AβPP ^{SWE} /Neuro-2a cells	Neuro-2a cells	FAAH	Increased activity and expression	[93]
Human AD patient	Cortex, blood	FAAH protein, mRNA and activity	Increased	[79, 192]
Human AD patient	Cortex	AEA and NarPE	Decreased	[93]
Human AD patient	Plasma	AEA and 2-AG	Unchanged	[98]
PS1/AβPP mice	Whole brain	AEA and 2-AG	Increased	[99]
Rats (Aβ ₄₂ insult)	C6 glioma cells, Hippocampus	AEA and 2-AG	2-AG-Increased	[87, 101]
AβPP ^{swe} /PS1ΔE9 mice	Frontal cortex, Hippocampus and Striatum	AEA, 2-AG, PEA and OEA	AEA- decreased Decreased only in striatum	[193]
Human AD patient	Hippocampus	DAGL, MAGL, ABHD6	DAGL- increased MAGL- decreased ABHD6- abolished	[80]

CB₁ and CB₂, cannabinoid receptors; BLA, basolateral amygdala; DS, Down's syndrome; FAAH, fatty acid amide hydrolase; NarPE, 2-docosahexaenoyl-sn-glycerophosphoethanolamine-N-arachidonoyl; AEA, anandamide; 2-AG, 2-arachidonoylglycerol; DAGL, diacylglycerol lipase; MAGL, monoacylglycerol lipase; ABHD6, serine hydrolase α/β hydrolase 6.

increased CB₁ receptor activity during the initial stages of AD might indicate neuroprotective action mediated by eCBs in response to initial neuronal damage.

Differently from CB₁ receptor, the relationship between CB₂ receptor and FAAH in AD pathology is well documented in the literature. In fact, postmortem

brains from patients with AD revealed that CB₂ receptors and FAAH are selectively overexpressed in cells that are associated to Aβ-enriched neuritic plaques [79, 80, 82, 83, 91, 92]. The hydrolytic activity of FAAH is enhanced in Aβ₄₂ plaques and surrounding areas [79, 93]. Increased FAAH activity may contribute to inflam-

matory processes by increasing AA (precursor for proinflammatory molecules) through increased AEA metabolism in astrocyte cells surrounding plaques. Moreover, FAAH is selectively overexpressed in reactive astrocytes and CB₂ receptors are overexpressed in activated microglial cells in AD [79, 94, 95]. Similarly, in Down's syndrome, characterized by A β deposition, increased FAAH activity and CB₂ expression have been observed [95]. Moreover, increased levels of CB₂ receptors were positively correlated with A β ₄₂ and senile plaque score [83]. Apart from human studies, transgenic model of AD has also revealed overexpression of CB₂ receptors in brain areas affected by the AD-pathology [96]. Increased CB₂ mRNA in peripheral blood has been suggested as a peripheral biomarker for the early diagnosis of AD [97]. Pretreatment with A β ₄₂ to rats and C6 rat astrogloma cells also increases CB₂ receptor expression [87].

Since AEA and, to a lesser extent, 2-AG are the substrates of FAAH, reduction in AEA and/or 2-AG can be expected in brain areas severely affected by AD pathology. In line with this, Jung and colleagues reported that AEA and its precursor 1-stearoyl, 2-docosahexaenoyl-sn-glycerophosphoethanolamine-N-arachidonoyl (NarPE) levels, but not 2-AG, were significantly reduced in cortex of AD patients [93]. However, AEA and 2-AG plasma levels were unchanged in AD patients compared to healthy volunteers [98]. Moreover, AEA and NarPE levels in cortex were positively correlated to cognitive impairment and inversely correlated to A β ₄₂; however, no correlation was found with plasma eCBs and cognitive performance [93, 98]. Conversely, AEA and 2-AG levels were found to be increased in brains of the PS1/A β PP transgenic mice of AD [99]. Mulder and colleagues found that 2-AG signaling is altered in postmortem AD brains. The expression of 2-AG synthesizing enzyme, i.e., DAG lipase, was significantly and selectively increased in microglia surrounding senile plaques [80, 100]. The activity of 2-AG degrading enzymes, MAGL and ABHD6, was differentially altered in hippocampal neurons. ABHD6 expression was completely abolished and MAGL expression was lowered in NFT-bearing pyramidal neurons. This study demonstrated that AD progression slows down the termination of 2-AG signaling and that could contribute to synapse silencing particularly around senile plaques [80]. Apart from postmortem analyses and transgenic models of AD, studies on animal models of AD induced by acute administration of A β ₄₂ have also shown the increase of DAG lipase and 2-AG levels [87, 101].

BENEFICIAL EFFECTS OF CANNABINOIDS IN TREATMENT OF ALZHEIMER'S DISEASE

Increasing evidence suggests that the eCB system could be a potential target for the treatment of AD. During the last decade, an ample number of interesting studies allowed for a new perspective into the prevention and/or treatment of AD focusing on the eCB system (for review, see [5–10, 74–76, 102–104]). Cannabinoids could exert neuroprotective, antioxidant, anti-apoptosis, and anti-inflammatory effects [77]. Cannabinoids play a neuroprotective role, through the CB-receptor activation, by preventing excitotoxicity, calcium efflux, and inflammation as well as by modulating other signaling pathways [105]. Most of the initial reports on the effects of cannabinoids in AD were investigated in *in vitro* models of A β -induced neuronal toxicity. Later, these investigations were extended to animal models of A β -induced toxicity and to transgenic murine models expressing plaques and/or tangles pathology. Table 2 compiles the *in vitro* and *in vivo* experimental evidence of beneficial effects of cannabinoids in AD treatment. Figure 1 summarizes the probable molecular and cellular mechanisms underlying these beneficial effects. In the following section the effects of cannabinoids on various pathological processes of AD will be discussed.

A β generation and clearance

Microglia plays an important role in phagocytosis of A β , and there is an inverse relationship between cytokine production and A β clearance [26, 106]. CB₂ activation is known to reduce microglia activity and inflammatory cytokines productions [107]. So it can be hypothesized that CB₂ agonist could lower A β plaque load by increasing A β clearance. In line with this hypothesis, it has been shown that *in vitro* activation of CB₂ receptor facilitates the removal of native A β from human frozen tissue sections as well as the removal of synthetic pathogenic peptide by a human macrophage cell line [108]. Moreover, a CB₂ agonist was able to induce a prompt A β clearance in A β -induced animal model of AD [109]. The mechanism underlying CB₂ mediated decrease in A β plaque load is not clear yet. However, it was suggested that it might be link to a lower the production of inflammatory cytokines and increase of A β phagocytosis that might decrease A β plaque load [107]. The role of CB₂ receptors in lowering A β plaques was further confirmed by a study where CB₂ receptors were deleted in A β PP mutant

Table 2
Beneficial effects of modulators of the endocannabinoid system and their molecular mechanisms in AD

Subjects	Treatment	Effects and mechanism involved	Ref.
Endocannabinoids			
Ntera 2/cl-D1 neurons (A β insult)	AEA	↓ A β toxicity	[149]
Wistar rats (A β_{42} insult)	Noladin ether	MAPK pathway activation	[101]
	VDM-11	Reversed hippocampal damage Improved memory retention	
PC12 cells	AEA	↑ cell viability	[150]
SH-SY5Y cells (A β_{40} and peroxide insult)		CB ₁ mediated effect	
vitro model of the BBB	2-AG	↑ A β clearance	[112]
	JZL185	↑ expression of LRP1	
	JZL 195		
Primary hippocampal neurons (A β_{25-35} , A β_{42} insult)	2-AG	↓ neurodegeneration	[145]
	URB602 JZL184	↓ apoptosis ↓ capsase-3 cleavage CB ₁ mediated effect ↓ ERK1/2 and NF κ B phosphorylation ↓ COX2 ↓ inflammation	[137]
Mouse astrocytes (A β treatment)	AEA, PEA and OEA		
eCB degradation enzyme inhibitors			
Primary cortical neurons (A β treatment)	AEA, 2-AG, URB597	↓ Apoptosis	[148]
A β PP/PS1 AD mouse	Genetic/pharmacological inactivation of MAGL	↓ lysosomal membrane permeabilization	[99]
		↓ arachidonic acid, PGE2, PGD2, TXB2	
5 \times FAD A β PP transgenic mice	JZL184	↓ GFAP, CD11b, TNF- α , IL-1 β , IL-6, A β_{42} , A β_{40} ↓ BACE1 expression ↓ A β levels ↓ neuroinflammation Improved learning and memory	[115]
Cannabinoid agonists			
microglial cells (A β insult)	HU-210, WIN55,212-2, and JWH-133	↓ microglia-mediated neurotoxicity	[82]
Human fetal astrocytes (IL-1 β insults)	WIN55,212-2 (mixed CB ₁ /CB ₂ agonist)	↓ production of inflammatory mediators	[134]
C6 rat glioma cells (A β insult)	WIN 55,212-2	↓ iNOS expression ↓ NO production	[121]
SD rats brain slices	WIN 55212-2	↓ acetylcholine release	[194]
Wistar rats (A β_{42} insult)	ACEA (CB ₁ agonist)	↓ caspase 3	[151]
	WIN-55212-2	Improved memory deficits ↓ Ca ⁺² currents in CA1 neurons	
Rats (A β_{42} treatment)	Win55,212-2	↓ inflammation CB ₁ , CB ₂ and PPAR- γ mediated	[140]
A β PP23/PS45 double transgenic mouse model of AD	HU210 (mixed CB ₁ /CB ₂ agonist)	Unchanged A β PP and A β levels	[172]
microglial cells (A β insult)	JWH-015 (CB ₂ agonist)	No effect on learning and memory ↓ microglial activation ↓ phosphorylation of JAK/STAT1 ↑ phagocytosis of A β_{42}	[107]
human brain microvascular endothelial cells, mice	JWH133 (CB ₂ agonist)	↓ intercellular adhesion molecule-1	[185]
Rats (A β_{40} insult)	MDA7 (CB ₂ agonist)	↓ vascular cell adhesion molecule-1 ↑ BBB integrity	[129]
		↓ CD11b expression ↓ GFAP expression ↓ interleukin-1 β ↑ A β clearance restored cognition and memory	

Table 2
(Continued)

