Δ⁹-THC-Caused Synaptic and Memory Impairments Are Mediated through COX-2 Signaling

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SUMMARY

Marijuana has been used for thousands of years as a treatment for medical conditions. However, untoward side effects limit its medical value. Here, we show that synaptic and cognitive impairments following repeated exposure to Δ⁹-tetrahydrocannabinol (Δ⁹-THC) are associated with the induction of cyclooxygenase-2 (COX-2), an inducible enzyme that converts arachidonic acid to prostanoids in the brain. COX-2 induction by Δ⁹-THC is mediated via CB1 receptor-coupled G protein βγ subunits. Pharmacological or genetic inhibition of COX-2 blocks downregulation and internalization of glutamate receptor subunits and alterations of the dendritic spine density of hippocampal neurons induced by repeated Δ⁹-THC exposures. Ablation of COX-2 also eliminates Δ⁹-THC-impaired hippocampal long-term synaptic plasticity, working, and fear memories. Importantly, the beneficial effects of decreasing β-amyloid plaques and neurodegeneration by Δ⁹-THC in Alzheimer’s disease animals are retained in the presence of COX-2 inhibition. These results suggest that the applicability of medical marijuana would be broadened by concurrent inhibition of COX-2.

INTRODUCTION

Marijuana has been used for thousands of years to treat chronic pain, multiple sclerosis, cancer, seizure disorders, nausea, anorexia, and inflammatory and neurodegenerative diseases (Robson, 2001; Russo, 2007). However, the undesirable neuro-psychological and cognitive side effects greatly limit the medical use of marijuana (Carlini, 2004). The major intoxicating effects of cannabis are the impairments in synaptic and cognitive function (Pope et al., 2001; Solowij et al., 2002; Messinis et al., 2006). These untoward effects are also the primary consequences of cannabis abuse. However, there are no currently FDA-approved effective medications for prevention and treatment of these cannabis-related disorders.

As it is clear now, Δ⁹-tetrahydrocannabinol (Δ⁹-THC) is the major psychoactive ingredient of marijuana (Gaoni and Mechoulam, 1964), and its effects are largely mediated through cannabinoid receptors (CB1R or CB2R), which are pertussis toxin (PTX)-sensitive G-protein-coupled receptors (Howlett, 1998; Pertwee et al., 2010). Previous studies demonstrate that deficits in long-term synaptic plasticity, learning, and memory by Δ⁹-THC exposure are primarily mediated through CB1R expressed in the brain (Lichtman and Martin, 1996; Hoffman et al., 2007; Puighermanal et al., 2009; Fan et al., 2010; Han et al., 2012). However, the molecular mechanisms underlying the synaptic and cognitive deficits elicited by repeated Δ⁹-THC exposure are largely unknown.

In the present study, we unexpectedly observed that Δ⁹-THC increases expression and activity of cyclooxygenase-2 (COX-2), an inducible enzyme that converts arachidonic acid to prostanoids both in vitro and in vivo via a CB1R-dependent mechanism. This action is opposite to the observations where the endogenous cannabinoid 2-arachidonylglycerol (2-AG) induces a CB1R-dependent suppression of COX-2 activity and expression in response to proinflammatory and excitotoxic insults (Zhang and Chen, 2008). The differential modulation of COX-2 by the exogenous cannabinoid Δ⁹-THC and endogenous cannabinoid 2-AG appears to result from intrinsic properties of the CB1R-coupled G protein. The COX-2 induction by Δ⁹-THC is mediated via Gβγ subunits, whereas COX-2 suppression by 2-AG is mediated through the Gxi subunit. Interestingly, the impairments in hippocampal long-term synaptic plasticity, working, and fear memories induced by repeated Δ⁹-THC exposure can be occluded or attenuated by pharmacological or genetic inhibition of COX-2. Finally, the beneficial effects of reducing Aβ and neurodegeneration by Δ⁹-THC are retained in the presence of COX-2 inhibition. Our results reveal a signaling pathway that is linked to synaptic and cognitive deficits induced by Δ⁹-THC.
exposure, suggesting that Δ⁹-THC would display its beneficial properties with fewer undesirable side effects when its COX-2 induction effect is inhibited, which may form a therapeutic intervention for medical treatments.