Subjects	Treatment	Effects and mechanism involved	Ref.
Tg A β PP mice	JWH-133 (CB ₂ agonist)	Improves cognitive performance ↓ Iba-1, COX-2, TNF- α ↓ A β ₄₀ , A β ₄₂ and CB ₂ ↓ GSK3- β tau phosphorylation kinase	[141]
Pharmacological or genetic inhibition of cannabinoid receptors			
swiss mice (A β _{25-35,42} insult)	Rimonabant (CB ₁ antagonist)	improves A β -induced amnesia	[173]
A β PP23/ CB ₁ ^{-/-} mice		↓ A β PP levels, plaque load ↓ neuroinflammation Impaired learning Memory deficits	[111]
A β PP/CB ₂ ^{-/-} mice		↑ soluble A β ₄₂ ↑ A β ₄₂ plaque ↑ microglia activation ↓ soluble tau	[110]
Phytocannabinoids			
Rat cortical neuron culture (glutamate insult)	Cannabidiol Δ^9 -THC	↓ glutamate toxicity	[158]
microglial cells C57/B16 Mice (A β ₄₀ insult)	Cannabidiol	-Antioxidant effect ↓ ATP induced Ca ⁺²	[131]
	WIN 55,212-2	↑ microglia migration	
	JWH-133	↓ NO, TNF- α , IL-6 ↓ cognitive impairment	
C57BL/6J mice (A β ₄₂ insult)	cannabidiol	↓ GFAP ↓ iNOS and IL-1b	[132]
AChE from Electrophorus electricus	Δ^9 -THC	inhibits AChE	[175]
N2a/A β PP _{swe} cells	Δ^9 -THC	↓ AChE-induced A β aggregation ↓ A β levels ↓ A β aggregation	[124]
PC12 neuronal cells (A β ₄₂ insult)	cannabidiol	↓ GSK-3 β and p-GSK-3 β ↓ tau hyperphosphorylation ↓ p-GSK-3 β	[122]
PC12 cells (A β ₄₂ insult)	cannabidiol	↑ β -catenin ↓ iNOS, NO ↓ p38 MAP kinase ↓ NF κ B	[135]
Primary cultured astrocytes Rats (A β ₄₂ insult)	cannabidiol	↓ NO, TNF- α , IL-6, S100B ↓ reactive gliosis ↑ neurogenesis Mediated through PPAR- γ	[133]
Neuroblastoma cells (A β ₄₂ insult) microglial	ACEA (CB ₁ agonist)	↓ A β fibrils	[109]
BV-2 cells (LPS insult)	JWH-015 (CB ₂ agonist)	↑ neuronal cell viability	
	Δ^9 -THC, cannabidiol, 2-AG, AEA	neuroprotective action	
PC12 cells (A β insult)	Cannabidiol	neuroprotective, anti-oxidative anti-apoptotic	[156]
A β PP/PS1 mice	Cannabidiol	Inhibits development of social recognition memory deficits	[170]
A β PP/PS1 mice	Cannabidiol + Δ^9 -THC	↑ dietary phytosterols ↓ learning impairment ↓ soluble A β ₄₂ peptide levels ↓ astrogliosis, microgliosis, and inflammatory-related molecules	[171]

mice (PDGFB-A β PP_{swe}Ind). Results from this study revealed that soluble A β and plaque deposition were significantly increased in A β PP/CB₂^{-/-} mice compared to A β PP/CB₂^{+/+} mice [110].

The exact role of CB₁ receptor is not yet clear in same context. Effect of cannabinoid treatment

on A β fibril and aggregate formation was recently reported. Biochemical and morphological assessment showed that Δ^9 -THC, among other cannabinoids (eCBs, CB₁ and CB₂ agonist), significantly reduced fibril and aggregate formation [109]. However, CB₁ receptor deletion from A β PP23 transgenic mouse

model of AD resulted in reduced amount of A β PP, reduced A β plaque load and less inflammation [110]. A β PP23/CB $_1^{-/-}$ mice showed lower body weight and most of the animals died before typical AD associated changes could become apparent [111]. Though the A β PP23/CB $_1^{-/-}$ study questioned the beneficial role of CB $_1$ receptors in the A β generation and clearance, another study by Bachmeier and colleagues [112] supported the hypothesis that CB $_1$ agonist could increase A β clearance from the brain. In fact, this study showed that CB receptor agonist or pharmacological elevation of eCBs significantly enhanced A β clearance from the brain [112]. eCBs increased A β clearance across the blood-brain barrier by increasing the expression of A β transport protein, lipoprotein receptor protein 1 (LRP1). Moreover, this study suggests that eCBs could decrease the A β brain burden not only due to changes in A β synthesis or release but also due to increase in A β transport from brain to periphery by the way of blood-brain barrier. It has been proposed that eCBs, through CB $_1$ receptor, activate PPAR- γ receptor, which has been shown to stimulate expression of LRP1 [113, 114]. Furthermore, MAGL inactivation reduced A β plaque load and also suppressed the expression of β -secretase (beta-site A β PP cleaving enzyme 1; BACE1), an enzyme involved in the production of A β_{42} [115].

Tau hyperphosphorylation

Abnormal hyperphosphorylation of tau prompts an accumulation of NFTs in axons of neurons, can impair normal axonal transport, disrupt synaptic plasticity, and finally induce cell loss [116]. The link connecting A β plaques and tau pathologies has remained elusive. Evidence suggests that abnormal activation of kinases like glycogen synthase kinase-3 β (GSK-3 β), MAPK family members as well as caspases may be responsible for hyperphosphorylation of tau [117, 118], and A β might be involved in the activation of these enzymes [119]. Along with various kinases, NO secreted from astrocytes induces tau hyperphosphorylation in neurons [120]. It has been shown that arachidonoyl-2'-chloroethylamide (ACEA), a selective CB $_1$ agonist, down regulates iNOS protein expression and NO production in astrocytes, and that leads to a significant inhibition of NO-dependent tau hyperphosphorylation in neurons [121]. In another report [122], it has been demonstrated that cannabidiol (a non psychoactive component of marijuana) inhibits hyperphosphorylation of tau protein in A β -stimulated neuronal cells. The effect of cannabidiol was mediated through the

Wnt/ β -catenin pathway [122]. Wnt activation leads to inhibition of GSK-3 β , which is also known as tau protein kinase, responsible for a massive tau protein hyperphosphorylation and relative NFT formation observed in brains of AD patients [123]. A recent report also demonstrated that Δ^9 -THC treatment inhibits activation of GSK-3 β in N2a-variant A β PP cells [124].

Neuroinflammation

Besides plaques and NFTs, neuroinflammation plays a major role in neurodegeneration and activation of various apoptosis pathways. The notion that A β is a pathological molecule is slowly changing and it seems that it represents a cellular adaptive strategy to oxidative stress [125]. A β is a proinflammatory molecule, which can induce its own production by increasing the expression of its synthesizing enzymes such as β -secretase (BACE1) and through various inflammatory pathways [125]. In particular, it has been recognized that A β is able to initiate an inflammatory response, which in turn activates microglia and recruits astrocytes, and therefore the release of inflammatory mediators (IL-1 β , TNF- α , and IL-6), reactive oxygen species (NO), and neurotoxic products that have been involved in neuronal and synaptic damage [31]. Neuroprotective effects of eCBs against brain injury and inflammation is associated with reduction of cytokines, ROS, and prostaglandins [126–128]. eCB modulators can reduce neuroinflammation in AD by inhibiting glial cell activation and generation of pro-inflammatory precursor molecules.

Regulation of glial cell activity

As discussed earlier in this review, CB $_2$ and FAAH expression is upregulated in microglia and astrocytes, respectively, in surrounding areas of neuritic plaques in AD brains. This notion suggests that both microglia and astrocytes play an important role in eCB signaling in AD pathology. It seems that upregulation of CB $_2$ receptor in AD is a defensive mechanism to limit inflammation and to clear plaques from the affected brain region [79, 110, 129]. CB $_2$ receptors are coupled to G $_{i/o}$ inhibitory proteins so that their activation is associated with inhibition of adenylyl cyclase and the cAMP/protein kinases A (PKA) dependent pathway [130]. CB $_2$ receptor activation could provide beneficial effects at various levels. In particular, CB $_2$ activation could 1) suppress activation of microglia, 2) reduce production of inflammatory molecules like IL-1 β , IL-6, TNF- α , NO, etc., 3) enhance microglial

proliferation, and 4) enhance microglial phagocytic activity [59, 82, 107, 108, 131].

The effects of non selective cannabinoid agonists on microglial activation were demonstrated by Ramirez and colleagues [82]. In their study authors investigated the effects of non selective cannabinoids and selective CB₂ agonists in A β -induced microglial cells [82]. As expected, A β peptide activated microglial cells with increased mitochondrial activity, TNF- α release, and cellular morphological changes. Cannabinoid treatment prevented the enhancement of TNF- α release and counteracted A β -mediated activation of microglia. Furthermore, mechanistic insight of beneficial effects provided by CB₂ receptor stimulation in AD was demonstrated. Stimulation of CB₂ receptor significantly attenuated CD40-mediated inhibition of microglial phagocytosis of A β ₄₂ peptide [107]. Cannabidiol dose dependently reduced A β -induced neuroinflammation by suppressing microglial activation, IL-1 β and iNOS expression [132].

It has been also shown that cannabinoid treatment, in activated astrocytes, inhibits synthesis of inflammatory chemokines and NO release [133]. Win55,212-2, an agonist of CB₁ and CB₂ receptors, inhibited inducible NO synthase (iNOS) and corresponding NO production in astrocytes activated by IL-1 β [134]. Win55,212-2 treatment also inhibited production of chemokines (CXCL10, CCL2, and CCL5) and TNF- α . Both selective CB₁ and CB₂ antagonists partially blocked these effects suggesting the involvement of both receptors [134]. Cannabidiol markedly down-regulates, in a PPAR- γ dependently manner, A β -induced reactive gliosis by reducing proinflammatory molecules and cytokine release [133]. PPAR- γ activation could inhibit NF κ B pathway, which is involved in the synthesis of inflammatory cytokines [135, 136]. In another report, different N-acylethanolamides (AEA, PEA, and OEA) were able to exert anti-inflammatory effects in A β -activated murine astrocytes [137]. Previous studies have shown that N-acylethanolamines activate anti-inflammatory nucleic acid receptor PPAR- α that causes formation of a multiprotein complex along with variable set of protein co-activators [138]. With this multiprotein complex, PPAR- α binds to responsive elements on DNA and enhances the transcription of various anti-inflammatory proteins, such as inhibitor of κ B- α (I κ B- α), that suppress the gene expression of pro-inflammatory components, such as cytokines (TNF- α , IL-1 β) including iNOS and COX-2 (see Fig. 1) [138, 139]. Anti-inflammatory effects of cannabinoids have been also demonstrated in A β -induced *in vivo* AD

models [129, 140] and transgenic mice models of AD [141].

Regulation of pro-inflammatory precursors

Phospholipase A2 (PLA2) enzymes are considered the primary source of AA for COX-mediated biosynthesis of prostaglandins [142]. Recently, Nomura and colleagues [143] have shown that MAGL-mediated hydrolysis of 2-AG can act as a distinct pathway to generate AA in the brain [143]. In line with this report, two independent research teams [99, 115] reported that the inactivation of MAGL reduced neuroinflammation, neurodegeneration, and the production and accumulation of A β plaques in the transgenic mice of AD. These effects were not mediated by CB₁ and/or CB₂ receptors but were caused by reduced production of AA [99, 136]. The inhibition of MAGL also improved the neuronal plasticity and learning and memory deficits [99, 115]. Inactivation of MAGL for eight weeks was sufficient to decrease production and deposition of A β plaques and the function of BACE1, the enzyme involved in making toxic A β in the brain (Fig. 2) [115]. These results suggest that MAGL contributes to the cause and development of AD and that the inhibition of MAGL might represent a promising potential therapeutic target.

MAGL inhibition can cause an elevation of 2-AG endogenous levels. In turn, 2-AG, by activating CB₁ receptor is able to suppress COX-2 elevation in response to inflammatory insult like lipopolysaccharide [144]. Furthermore, it was revealed that the neuroprotective effects of 2-AG were mediated by CB₁ but not by CB₂ or TRPV1 receptors [145]. CB₁ receptor activation by 2-AG suppresses phosphorylation of ERK1/2/p38MAPK/NF κ B in neurons, which further suppresses COX-2 expression (Fig. 2) [144, 145]. COX-2 plays an important role in production of prostaglandins, which are crucial in neuroinflammation [142]. Further research in this field revealed that PPAR- γ , mediates 2-AG-induced inhibition of NF κ B phosphorylation and COX-2 expression in response to pro-inflammatory IL-1 β . Moreover, 2-AG is able to restore IL-1 β -induced reduction of PPAR- γ expression in CB₁ dependent mechanism [146]. Inflammation activates the transcription factor NF κ B, for which β -secretase (BACE1) promoter harbors a highly conserved binding site that is functional [125]. Thus NF κ B activates BACE1 promoter, expression, and enzymatic activity leading to increased A β production. The prostaglandin PGE₂ after production stimulates the generation of A β through both EP2 and EP4 receptors (PGE₂ receptors). Activation of the EP4 receptor

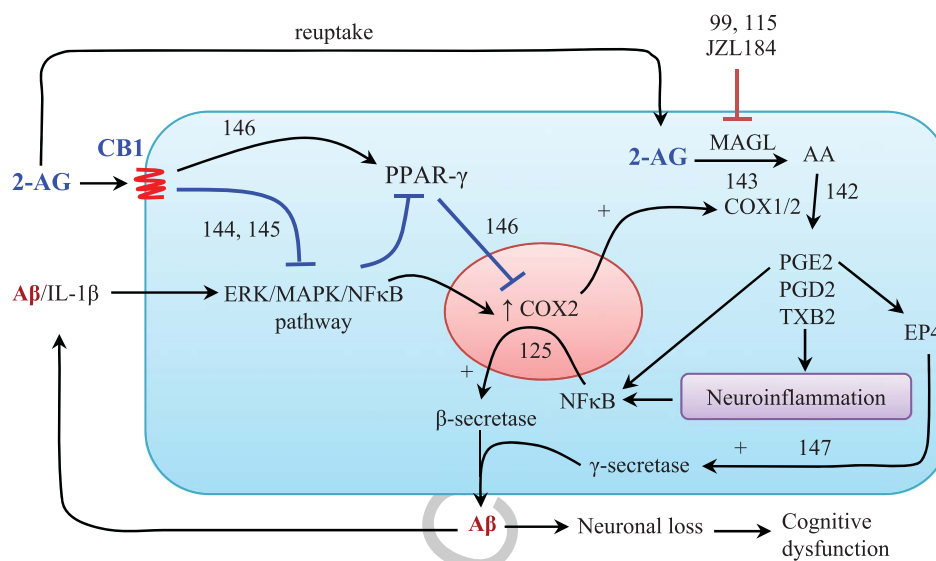


Fig. 2. Modulation of 2-AG signaling provides anti-inflammatory effects in AD. Through a CB₁-dependent mechanism, 2-AG increases PPAR- γ expression, which is suppressed by A β ₄₂ in AD. 2-AG directly, through CB₁ and PPAR- γ receptors, inhibits the expression of COX-2 and the synthesis of inflammatory cytokines. COX-2 plays a major role in the synthesis of proinflammatory prostaglandins from arachidonic acid (AA), which is a degradation product of 2-AG. Proinflammatory prostaglandins can increase neuroinflammation as well as the expression and activity of β - and γ -secretase resulting in increased A β production. Inflammation activates the transcription factor NF κ B, for which β -secretase (BACE1) promoter harbors a highly conserved binding site that is functional. Thus, NF κ B activates BACE1 promoter, expression, and enzymatic activity leading to increased A β production. Prostaglandin PGE₂ stimulates the generation of A β through both EP₂ and EP₄ receptors (PGE₂ receptors). Activation of the EP₄ receptor stimulates A β production through the endocytosis and the activation of γ -secretase. The inhibition of prostaglandin synthesis by MAGL inhibitors could suppress all these mechanisms.

stimulates A β production through endocytosis and activation of γ -secretase [147].

Neurodegeneration

A β has been shown to induce cell apoptosis in neuronal cells through a variety of mechanisms that include activation of caspase-3, lysosomal cathepsins, and lysosomal membrane permeabilization [17, 118]. Cannabinoids at physiological concentrations increase lysosomal stability and integrity [148]. Noonan and colleagues showed that eCBs can stabilize lysosomes against A β permeabilization and can increase cell survival. eCBs prevented upregulation of tumor suppressor protein, p53, and reduced its interaction with lysosomal membrane [148]. Moreover, 2-AG and AEA prevented A β -induced increase in DNA fragmentation and caspase-3 activation [101]. Acute *in vivo* administration of A β increases 2-AG release in the brain suggesting that endogenous 2-AG plays an important role in protecting neurons from A β -induced toxicity [101].

Milton and colleagues [149] showed the neuroprotective effects of eCBs (AEA and nodaline ether) on

A β -induced neurotoxicity. These effects were mediated by CB₁ receptors and the MAPK pathway activation as suggested by the finding that CB₁ antagonist and MAPK inhibitor blocked their neuroprotective effects. Another study confirmed the neuroprotective effect of AEA on A β -evoked neurotoxicity via a pathway unrelated to CB₁ and CB₂ [150]. In fact, selective CB₁ and CB₂ agonists were unable to protect neurons against A β challenge [150]. Further research revealed that increasing endogenous levels of 2-AG by MAGL inhibitor was able to protect hippocampal neurons from A β -induced neurodegeneration and apoptosis [145]. Active caspase-3 levels are increased in AD [118]. CB₁ agonist was also able to inhibit A β -induced activation of caspase-3 [145, 151]. CB₁ knock-out studies indicated that lack of CB₁ is associated with increased caspase activation and greater loss and/or alterations of myelin and axonal/neuronal proteins [152].

Oxidative damage and mitochondrial dysfunction

Enhanced oxidative stress in brain generally correlates with cognitive decline and with enhanced risk for development of neurodegenerative diseases. Among

the different pro-inflammatory proteins produced in response to A β -induced oxidative stress, iNOS and its enzymatic product NO [105, 153] are considered the most important neurotoxic effectors during AD. In particular, methionine-35 of A β ₄₂ is critical for oxidative stress (for more details, see [154]). NF κ B, a redox-sensitive transcription factor that is activated by a family of stress activated kinases (SAPK) including p38 MAP kinase [122], regulates the expression of different genes involved in cell differentiation, proliferation, and apoptosis, as well as in oxidative, inflammatory, and immune response [155]. As it is well known, NF κ B activation is of primary importance to induce iNOS protein transcription [156] both in A β -stimulated neuronal cells [156] and in postmortem AD brains [157]. It is well known that phytocannabinoids have anti-oxidant properties [158]. Cannabidiol is a well studied cannabinoid in this context. It has been shown that cannabidiol significantly decreases glutamate toxicity, Ca⁺² toxicity, iNOS expression, and NO production [131, 158]. Cannabidiol mediates these effects through inhibition of p38 MAPK and NF κ B pathways probably through involvement of the PPAR- γ receptor [132, 133, 135]. Moreover, CB₁ agonists were also shown to decrease iNOS and NO production [121, 131]. In another study, cannabidiol treatment significantly decreased ROS, lipid peroxidation, caspase-3 levels, DNA fragmentation and intracellular calcium [156].

CB₁ receptors are also expressed on mitochondria and regulate its activity [71]. Activation of mitochondrial CB₁ receptors can decrease oxidative metabolism, oxygen consumption, ROS production, and oxidative phosphorylation [71, 159–161]. In oxidative stress conditions, cannabinoids have shown protective actions against mitochondrial damage and have decreased Ca⁺²-induced cytochrome c release from mitochondria (Fig. 1) [162–164].

Memory and learning impairments

CB₁-mediated effects of cannabinoids on learning and memory have been reported for many years [165]. eCBs are involved in modulation of long-term plasticity such as LTP [166], a cellular model of learning and memory. Activation of CB₁ receptors on the GABAergic neurons leads to a decrease in GABA release [166] and thus to formation of the depolarization-induced suppression of GABAergic inhibition (DSI). Importantly, DSI temporarily removes GABAergic inhibitory tone and facilitates LTP of pyramidal neurons. It has been reported that A β strongly suppresses

LTP in hippocampal synapses and this is one of the cause for observed learning and memory deficits in AD [167]. Recently, Orr and colleagues demonstrated a possible role of eCB signaling in A β -induced reduction in LTP and excitatory postsynaptic potential-spike coupling (E-S) potentiation [168]. In this study, authors showed that A β inhibits E-S potentiation through suppression of CB₁-dependent synaptic disinhibition. This effect is not a direct effect on excitatory synapses but rather it is an indirect effect, which involves the reduction of eCB mediated GABAergic disinhibition. In another study, it has been shown that deletion of CB₁ receptors from the forebrain GABAergic, but not glutamatergic neurons, led to a neuronal loss and increased neuroinflammation in the hippocampus as observed in brain aging [169]. The same authors suggested that CB₁ receptor activity on hippocampal GABAergic neurons protects against age-dependent cognitive decline by reducing pyramidal cell degeneration and neuroinflammation [169].

Moreover, the consequences of CB₁ receptor deficiency on development of AD pathology were studied by knocking out CB₁ receptor in A β PP23 mice of AD. A β PP23/CB₁^{-/-} mice showed worsen cognitive deficits than A β PP23 mice, thus suggesting that CB₁ deficiency can worsen AD-related learning and memory deficits [111]. Moreover, an eCB re-uptake inhibitor, VDM-11, reversed A β -induced hippocampal damage and memory impairment in passive avoidance test [101]. Further research in this field revealed that cannabinoid treatment was able to prevent A β -induced memory impairments in rats and that CB₁, but not CB₂, receptors may be directly involved in improving A β -induced memory impairments and intrinsic electrophysiological properties of hippocampal pyramidal neurons [151]. Fakhfour and colleagues [140] showed that administration of the synthetic cannabinoid agonist, Win55,212-2, significantly improved memory functions and decreased the elevated levels of neuroinflammatory markers like TNF- α , active caspase-3, and nuclear NF κ B. Antagonist experiment confirmed that these neuroprotective effects of Win55,212-2 were partially mediated by CB₁ and CB₂ receptors [140]. Through CB₁ receptor, Win55,212-2 increased PPAR- γ pathway by increasing its transcription activity and provided neuroprotection [140]. Furthermore, the effects of cannabinoids were studied in transgenic murine models of AD. Prolonged oral treatment of CB₂ receptor agonist (JWH-133) was able to improve cognitive impairments and decrease microglial activation in Tg2576 mice, while Win55,212-2 was ineffective [141]. Moreover, both cannabinoids significantly

reduced the expression of CB₂ receptor, TNF- α and COX-2 suggesting a critical role of CB₂ in inflammatory processes in AD [141]. Recently, it has been shown that long-term treatment with cannabidiol was able to prevent the development of social recognition deficits in the A β PP/PS1 mouse model of AD [170]. The authors further revealed that these effects were not associated with decreased A β plaque load or oxidative changes while they noticed subtle effects induced by cannabidiol on neuroinflammation and cholesterol levels [170]. Moreover, a different study conducted on the same model showed that a combined treatment with cannabidiol and Δ^9 -THC reduced learning impairment, decreased soluble A β_{42} peptide levels and caused a change in plaques composition [171].

However, there are few reports that do not support beneficial effects of cannabinoids in AD treatment. Chen and colleagues found that chronic administration of the cannabinoid agonist HU-210 to A β PP23/PS45 double transgenic mice did not improve water maze performance or a contextual fear conditioning task [172]. HU-210 neither altered A β PP processing and neuritic plaque formation nor enhanced hippocampal neurogenesis in A β PP23/PS45 transgenic mice. It has been reported that CB₁ blockade by rimonabant improved A β -induced memory impairments in mice tested in a passive avoidance paradigm. The authors suggested that such memory improvement might be due to the increased acetylcholine release in the brain [173].

Additional effects of cannabinoids

Apart from aforementioned mechanisms, few cannabinoids exert their therapeutic effects in similar way of currently US-FDA approved drugs for AD treatment. Most of the drugs currently used in AD treatment (donepezil, rivastigmine, and galantamine) are inhibitors of AChE. AChE is involved in degradation of neurotransmitter acetylcholine (ACh), which is reduced in AD [174]. Active component of marijuana, Δ^9 -THC, has been demonstrated to competitively inhibit AChE and to thus increase ACh levels [175]. Moreover, Δ^9 -THC prevented AChE-induced aggregation of A β which can reduce plaques formation [175]. In addition to Δ^9 -THC, other CB agonists also showed to have AChE and butyrylcholinesterase inhibition properties [176]. Alternative strategies based on multiple targets such as CB receptors and cholinesterase with single compound is gaining acceptance for treatment of AD.

Besides AChE inhibitors, current AD treatment includes memantine, a NMDA receptor antagonist, which reduces excitotoxicity by inhibiting Ca⁺² influx. In similar way, HU-211 (synthetic cannabinoid devoid of CB₁ and CB₂ agonist activity) protects neurons from excitotoxicity by antagonizing NMDA receptors [177–179].

Moreover, recently it was demonstrated that eCBs can modulate A β -induced alterations in Notch signaling. Notch signaling plays a pivotal role in neurodevelopment, and it is also involved in control of neurogenesis, neuritic growth, synaptic plasticity, and long term memory [180, 181]. In advance neurodegeneration, Notch signaling is reduced [180]. Long term spatial deficits were observed in Notch mutant mice [182]. It has been shown that A β negatively regulates Notch-1 signaling by increasing expression of Numb, the endogenous negative regulator of Notch-1 cleavage [183]. Interestingly, AEA, through CB₁ receptors, was able to reverse this effect by increasing expression of Notch-1 signaling components like nicastrine, Notch intracellular domain, Hes1 and Hes5 (see Fig. 1). Moreover, AEA and 2-AG were also able to inhibit A β -induced expression of Numb [183].

Furthermore, cannabinoids could provide beneficial effects by modulating cerebral blood flow functions. AD is characterized by a decreased regional cerebral blood flow that could result in decrease brain supply of oxygen, glucose, and nutrients. Cannabinoids can improve blood flow to the brain as CB₁ receptor activation can elicit vasodilatation [184]. Moreover, as discussed earlier, cannabinoids can increase A β clearance at blood brain barrier [112]. CB₂ receptor activation has been shown to improve blood-brain barrier integrity by decreasing adhesion of leukocytes to endothelial cells under inflammatory conditions [185], which may reduce further exaggeration of inflammation.

However, besides beneficial effects, cannabinoids (especially at high doses) may exert unwanted cannabimimetic and psychiatric side effects such as hypolocomotion, hypothermia, aversion, and anxiety-related behaviors [186–189]. Moreover, CB₁ receptor activation may precipitate episodes of psychosis and panic while its inhibition may lead to depression and anxiety-related disorders (for more details, see [190]). Furthermore, CB₁ agonists may worsen AD by inhibiting acetylcholine release in the brain [7]. CB₂ agonist and inhibitors of endocannabinoid deactivating enzymes seems to be devoid of such side effects. Therefore, much attention has been focused on this kind of compounds as potentially useful for the AD treatment.

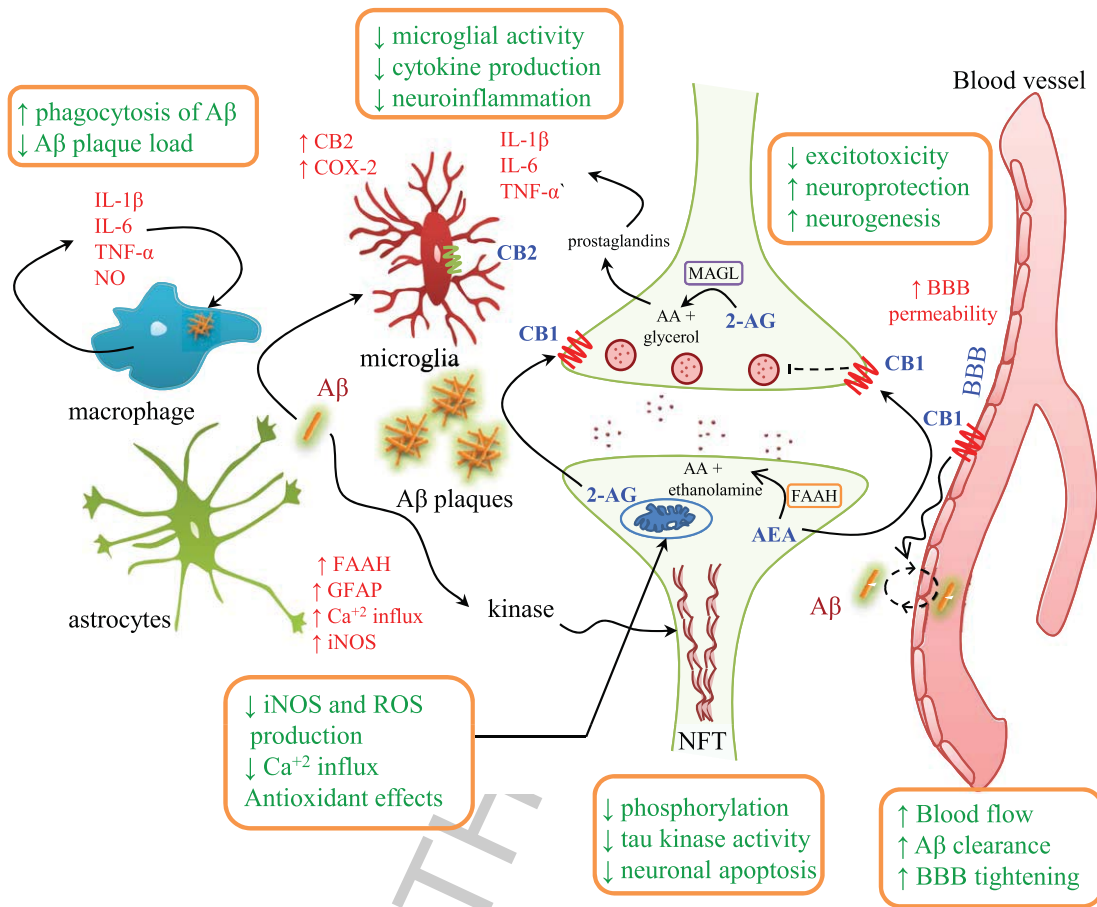


Fig. 3. Schematic diagram showing the beneficial effects of cannabinoid treatment in AD. Cannabinoid treatment can modulate multiple disease processes, which could reduce A β and phosphorylated tau deposition, neuroinflammation, oxidative damage, microglial activation, and excitotoxicity. Moreover, it can provide beneficial effects by increasing A β clearance, neurogenesis, neuroprotection and cerebral blood flow.

CONCLUSIONS

The advances in AD research in the last decade have revealed that this disease is multifaceted in nature and is linked to different multiple mechanisms in the brain. A novel, more effective therapeutic approach for AD treatment should target multiple mechanism of disease progression. A large body of evidence suggested the involvement of the eCB system in the neurodegenerative process associated with AD. A β deposition in the brain is linked to significant changes in the expression pattern of CB2 receptors and FAAH enzyme. CB2 receptors and FAAH are selectively and abundantly overexpressed in microglia and astrocytes, respectively, in vicinity of A β neuritic plaques. AEA and its precursor NarPE levels are decreased in frontal cortex. In contrast, 2-AG degrading enzymes MAGL and ABHD6 activity is reduced in plaques and sur-

rounding area. Over all AEA signaling is lowered and 2-AG signaling is increased in the vicinity of plaques. CB1 receptors expression in AD is still controversial and brain region specific. Although results of different groups are sometimes conflicting, a decline in the eCB system activity in AD is probable.

This review proposes cannabinoids as potential therapeutics, which can target simultaneously neurodegeneration, neuroinflammation, oxidative damage, cognitive impairments, and clearance of A β from the brain. Figure 3 summarizes the beneficial effects of cannabinoids in AD treatment. Elevation of CB receptor activity either by pharmacological blockade of enzymes responsible for eCBs degradation or by direct receptor agonist could be a promising strategy for slowing down the progression of AD and alleviating its symptoms. Although increased CB $_2$ expression and hydrolyzing FAAH activity is well

documented in human AD patients as well as animal models of AD, a combination therapy of CB₂ agonist and FAAH inhibitor did not receive much research attention. This combination therapy could potentially lead to more effective treatment for AD, as they would target the altered eCB signaling in AD patients and could thereby reduce neuro-inflammation through reduced pro-inflammatory eicosanoids production and microglial activation. However, treatment with FAAH inhibitors should be done with caution as FAAH knockout astrocytes showed exaggerated inflammation [137].

Endogenous or exogenous cannabinoids, through cannabinoid receptors and/or PPAR control the activity of various signaling pathways like MAPK, NFκB, Notch-1, and Wnt/β-catenin pathways. Through these pathways, cannabinoids could reduce inflammation, generation of Aβ plaques, and NFTs resulting in improvement of synaptic structure, synaptic plasticity, and learning and memory deficits. However, the pharmacological modulation of eCB signaling should be done considering the disease stage.

ACKNOWLEDGMENTS

This work was supported by Grant PRIN 2009 (to T.C.) and by Sapienza intramural research grants (Ricerche di Ateneo 2013, to S.G.).

Authors' disclosures available online (<http://www.j-alz.com/disclosures/view.php?id=2469>).

REFERENCES

- [1] Wortmann M (2012) Dementia: A global health priority - highlights from an ADI and World Health Organization report. *Alzheimers Res Ther* **4**, 40.
- [2] Anand R, Gill KD, Mahdi AA (2014) Therapeutics of Alzheimer's disease: Past, present and future. *Neuropharmacology* **76 Part A**, 27-50.
- [3] Mapstone M, Cheema AK, Fiandaca MS, Zhong X, Mhyre TR, Macarthur LH, Hall WJ, Fisher SG, Peterson DR, Haley JM, Nazar MD, Rich SA, Berlau DJ, Peltz CB, Tan MT, Kawas CH, Federoff HJ (2014) Plasma phospholipids identify antecedent memory impairment in older adults. *Nat Med* **20**, 415-418.
- [4] Walther S, Mahlberg R, Eichmann U, Kunz D (2006) Delta-9-tetrahydrocannabinol for nighttime agitation in severe dementia. *Psychopharmacology (Berl)* **185**, 524-528.
- [5] Maroof N, Pardon MC, Kendall DA (2013) Endocannabinoid signalling in Alzheimer's disease. *Biochem Soc Trans* **41**, 1583-1587.
- [6] Karl T, Cheng D, Garner B, Arnold JC (2012) The therapeutic potential of the endocannabinoid system for Alzheimer's disease. *Expert Opin Ther Targets* **16**, 407-420.
- [7] Bisogno T, Di Marzo V (2008) The role of the endocannabinoid system in Alzheimer's disease: Facts and hypotheses. *Curr Pharm Des* **14**, 2299-3305.
- [8] Aso E, Ferrer I (2014) Cannabinoids for treatment of Alzheimer's disease: Moving toward the clinic. *Front Pharmacol* **5**, 37.
- [9] D'Addario C, Di Francesco A, Trabace L, Finazzi Agro A, Cuomo V, Maccarrone M (2013) Endocannabinoid signaling in Alzheimer's disease: Current knowledge and future directions. *J Biol Regul Homeost Agents* **27**, 61-73.
- [10] Fagan SG, Campbell VA (2014) The influence of cannabinoids on generic traits of neurodegeneration. *Br J Pharmacol* **171**, 1347-1360.
- [11] Querfurth HW, LaFerla FM (2010) Alzheimer's disease. *N Engl J Med* **362**, 329-344.
- [12] DeKosky ST, Scheff SW (1990) Synapse loss in frontal cortex biopsies in Alzheimer's disease: Correlation with cognitive severity. *Ann Neurol* **27**, 457-464.
- [13] Selkoe DJ (1989) Amyloid beta protein precursor and the pathogenesis of Alzheimer's disease. *Cell* **58**, 611-612.
- [14] Iqbal K, Grundke-Iqbal I (2002) Neurofibrillary pathology leads to synaptic loss and not the other way around in Alzheimer disease. *J Alzheimers Dis* **4**, 235-238.
- [15] Beach TG, Walker R, McGeer EG (1989) Patterns of gliosis in Alzheimer's disease and aging cerebrum. *Glia* **2**, 420-436.
- [16] Rogers J, Lubner-Narod J, Styren SD, Civin WH (1988) Expression of immune system-associated antigens by cells of the human central nervous system: Relationship to the pathology of Alzheimer's disease. *Neurobiol Aging* **9**, 339-349.
- [17] LaFerla FM (2010) Pathways linking Abeta and tau pathologies. *Biochem Soc Trans* **38**, 993-995.
- [18] Cruts M, Van Broeckhoven C (1998) Molecular genetics of Alzheimer's disease. *Ann Med* **30**, 560-565.
- [19] Crews L, Masliah E (2010) Molecular mechanisms of neurodegeneration in Alzheimer's disease. *Hum Mol Genet* **19**, R12-R20.
- [20] Klein WL (2013) Synaptotoxic amyloid-beta oligomers: A molecular basis for the cause, diagnosis, and treatment of Alzheimer's disease? *J Alzheimers Dis* **33 Suppl 1**, S49-S65.
- [21] Klein WL, Krafft GA, Finch CE (2001) Targeting small Abeta oligomers: The solution to an Alzheimer's disease conundrum? *Trends Neurosci* **24**, 219-224.
- [22] Walsh DM, Selkoe DJ (2004) Oligomers on the brain: The emerging role of soluble protein aggregates in neurodegeneration. *Protein Pept Lett* **11**, 213-228.
- [23] Mukhamedyarov MA, Zefirov AL (2013) The influence of beta-amyloid peptide on the functions of excitable tissues: Physiological and pathological aspects. *Usp Fiziol Nauk* **44**, 55-71.
- [24] Walsh DM, Selkoe DJ (2004) Deciphering the molecular basis of memory failure in Alzheimer's disease. *Neuron* **44**, 181-193.
- [25] McGeer PL, McGeer EG, Yasojima K (2000) Alzheimer disease and neuroinflammation. *J Neural Transm Suppl* **59**, 53-57.
- [26] Streit WJ (2004) Microglia and Alzheimer's disease pathogenesis. *J Neurosci Res* **77**, 1-8.
- [27] Munoz L, Ammit AJ (2010) Targeting p38 MAPK pathway for the treatment of Alzheimer's disease. *Neuropharmacology* **58**, 561-568.
- [28] Shigematsu K, McGeer PL, Walker DG, Ishii T, McGeer EG (1992) Reactive microglia/macrophages phagocytose amyloid precursor protein produced by neurons following neural damage. *J Neurosci Res* **31**, 443-453.
- [29] Combs CK, Johnson DE, Cannady SB, Lehman TM, Landreth GE (1999) Identification of microglial signal

- transduction pathways mediating a neurotoxic response to amyloidogenic fragments of beta-amyloid and prion proteins. *J Neurosci* **19**, 928-939.
- [30] Sondag CM, Dhawan G, Combs CK (2009) Beta amyloid oligomers and fibrils stimulate differential activation of primary microglia. *J Neuroinflammation* **6**, 1.
- [31] Sastre M, Klockgether T, Heneka MT (2006) Contribution of inflammatory processes to Alzheimer's disease: Molecular mechanisms. *Int J Dev Neurosci* **24**, 167-176.
- [32] White JA, Manelli AM, Holmberg KH, Van Eldik LJ, Ladu MJ (2005) Differential effects of oligomeric and fibrillar amyloid-beta 1-42 on astrocyte-mediated inflammation. *Neurobiol Dis* **18**, 459-465.
- [33] Arroyo DS, Soria JA, Gaviglio EA, Rodriguez-Galan MC, Iribarren P (2011) Toll-like receptors are key players in neurodegeneration. *Int Immunopharmacol* **11**, 1415-1421.
- [34] Reed-Geaghan EG, Savage JC, Hise AG, Landreth GE (2009) CD14 and toll-like receptors 2 and 4 are required for fibrillar A β -stimulated microglial activation. *J Neurosci* **29**, 11982-11992.
- [35] Izumi Y, Tokuda K, Zorumski CF (2008) Long-term potentiation inhibition by low-level N-methyl-D-aspartate receptor activation involves calcineurin, nitric oxide, and p38 mitogen-activated protein kinase. *Hippocampus* **18**, 258-265.
- [36] Moulton PR, Correa SA, Collingridge GL, Fitzjohn SM, Bashir ZI (2008) Co-activation of p38 mitogen-activated protein kinase and protein tyrosine phosphatase underlies metabotropic glutamate receptor-dependent long-term depression. *J Physiol* **586**, 2499-2510.
- [37] Piomelli D (2003) The molecular logic of endocannabinoid signalling. *Nat Rev Neurosci* **4**, 873-884.
- [38] Freund TF, Katona I, Piomelli D (2003) Role of endogenous cannabinoids in synaptic signaling. *Physiol Rev* **83**, 1017-1066.
- [39] Devane WA, Hanus L, Breuer A, Pertwee RG, Stevenson LA, Griffin G, Gibson D, Mandelbaum A, Etinger A, Mechoulam R (1992) Isolation and structure of a brain constituent that binds to the cannabinoid receptor. *Science* **258**, 1946-1949.
- [40] Sugiura T, Kondo S, Sukagawa A, Nakane S, Shinoda A, Itoh K, Yamashita A, Waku K (1995) 2-Arachidonoylglycerol: A possible endogenous cannabinoid receptor ligand in brain. *Biochem Biophys Res Commun* **215**, 89-97.
- [41] Mechoulam R, Ben-Shabat S, Hanus L, Ligumsky M, Kaminski NE, Schatz AR, Gopher A, Almog S, Martin BR, Compton DR, et al. (1995) Identification of an endogenous 2-monoglyceride, present in canine gut, that binds to cannabinoid receptors. *Biochem Pharmacol* **50**, 83-90.
- [42] Di Marzo V, Fontana A, Cadas H, Schinelli S, Cimino G, Schwartz JC, Piomelli D (1994) Formation and inactivation of endogenous cannabinoid anandamide in central neurons. *Nature* **372**, 686-691.
- [43] Sugiura T, Kondo S, Sukagawa A, Tonegawa T, Nakane S, Yamashita A, Waku K (1996) Enzymatic synthesis of anandamide, an endogenous cannabinoid receptor ligand, through N-acylphosphatidylethanolamine pathway in testis: Involvement of Ca²⁺-dependent transacylase and phosphodiesterase activities. *Biochem Biophys Res Commun* **218**, 113-117.
- [44] Di Marzo V, Bisogno T, De Petrocellis L, Melck D, Orlando P, Wagner JA, Kunos G (1999) Biosynthesis and inactivation of the endocannabinoid 2-arachidonoylglycerol in circulating and tumoral macrophages. *Eur J Biochem* **264**, 258-267.
- [45] Walter L, Franklin A, Witting A, Wade C, Xie Y, Kunos G, Mackie K, Stella N (2003) Nonpsychotropic cannabinoid receptors regulate microglial cell migration. *J Neurosci* **23**, 1398-1405.
- [46] Gonthier MP, Hoareau L, Festy F, Matias I, Valenti M, Bes-Houtmann S, Rouch C, Robert-Da Silva C, Chesne S, Lefebvre d'Helencourt C, Cesari M, Di Marzo V, Roche R (2007) Identification of endocannabinoids and related compounds in human fat cells. *Obesity (Silver Spring)* **15**, 837-845.
- [47] Gauthier KM, Baewer DV, Hittner S, Hillard CJ, Nithipatikom K, Reddy DS, Falck JR, Campbell WB (2005) Endothelium-derived 2-arachidonoylglycerol: An intermediate in vasodilatory eicosanoid release in bovine coronary arteries. *Am J Physiol Heart Circ Physiol* **288**, H1344-H1351.
- [48] Sugiura T, Kondo S, Kishimoto S, Miyashita T, Nakane S, Kodaka T, Suhara Y, Takayama H, Waku K (2000) Evidence that 2-arachidonoylglycerol but not N-palmitoylethanolamine or anandamide is the physiological ligand for the cannabinoid CB2 receptor. Comparison of the agonistic activities of various cannabinoid receptor ligands in HL-60 cells. *J Biol Chem* **275**, 605-612.
- [49] Maccarrone M, Dainese E, Oddi S (2010) Intracellular trafficking of anandamide: New concepts for signaling. *Trends Biochem Sci* **35**, 601-608.
- [50] Matsuda LA, Lolait SJ, Brownstein MJ, Young AC, Bonner TI (1990) Structure of a cannabinoid receptor and functional expression of the cloned cDNA. *Nature* **346**, 561-564.
- [51] Galiegue S, Mary S, Marchand J, Dussosoy D, Carriere D, Carayon P, Bouaboula M, Shire D, Le Fur G, Casellas P (1995) Expression of central and peripheral cannabinoid receptors in human immune tissues and leukocyte subpopulations. *Eur J Biochem* **232**, 54-61.
- [52] Munro S, Thomas KL, Abu-Shaar M (1993) Molecular characterization of a peripheral receptor for cannabinoids. *Nature* **365**, 61-65.
- [53] Gong JP, Onaivi ES, Ishiguro H, Liu QR, Tagliaferro PA, Brusco A, Uhl GR (2006) Cannabinoid CB2 receptors: Immunohistochemical localization in rat brain. *Brain Res* **1071**, 10-23.
- [54] Onaivi ES, Ishiguro H, Gong JP, Patel S, Perchuk A, Meozzi PA, Myers L, Mora Z, Tagliaferro P, Gardner E, Brusco A, Akinshola BE, Liu QR, Hope B, Iwasaki S, Arinami T, Teasensfitz L, Uhl GR (2006) Discovery of the presence and functional expression of cannabinoid CB2 receptors in brain. *Ann N Y Acad Sci* **1074**, 514-536.
- [55] Ashton JC, Friberg D, Darlington CL, Smith PF (2006) Expression of the cannabinoid CB2 receptor in the rat cerebellum: An immunohistochemical study. *Neurosci Lett* **396**, 113-116.
- [56] Van Sickle MD, Duncan M, Kingsley PJ, Mouihate A, Urbani P, Mackie K, Stella N, Makriyannis A, Piomelli D, Davison JS, Marnett LJ, Di Marzo V, Pittman QJ, Patel KD, Sharkey KA (2005) Identification and functional characterization of brainstem cannabinoid CB2 receptors. *Science* **310**, 329-332.
- [57] Atwood BK, Mackie K (2010) CB2: A cannabinoid receptor with an identity crisis. *Br J Pharmacol* **160**, 467-479.
- [58] Lou ZY, Chen C, He Q, Zhao CB, Xiao BG (2011) Targeting CB(2) receptor as a neuroinflammatory modulator in experimental autoimmune encephalomyelitis. *Mol Immunol* **49**, 453-461.
- [59] Stella N (2009) Endocannabinoid signaling in microglial cells. *Neuropharmacology* **56 (Suppl 1)**, 244-253.

- [60] Cabral GA, Griffin-Thomas L (2009) Emerging role of the cannabinoid receptor CB2 in immune regulation: Therapeutic prospects for neuroinflammation. *Expert Rev Mol Med* **11**, e3.
- [61] Pertwee RG, Howlett AC, Abood ME, Alexander SP, Di Marzo V, Elphick MR, Greasley PJ, Hansen HS, Kunos G, Mackie K, Mechoulam R, Ross RA (2010) International union of basic and clinical pharmacology. LXXIX. Cannabinoid receptors and their ligands: Beyond CB(1) and CB(2). *Pharmacol Rev* **62**, 588-631.
- [62] Pertwee RG (2007) GPR55: A new member of the cannabinoid receptor clan? *Br J Pharmacol* **152**, 984-986.
- [63] Caterina MJ, Schumacher MA, Tominaga M, Rosen TA, Levine JD, Julius D (1997) The capsaicin receptor: A heat-activated ion channel in the pain pathway. *Nature* **389**, 816-824.
- [64] Cravatt BF, Giang DK, Mayfield SP, Boger DL, Lerner RA, Gilula NB (1996) Molecular characterization of an enzyme that degrades neuromodulatory fatty-acid amides. *Nature* **384**, 83-87.
- [65] Hwang J, Adamson C, Butler D, Janero DR, Makriyannis A, Bahr BA (2010) Enhancement of endocannabinoid signaling by fatty acid amide hydrolase inhibition: A neuroprotective therapeutic modality. *Life Sci* **86**, 615-623.
- [66] Goparaju SK, Ueda N, Taniguchi K, Yamamoto S (1999) Enzymes of porcine brain hydrolyzing 2-arachidonoylglycerol, an endogenous ligand of cannabinoid receptors. *Biochem Pharmacol* **57**, 417-423.
- [67] Castillo Pablo E, Younts Thomas J, Chávez Andrés E, Hashimoto Y (2012) Endocannabinoid signaling and synaptic function. *Neuron* **76**, 70-81.
- [68] Chavez AE, Chiu CQ, Castillo PE (2010) TRPV1 activation by endogenous anandamide triggers postsynaptic long-term depression in dentate gyrus. *Nat Neurosci* **13**, 1511-1518.
- [69] Brailoiu GC, Oprea TI, Zhao P, Abood ME, Brailoiu E (2011) Intracellular cannabinoid type 1 (CB1) receptors are activated by anandamide. *J Biol Chem* **286**, 29166-29174.
- [70] Rozenfeld R, Devi LA (2008) Regulation of CB1 cannabinoid receptor trafficking by the adaptor protein AP-3. *FASEB J* **22**, 2311-2322.
- [71] Benard G, Massa F, Puente N, Lourenco J, Bellocchio L, Soria-Gomez E, Matias I, Delamarre A, Metna-Laurent M, Cannich A, Hebert-Chatelain E, Mülle C, Ortega-Gutierrez S, Martin-Fontecha M, Klugmann M, Guggenhuber S, Lutz B, Gertsch J, Chaouloff F, Lopez-Rodriguez ML, Grandes P, Rossignol R, Marsicano G (2012) Mitochondrial CB(1) receptors regulate neuronal energy metabolism. *Nat Neurosci* **15**, 558-564.
- [72] Hopper MW, Vogel FS (1976) The limbic system in Alzheimer's disease. A neuropathologic investigation. *Am J Pathol* **85**, 1-20.
- [73] Mackie K (2005) Distribution of cannabinoid receptors in the central and peripheral nervous system. *Handb Exp Pharmacol*, 299-325.
- [74] Pazos MR, Nunez E, Benito C, Tolon RM, Romero J (2004) Role of the endocannabinoid system in Alzheimer's disease: New perspectives. *Life Sci* **75**, 1907-1915.
- [75] Koppel J, Davies P (2008) Targeting the endocannabinoid system in Alzheimer's disease. *J Alzheimers Dis* **15**, 495-504.
- [76] Benito C, Nunez E, Pazos MR, Tolon RM, Romero J (2007) The endocannabinoid system and Alzheimer's disease. *Mol Neurobiol* **36**, 75-81.
- [77] Campbell VA, Gowran A (2007) Alzheimer's disease; taking the edge off with cannabinoids? *Br J Pharmacol* **152**, 655-662.
- [78] Westlake TM, Howlett AC, Bonner TI, Matsuda LA, Herkenham M (1994) Cannabinoid receptor binding and messenger RNA expression in human brain: An *in vitro* receptor autoradiography and *in situ* hybridization histochemistry study of normal aged and Alzheimer's brains. *Neuroscience* **63**, 637-652.
- [79] Benito C, Nunez E, Tolon RM, Carrier EJ, Rabano A, Hillard CJ, Romero J (2003) Cannabinoid CB2 receptors and fatty acid amide hydrolase are selectively overexpressed in neuritic plaque-associated glia in Alzheimer's disease brains. *J Neurosci* **23**, 11136-11141.
- [80] Mulder J, Zilberter M, Pasquare SJ, Alpar A, Schulte G, Ferreira SG, Kofalvi A, Martin-Moreno AM, Keimpema E, Tanila H, Watanabe M, Mackie K, Hortobagyi T, de Ceballos ML, Harkany T (2011) Molecular reorganization of endocannabinoid signalling in Alzheimer's disease. *Brain* **134**, 1041-1060.
- [81] Lee JH, Agacinski G, Williams JH, Wilcock GK, Esiri MM, Francis PT, Wong PT, Chen CP, Lai MK (2010) Intact cannabinoid CB1 receptors in the Alzheimer's disease cortex. *Neurochem Int* **57**, 985-989.
- [82] Ramirez BG, Blazquez C, Gomez del Pulgar T, Guzman M, de Ceballos ML (2005) Prevention of Alzheimer's disease pathology by cannabinoids: Neuroprotection mediated by blockade of microglial activation. *J Neurosci* **25**, 1904-1913.
- [83] Solas M, Francis PT, Franco R, Ramirez MJ (2013) CB2 receptor and amyloid pathology in frontal cortex of Alzheimer's disease patients. *Neurobiol Aging* **34**, 805-808.
- [84] Farkas S, Nagy K, Palkovits M, Kovács GG, Jia Z, Donohue S, Pike V, Hallidin C, Máthé D, Harkany T, Gulyás B, Csiba L (2012) [125I]SD-7015 reveals fine modalities of CB1 cannabinoid receptor density in the prefrontal cortex during progression of Alzheimer's disease. *Neurochem Int* **60**, 286-291.
- [85] Bedse G, Romano A, Cianci S, Lavecchia AM, Lorenzo P, Elphick MR, Laferla FM, Vendemiale G, Grillo C, Altieri F, Cassano T, Gaetani S (2014) Altered expression of the CB1 cannabinoid receptor in the triple transgenic mouse model of Alzheimer's disease. *J Alzheimers Dis* **40**, 701-712.
- [86] Kalifa S, Polston EK, Allard JS, Manaye KF (2011) Distribution patterns of cannabinoid CB1 receptors in the hippocampus of APP^{swe}/PS1^{DeltaE9} double transgenic mice. *Brain Res* **1376**, 94-100.
- [87] Esposito G, Iuvone T, Savani C, Scuderi C, De Filippis D, Papa M, Di Marzo V, Steardo L (2007) Opposing control of cannabinoid receptor stimulation on amyloid-beta-induced reactive gliosis: *In vitro* and *in vivo* evidence. *J Pharmacol Exp Ther* **322**, 1144-1152.
- [88] Ahmad R, Goffin K, Van den Stock J, De Winter F-L, Cleeren E, Bormans G, Tournoy J, Persoons P, Van Laere K, Vandenbulcke M (2014) *In vivo* type 1 cannabinoid receptor availability in Alzheimer's disease. *Eur Neuropsychopharmacol* **24**, 242-250.
- [89] Wang L, Liu J, Harvey-White J, Zimmer A, Kunos G (2003) Endocannabinoid signaling via cannabinoid receptor 1 is involved in ethanol preference and its age-dependent decline in mice. *Proc Natl Acad Sci U S A* **100**, 1393-1398.
- [90] Manuel I, Gonzalez de San Roman E, Giralt MT, Ferrer I, Rodriguez-Puertas R (2014) Type-1 cannabinoid receptor activity during Alzheimer's disease progression. *J Alzheimers Dis* **42**, 761-766.

- [91] Halleskog C, Mulder J, Dahlstrom J, Mackie K, Hortobagyi T, Tanila H, Kumar Puli L, Farber K, Harkany T, Schulte G (2011) WNT signaling in activated microglia is proinflammatory. *Glia* **59**, 119-131.
- [92] Grunblatt E, Zander N, Bartl J, Jie L, Monoranu CM, Arzberger T, Ravid R, Roggendorf W, Gerlach M, Riederer P (2007) Comparison analysis of gene expression patterns between sporadic Alzheimer's and Parkinson's disease. *J Alzheimers Dis* **12**, 291-311.
- [93] Jung KM, Astarita G, Yasar S, Vasilevko V, Cribbs DH, Head E, Cotman CW, Piomelli D (2012) An amyloid beta42-dependent deficit in anandamide mobilization is associated with cognitive dysfunction in Alzheimer's disease. *Neurobiol Aging* **33**, 1522-1532.
- [94] Nunez E, Benito C, Pazos MR, Barbachano A, Fajardo O, Gonzalez S, Tolon RM, Romero J (2004) Cannabinoid CB2 receptors are expressed by perivascular microglial cells in the human brain: An immunohistochemical study. *Synapse* **53**, 208-213.
- [95] Nunez E, Benito C, Tolon RM, Hillard CJ, Griffin WS, Romero J (2008) Glial expression of cannabinoid CB(2) receptors and fatty acid amide hydrolase are beta amyloid-linked events in Down's syndrome. *Neuroscience* **151**, 104-110.
- [96] Horti AG, Gao Y, Ravert HT, Finley P, Valentine H, Wong DF, Endres CJ, Savonenko AV, Dannals RF (2010) Synthesis and biodistribution of [¹¹C]A-836339, a new potential radioligand for PET imaging of cannabinoid type 2 receptors (CB2). *Bioorg Med Chem* **18**, 5202-5207.
- [97] Grunblatt E, Bartl J, Zehetmayer S, Ringel TM, Bauer P, Riederer P, Jacob CP (2009) Gene expression as peripheral biomarkers for sporadic Alzheimer's disease. *J Alzheimers Dis* **16**, 627-634.
- [98] Koppel J, Bradshaw H, Goldberg TE, Khalili H, Marambaud P, Walker MJ, Pazos M, Gordon ML, Christen E, Davies P (2009) Endocannabinoids in Alzheimer's disease and their impact on normative cognitive performance: A case-control and cohort study. *Lipids Health Dis* **8**, 2.
- [99] Piro JR, Benjamin DI, Duerr JM, Pi Y, Gonzales C, Wood KM, Schwartz JW, Nomura DK, Samad TA (2012) A dysregulated endocannabinoid-eicosanoid network supports pathogenesis in a mouse model of Alzheimer's disease. *Cell Rep* **1**, 617-623.
- [100] Farooqui AA, Liss H, Horrocks LA (1988) Neurochemical aspects of Alzheimer's disease: Involvement of membrane phospholipids. *Metab Brain Dis* **3**, 19-35.
- [101] van der Stelt M, Mazzola C, Esposito G, Matias I, Petrosino S, De Filippis D, Micale V, Steardo L, Drago F, Iuvone T, Di Marzo V (2006) Endocannabinoids and beta-amyloid-induced neurotoxicity *in vivo*: Effect of pharmacological elevation of endocannabinoid levels. *Cell Mol Life Sci* **63**, 1410-1424.
- [102] Campillo NE, Paez JA (2009) Cannabinoid system in neurodegeneration: New perspectives in Alzheimer's disease. *Mini Rev Med Chem* **9**, 539-559.
- [103] Micale V, Mazzola C, Drago F (2007) Endocannabinoids and neurodegenerative diseases. *Pharmacol Res* **56**, 382-392.
- [104] Ruiz-Valdepeñas L, Benito C, Tolón RM, Martínez Orgado JA, Romero J (2010) The endocannabinoid system and amyloid-related diseases. *Exp Neurol* **224**, 66-73.
- [105] Bilkei-Gorzo A (2012) The endocannabinoid system in normal and pathological brain ageing. *Philos Trans R Soc Lond B Biol Sci* **367**, 3326-3341.
- [106] Hickman SE, Allison EK, El Khoury J (2008) Microglial dysfunction and defective beta-amyloid clearance pathways in aging Alzheimer's disease mice. *J Neurosci* **28**, 8354-8360.
- [107] Ehrhart J, Obregon D, Mori T, Hou H, Sun N, Bai Y, Klein T, Fernandez F, Tan J, Shytle RD (2005) Stimulation of cannabinoid receptor 2 (CB2) suppresses microglial activation. *J Neuroinflammation* **2**, 29.
- [108] Tolón RM, Núñez E, Pazos MR, Benito C, Castillo AI, Martínez-Orgado JA, Romero J (2009) The activation of cannabinoid CB2 receptors stimulates *in situ* and *in vitro* beta-amyloid removal by human macrophages. *Brain Res* **1283**, 148-154.
- [109] Janefjord E, Maag JL, Harvey BS, Smid SD (2014) Cannabinoid effects on beta amyloid fibril and aggregate formation, neuronal and microglial-activated neurotoxicity *in vitro*. *Cell Mol Neurobiol* **34**, 31-42.
- [110] Koppel J, Vingtdoux V, Marambaud P, d'Abramo C, Jimenez H, Stauber M, Friedman R, Davies P (2013) CB(2) receptor deficiency increases amyloid pathology and alters tau processing in a transgenic mouse model of Alzheimer's disease. *Mol Med* **19**, 357-364.
- [111] Stumm C, Hiebel C, Hanstein R, Purrio M, Nagel H, Conrad A, Lutz B, Behl C, Clement AB (2013) Cannabinoid receptor 1 deficiency in a mouse model of Alzheimer's disease leads to enhanced cognitive impairment despite of a reduction in amyloid deposition. *Neurobiol Aging* **34**, 2574-2584.
- [112] Bachmeier C, Beaulieu-Abdelahad D, Mullan M, Paris D (2013) Role of the cannabinoid system in the transit of beta-amyloid across the blood-brain barrier. *Mol Cell Neurosci* **56**, 255-262.
- [113] Gauthier A, Vassiliou G, Benoist F, McPherson R (2003) Adipocyte low density lipoprotein receptor-related protein gene expression and function is regulated by peroxisome proliferator-activated receptor gamma. *J Biol Chem* **278**, 11945-11953.
- [114] Shibata M, Yamada S, Kumar SR, Calero M, Bading J, Frangione B, Holtzman DM, Miller CA, Strickland DK, Ghiso J, Zlokovic BV (2000) Clearance of Alzheimer's amyloid-ss(1-40) peptide from brain by LDL receptor-related protein-1 at the blood-brain barrier. *J Clin Invest* **106**, 1489-1499.
- [115] Chen R, Zhang J, Wu Y, Wang D, Feng G, Tang YP, Teng Z, Chen C (2012) Monoacylglycerol lipase is a therapeutic target for Alzheimer's disease. *Cell Rep* **2**, 1329-1339.
- [116] Duan Y, Dong S, Gu F, Hu Y, Zhao Z (2012) Advances in the pathogenesis of Alzheimer's disease: Focusing on tau-mediated neurodegeneration. *Transl Neurodegener* **1**, 24.
- [117] Churcher I (2006) Tau therapeutic strategies for the treatment of Alzheimer's disease. *Curr Top Med Chem* **6**, 579-595.
- [118] Rohn TT (2010) The role of caspases in Alzheimer's disease; potential novel therapeutic opportunities. *Apoptosis* **15**, 1403-1409.
- [119] Gamblin TC, Chen F, Zambrano A, Abraha A, Lagalwar S, Guillozet AL, Lu M, Fu Y, Garcia-Sierra F, LaPointe N, Miller R, Berry RW, Binder LI, Cryns VL (2003) Caspase cleavage of tau: Linking amyloid and neurofibrillary tangles in Alzheimer's disease. *Proc Natl Acad Sci U S A* **100**, 10032-10037.
- [120] Saez TE, Pehar M, Vargas M, Barbeito L, Maccioni RB (2004) Astrocytic nitric oxide triggers tau hyperphosphorylation in hippocampal neurons. *In Vivo* **18**, 275-280.
- [121] Esposito G, De Filippis D, Steardo L, Scuderi C, Savani C, Cuomo V, Iuvone T (2006) CB1 receptor selective activa-

- tion inhibits β -amyloid-induced iNOS protein expression in C6 cells and subsequently blunts tau protein hyperphosphorylation in co-cultured neurons. *Neurosci Lett* **404**, 342-346.
- [122] Esposito G, De Filippis D, Carnuccio R, Izzo AA, Iuvone T (2006) The marijuana component cannabidiol inhibits beta-amyloid-induced tau protein hyperphosphorylation through Wnt/beta-catenin pathway rescue in PC12 cells. *J Mol Med (Berl)* **84**, 253-258.
- [123] Sperber BR, Leight S, Goedert M, Lee VM (1995) Glycogen synthase kinase-3 beta phosphorylates tau protein at multiple sites in intact cells. *Neurosci Lett* **197**, 149-153.
- [124] Cao C, Li Y, Liu H, Bai G, Mayl J, Lin X, Sutherland K, Nabar N, Jianfeng C (2014) The potential therapeutic effects of THC on Alzheimer's disease. *J Alzheimers Dis* **42**, 973-984.
- [125] Chami L, Checler F (2012) BACE1 is at the crossroad of a toxic vicious cycle involving cellular stress and beta-amyloid production in Alzheimer's disease. *Mol Neurodegener* **7**, 52.
- [126] Howlett AC, Mukhopadhyay S, Norford DC (2006) Endocannabinoids and reactive nitrogen and oxygen species in neuropathologies. *J Neuroimmune Pharmacol* **1**, 305-316.
- [127] Panikashvili D, Mechoulam R, Beni SM, Alexandrovich A, Shohami E (2005) CB1 cannabinoid receptors are involved in neuroprotection via NF-kappa B inhibition. *J Cereb Blood Flow Metab* **25**, 477-484.
- [128] Panikashvili D, Shein NA, Mechoulam R, Trembovler V, Kohen R, Alexandrovich A, Shohami E (2006) The endocannabinoid 2-AG protects the blood-brain barrier after closed head injury and inhibits mRNA expression of proinflammatory cytokines. *Neurobiol Dis* **22**, 257-264.
- [129] Wu J, Bie B, Yang H, Xu JJ, Brown DL, Naguib M (2013) Activation of the CB2 receptor system reverses amyloid-induced memory deficiency. *Neurobiol Aging* **34**, 791-804.
- [130] Howlett AC, Barth F, Bonner TI, Cabral G, Casellas P, Devane WA, Felder CC, Herkenham M, Mackie K, Martin BR, Mechoulam R, Pertwee RG (2002) International union of pharmacology. XXVII. Classification of cannabinoid receptors. *Pharmacol Rev* **54**, 161-202.
- [131] Martin-Moreno AM, Reigada D, Ramirez BG, Mechoulam R, Innamorato N, Cuadrado A, de Ceballos ML (2011) Cannabidiol and other cannabinoids reduce microglial activation *in vitro* and *in vivo*: Relevance to Alzheimer's disease. *Mol Pharmacol* **79**, 964-973.
- [132] Esposito G, Scuderi C, Savani C, Steardo L, De Filippis D, Cottone P, Iuvone T, Cuomo V, Steardo L (2007) Cannabidiol *in vivo* blunts beta-amyloid induced neuroinflammation by suppressing IL-1beta and iNOS expression. *Br J Pharmacol* **151**, 1272-1279.
- [133] Esposito G, Scuderi C, Valenza M, Togni GI, Latina V, De Filippis D, Cipriano M, Carratu MR, Iuvone T, Steardo L (2011) Cannabidiol reduces A β -induced neuroinflammation and promotes hippocampal neurogenesis through PPARgamma involvement. *PLoS One* **6**, e28668.
- [134] Sheng WS, Hu S, Min X, Cabral GA, Lokensgard JR, Peterson PK (2005) Synthetic cannabinoid WIN55,212-2 inhibits generation of inflammatory mediators by IL-1beta-stimulated human astrocytes. *Glia* **49**, 211-219.
- [135] Esposito G, De Filippis D, Maiuri MC, De Stefano D, Carnuccio R, Iuvone T (2006) Cannabidiol inhibits inducible nitric oxide synthase protein expression and nitric oxide production in β -amyloid stimulated PC12 neurons through p38 MAP kinase and NF- κ B involvement. *Neurosci Lett* **399**, 91-95.
- [136] Xu JY, Chen C (2014) Endocannabinoids in synaptic plasticity and neuroprotection. *Neuroscientist*. doi: 10.1177/1073858414524632
- [137] Benito C, Tolon RM, Castillo AI, Ruiz-Valdepenas L, Martinez-Orgado JA, Fernandez-Sanchez FJ, Vazquez C, Cravatt BF, Romero J (2012) beta-Amyloid exacerbates inflammation in astrocytes lacking fatty acid amide hydrolase through a mechanism involving PPAR-alpha, PPAR-gamma and TRPV1, but not CB(1) or CB(2) receptors. *Br J Pharmacol* **166**, 1474-1489.
- [138] Gervois P, Mansouri RM (2012) PPARalpha as a therapeutic target in inflammation-associated diseases. *Expert Opin Ther Targets* **16**, 1113-1125.
- [139] Piomelli D, Sasso O (2014) Peripheral gating of pain signals by endogenous lipid mediators. *Nat Neurosci* **17**, 164-174.
- [140] Fakhfour G, Ahmadiani A, Rahimian R, Grolla AA, Moradi F, Haeri A (2012) WIN55212-2 attenuates amyloid-beta-induced neuroinflammation in rats through activation of cannabinoid receptors and PPAR-gamma pathway. *Neuropharmacology* **63**, 653-666.
- [141] Martin-Moreno AM, Brera B, Spuch C, Carro E, Garcia-Garcia L, Delgado M, Pozo MA, Innamorato NG, Cuadrado A, de Ceballos ML (2012) Prolonged oral cannabinoid administration prevents neuroinflammation, lowers beta-amyloid levels and improves cognitive performance in Tg APP 2576 mice. *J Neuroinflammation* **9**, 8.
- [142] Alhouayek M, Muccioli GG (2014) COX-2-derived endocannabinoid metabolites as novel inflammatory mediators. *Trends Pharmacol Sci* **35**, 284-292.
- [143] Nomura DK, Morrison BE, Blankman JL, Long JZ, Kinsey SG, Marcondes MC, Ward AM, Hahn YK, Lichtman AH, Conti B, Cravatt BF (2011) Endocannabinoid hydrolysis generates brain prostaglandins that promote neuroinflammation. *Science* **334**, 809-813.
- [144] Zhang J, Chen C (2008) Endocannabinoid 2-arachidonoylglycerol protects neurons by limiting COX-2 elevation. *J Biol Chem* **283**, 22601-22611.
- [145] Chen X, Zhang J, Chen C (2011) Endocannabinoid 2-arachidonoylglycerol protects neurons against beta-amyloid insults. *Neuroscience* **178**, 159-168.
- [146] Du H, Chen X, Zhang J, Chen C (2011) Inhibition of COX-2 expression by endocannabinoid 2-arachidonoylglycerol is mediated via PPAR-gamma. *Br J Pharmacol* **163**, 1533-1549.
- [147] Hoshino T, Namba T, Takehara M, Murao N, Matsushima T, Sugimoto Y, Narumiya S, Suzuki T, Mizushima T (2012) Improvement of cognitive function in Alzheimer's disease model mice by genetic and pharmacological inhibition of the EP(4) receptor. *J Neurochem* **120**, 795-805.
- [148] Noonan J, Tanveer R, Klompas A, Gowran A, McKiernan J, Campbell VA (2010) Endocannabinoids prevent beta-amyloid-mediated lysosomal destabilization in cultured neurons. *J Biol Chem* **285**, 38543-38554.
- [149] Milton NG (2002) Anandamide and noladin ether prevent neurotoxicity of the human amyloid-beta peptide. *Neurosci Lett* **332**, 127-130.
- [150] Harvey BS, Ohlsson KS, Mååg JLV, Musgrave IF, Smid SD (2012) Contrasting protective effects of cannabinoids against oxidative stress and amyloid- β evoked neurotoxicity *in vitro*. *Neurotoxicology* **33**, 138-146.
- [151] Haghani M, Shabani M, Javan M, Motamedi F, Janahmadi M (2012) CB1 cannabinoid receptor activation rescues amyloid beta-induced alterations in behaviour and intrinsic electrophysiological properties of rat hippocampal CA1 pyramidal neurones. *Cell Physiol Biochem* **29**, 391-406.

- [152] Jackson SJ, Pryce G, Diemel LT, Cuzner ML, Baker D (2005) Cannabinoid-receptor 1 null mice are susceptible to neurofilament damage and caspase 3 activation. *Neuroscience* **134**, 261-268.
- [153] Cardenas A, Moro MA, Hurtado O, Leza JC, Lizasoain I (2005) Dual role of nitric oxide in adult neurogenesis. *Brain Res Brain Res Rev* **50**, 1-6.
- [154] Butterfield DA, Sultana R (2011) Methionine-35 of Abeta(1-42): Importance for oxidative stress in Alzheimer disease. *J Amino Acid* **2011**, 198430.
- [155] Moncada S, Rees DD, Schulz R, Palmer RM (1991) Development and mechanism of a specific supersensitivity to nitrovasodilators after inhibition of vascular nitric oxide synthesis *in vivo*. *Proc Natl Acad Sci U S A* **88**, 2166-2170.
- [156] Iuvone T, Esposito G, Esposito R, Santamaria R, Di Rosa M, Izzo AA (2004) Neuroprotective effect of cannabidiol, a non-psychoactive component from *Cannabis sativa*, on beta-amyloid 1-42 *in vitro*. *Neurosci Lett* **322**, 121-125.
- [157] Haas J, Storch-Hagenlocher B, Biessmann A, Wildemann B (2002) Inducible nitric oxide synthase and argininosuccinate synthetase: Co-induction in brain tissue of patients with Alzheimer's dementia and following stimulation with beta-amyloid 1-42 *in vitro*. *Neurosci Lett* **322**, 121-125.
- [158] Hampson AJ, Grimaldi M, Axelrod J, Wink D (1998) Cannabidiol and (-)-Delta9-tetrahydrocannabinol are neuroprotective antioxidants. *Proc Natl Acad Sci U S A* **95**, 8268-8273.
- [159] Athanasiou A, Clarke AB, Turner AE, Kumaran NM, Vakilpour S, Smith PA, Bagiokou D, Bradshaw TD, Westwell AD, Fang L, Lobo DN, Constantinescu CS, Calabrese V, Loesch A, Alexander SPH, Clothier RH, Kendall DA, Bates TE (2007) Cannabinoid receptor agonists are mitochondrial inhibitors: A unified hypothesis of how cannabinoids modulate mitochondrial function and induce cell death. *Biochem Biophys Res Commun* **364**, 131-137.
- [160] Chiu P, Karler R, Craven C, Olsen DM, Turkkanis SA (1975) The influence of delta9-tetrahydrocannabinol, cannabidiol and cannabidiol on tissue oxygen consumption. *Res Commun Chem Pathol Pharmacol* **12**, 267-286.
- [161] Zaccagnino P, Corcelli A, Baronio M, Lorusso M (2011) Anandamide inhibits oxidative phosphorylation in isolated liver mitochondria. *FEBS Lett* **585**, 429-434.
- [162] Velez-Pardo C, Jimenez-Del-Rio M, Lores-Arnaiz S, Bustamante J (2010) Protective effects of the synthetic cannabinoids CP55,940 and JWH-015 on rat brain mitochondria upon paraquat exposure. *Neurochem Res* **35**, 1323-1332.
- [163] Zaccagnino P, D'Orta S, Romano LL, Di Venere A, Sardanelli AM, Lorusso M (2012) The endocannabinoid 2-arachidonoylglycerol decreases calcium induced cytochrome c release from liver mitochondria. *J Bioenerg Biomembr* **44**, 273-280.
- [164] Catanzaro G, Rapino C, Oddi S, Maccarrone M (2009) Anandamide increases swelling and reduces calcium sensitivity of mitochondria. *Biochem Biophys Res Commun* **388**, 439-442.
- [165] Marsicano G, Lafenetre P (2009) Roles of the endocannabinoid system in learning and memory. *Curr Top Behav Neurosci* **1**, 201-230.
- [166] Katona I, Freund TF (2008) Endocannabinoid signaling as a synaptic circuit breaker in neurological disease. *Nat Med* **14**, 923-930.
- [167] Chen QS, Kagan BL, Hirakura Y, Xie CW (2000) Impairment of hippocampal long-term potentiation by Alzheimer amyloid beta-peptides. *J Neurosci Res* **60**, 65-72.
- [168] Orr AL, Hanson JE, Li D, Klotz A, Wright S, Schenk D, Seubert P, Madison DV (2014) beta-Amyloid inhibits E-S potentiation through suppression of cannabinoid receptor 1-dependent synaptic disinhibition. *Neuron* **82**, 1334-1345.
- [169] Albayram O, Alferink J, Pitsch J, Piyanova A, Neitzert K, Poppensieker K, Mauer D, Michel K, Legler A, Becker A, Monory K, Lutz B, Zimmer A, Bilkei-Gorzo A (2011) Role of CB1 cannabinoid receptors on GABAergic neurons in brain aging. *Proc Natl Acad Sci U S A* **108**, 11256-11261.
- [170] Cheng D, Spiro AS, Jenner AM, Garner B, Karl T (2014) Long-term cannabidiol treatment prevents the development of social recognition memory deficits in Alzheimer's disease transgenic mice. *J Alzheimers Dis* **42**, 1383-1396.
- [171] Aso E, Sánchez-Pla A, Vegas-Lozano E, Maldonado R, Ferrer I (2014) Cannabis-based medicine reduces multiple pathological processes in AβPP/PS1 mice. *J Alzheimers Dis* **43**, 977-991.
- [172] Chen B, Bromley-Brits K, He G, Cai F, Zhang X, Song W (2010) Effect of synthetic cannabinoid HU210 on memory deficits and neuropathology in Alzheimer's disease mouse model. *Curr Alzheimer Res* **7**, 255-261.
- [173] Mazzola C, Micale V, Drago F (2003) Amnesia induced by beta-amyloid fragments is counteracted by cannabinoid CB1 receptor blockade. *Eur J Pharmacol* **477**, 219-225.
- [174] Francis PT, Palmer AM, Snape M, Wilcock GK (1999) The cholinergic hypothesis of Alzheimer's disease: A review of progress. *J Neurol Neurosurg Psychiatry* **66**, 137-147.
- [175] Eubanks LM, Rogers CJ, Beuscher AE, Koob GF, Olson AJ, Dickerson TJ, Janda KD (2006) A molecular link between the active component of marijuana and Alzheimer's disease pathology. *Mol Pharm* **3**, 773-777.
- [176] Gonzalez-Naranjo P, Campillo NE, Perez C, Paez JA (2013) Multitarget cannabinoids as novel strategy for Alzheimer disease. *Curr Alzheimer Res* **10**, 229-239.
- [177] Nadler V, Mechoulam R, Sokolovsky M (1993) Blockade of 45Ca²⁺ influx through the N-methyl-D-aspartate receptor ion channel by the non-psychoactive cannabinoid HU-211. *Brain Res* **622**, 79-85.
- [178] Eshhar N, Striem S, Biegon A (1993) HU-211, a non-psychoactive cannabinoid, rescues cortical neurons from excitatory amino acid toxicity in culture. *Neuroreport* **5**, 237-240.
- [179] Eshhar N, Striem S, Kohen R, Tirosh O, Biegon A (1995) Neuroprotective and antioxidant activities of HU-211, a novel NMDA receptor antagonist. *Eur J Pharmacol* **283**, 19-29.
- [180] Woo HN, Park JS, Gwon AR, Arumugam TV, Jo DG (2009) Alzheimer's disease and Notch signaling. *Biochem Biophys Res Commun* **390**, 1093-1097.
- [181] Bray SJ (2006) Notch signalling: A simple pathway becomes complex. *Nat Rev Mol Cell Biol* **7**, 678-689.
- [182] Costa RM, Honjo T, Silva AJ (2003) Learning and memory deficits in Notch mutant mice. *Curr Biol* **13**, 1348-1354.
- [183] Tanveer R, Gowran A, Noonan J, Keating SE, Bowie AG, Campbell VA (2012) The endocannabinoid, anandamide, augments Notch-1 signaling in cultured cortical neurons exposed to amyloid-beta and in the cortex of aged rats. *J Biol Chem* **287**, 34709-34721.

- [184] Wagner JA, Járai Z, Bátkai S, Kunos G (2001) Hemodynamic effects of cannabinoids: Coronary and cerebral vasodilation mediated by cannabinoid CB1 receptors. *Eur J Pharmacol* **423**, 203-210.
- [185] Ramirez SH, Hasko J, Skuba A, Fan S, Dykstra H, McCormick R, Reichenbach N, Krizbai I, Mahadevan A, Zhang M, Tuma R, Son YJ, Persidsky Y (2012) Activation of cannabinoid receptor 2 attenuates leukocyte-endothelial cell interactions and blood-brain barrier dysfunction under inflammatory conditions. *J Neurosci* **32**, 4004-4016.
- [186] Ahn K, McKinney MK, Cravatt BF (2008) Enzymatic pathways that regulate endocannabinoid signaling in the nervous system. *Chem Rev* **108**, 1687-1707.
- [187] Martin BR, Compton DR, Little PJ, Martin TJ, Beardsley PM (1987) Pharmacological evaluation of agonistic and antagonistic activity of cannabinoids. *NIDA Res Monogr* **79**, 108-122.
- [188] Monory K, Blaudzun H, Massa F, Kaiser N, Lemberger T, Schutz G, Wotjak CT, Lutz B, Marsicano G (2007) Genetic dissection of behavioural and autonomic effects of Delta(9)-tetrahydrocannabinol in mice. *PLoS Biol* **5**, e269.
- [189] Viveros MP, Marco EM, File SE (2005) Endocannabinoid system and stress and anxiety responses. *Pharmacol Biochem Behav* **81**, 331-342.
- [190] Moreira FA, Grieb M, Lutz B (2009) Central side-effects of therapies based on CB1 cannabinoid receptor agonists and antagonists: Focus on anxiety and depression. *Best Pract Res Clin Endocrinol Metab* **23**, 133-144.
- [191] Karkkaine E, Tanila H, Laitinen JT (2012) Functional autoradiography shows unaltered cannabinoid CB1 receptor signalling in hippocampus and cortex of APP/PS1 transgenic mice. *CNS Neurol Disord Drug Targets* **11**, 1038-1044.
- [192] D'Addario C, Di Francesco A, Arosio B, Gussago C, Dell'Osso B, Bari M, Galimberti D, Scarpini E, Altamura AC, Mari D, Maccarrone M (2012) Epigenetic regulation of fatty acid amide hydrolase in Alzheimer disease. *PLoS One* **7**, e39186.
- [193] Maroof N, Ravipati S, Pardon MC, Barrett DA, Kendall DA (2014) Reductions in endocannabinoid levels and enhanced coupling of cannabinoid receptors in the striatum are accompanied by cognitive impairments in the A β PPswe/PS1 Δ E9 mouse model of Alzheimer's disease. *J Alzheimers Dis*. doi: 10.3233/JAD-131961, in press.
- [194] Gifford AN, Bruneus M, Gatley SJ, Volkow ND (2000) Cannabinoid receptor-mediated inhibition of acetylcholine release from hippocampal and cortical synaptosomes. *Br J Pharmacol* **131**, 645-650.