RESULTS

Δ⁹-THC Induces Dose- and Time-Dependent Increase in COX-2 Expression

Identification of CB1Rs led to discovery of several endogenous cannabinoids, including anandamide (AEA) and 2-arachidonylglycerol (2-AG), which are the most-studied endocannabinoids involved in a variety of physiological, pharmacological, and pathological processes (Kano et al., 2009; Pertwee et al., 2010). 2-AG, the most abundant endocannabinoid, plays significant roles in synaptic modification, resolution of neuroinflammation, and neuronal survival (Alger, 2009; Chevaleyre et al., 2006; Lovinger, 2008; Panikashvili et al., 2001; Zhang and Chen, 2008). In particular, its anti-inflammatory and neuroprotective roles in synaptic modification, resolution of neuroinflammation, and neuronal survival appear to be through limiting COX-2 signaling (Chen et al., 2011; Du et al., 2011; Zhang and Chen, 2008). Because acute inhibition of COX-2 by selective COX-2 inhibitors has been shown to decrease hippocampal long-term potentiation (LTP) and impairs memory consolidation (Chen et al., 2002; Teather et al., 2002; Cowley et al., 2008), we thus wondered whether impairments of synaptic plasticity and memory by marijuana result from a COX-2 suppressive effect. To assess this, we first analyzed hippocampal expression and activity of COX-2 in mice that received Δ⁹-THC. Unexpectedly, in vivo exposure to Δ⁹-THC produced a dose- and time-dependent induction of COX-2 in the brain, rather than suppression (Figures 1A and 1B), whereas expression of COX-1 was unaffected by Δ⁹-THC (Figure S1A available online). The increase in COX-2 expression induced by Δ⁹-THC was accompanied by elevated production of prostaglandin E₂ (PGE₂), which could be inhibited by the selective COX-2 inhibitor Celebrex or genetic inhibition of COX-2 (Figures 1C and S1B). To confirm the ability of exogenous cannabinoids to induce COX-2, we assessed COX-2 expression and PGE₂ production in animals injected with the synthetic cannabinoid CP55,940 (CP). As expected, CP produced more pronounced effects on COX-2 expression and PGE₂ synthesis (Figures S1C–S1E). The increase in PGE₂ could be blocked by NS398, another selective COX-2 inhibitor. In addition, we observed that COX-2 expression was steadily elevated in animals injected with Δ⁹-THC once daily for 7 consecutive days, although the magnitude of increase in COX-2 was not as intensified as that of a single injection (Figure 1D). This indicates that expression of COX-2 is persistently elevated upon repeated exposure to Δ⁹-THC (Figure S7).

COX-2 Induction by Δ⁹-THC Is CB1R Dependent

Because undesirable side effects elicited by cannabinoids are primarily mediated by CB1R (Lichtman and Martin, 1996; Hoffman et al., 2007; Han et al., 2012), we wondered whether COX-2 induction by Δ⁹-THC is mediated via CB1R. As shown in Figures 1E and 1F, Δ⁹-THC-induced increase in COX-2 in the hippocampus was blocked either by Rimonabant (RIM), a selective CB1R antagonist, or by genetic deletion of CB1R. To determine whether the increase in COX-2 by Δ⁹-THC occurs in neurons or astroglial cells, we made different conditions in cultures as described previously (Zhang and Chen, 2008). We found that, although Δ⁹-THC induced a CB1R-dependent increase in COX-2 expression both in neuronal and astroglial cell-enriched
cultures, the increase was more pronounced in astroglial cell-enriched cultures than in neuronal culture (Figure 1G). Our data provide convincing evidence that COX-2 induction by Δ9-THC both in vivo and in vitro is mediated via CB1R.

**COX-2 Induction by Δ9-THC Is via CB1R-Coupled G Protein βγ Subunits**

Because the suppression of COX-2 by 2-AG in response to proinflammatory stimuli occurs via a CB1R-dependent mechanism (Zhang and Chen, 2008), we questioned why the exogenous cannabinoid Δ9-THC increases COX-2 and why the endogenous cannabinoid 2-AG suppresses COX-2 acting through the same CB1R-dependent mechanism, and we speculated that CB1R may not be the key molecule responsible for differential regulation of COX-2 expression upon exposure to cannabinoids. CB1R is coupled to a PTX-sensitive Gi/o protein, and activation of CB1R releases Gβγ subunits from the GTP-bound Gαi subunit (Howlett, 1998; Pertwee et al., 2010). Earlier studies show that activation of CB1R is capable of inducing Gβγ-mediated response (Guo and Ikeda, 2004; Wilson et al., 2001; Yao et al., 2003). We hypothesized that Gβγ and Gαi may differentially mediate COX-2 induction or suppression by exogenous Δ9-THC or endogenous 2-AG. To test this prediction, we first overexpressed Gβγ subunits by transfection with plasmids carrying β1 and γ2 subunits in NG108-15 cells, which express native CB1R (Figures S2A and S2B). Whereas Δ9-THC still increased expression of COX-2 mRNA in culture transfected with the control vector, it did not increase COX-2 in culture overexpressing β1 and γ2 subunits (Figure 2A). In subsequent experiments, β1 and γ2 subunits were silenced by small hairpin RNA (shRNA). Knockdown of β1γ2 by shRNA suppressing endogenous β1γ2 also blocked COX-2 induction by Δ9-THC in NG108-15 cells, and the blockade was rescued by concurrently expressing shRNA-resistant β1γ2 (Figures 2A and S2E). This indicates that COX-2 induction by Δ9-THC is likely mediated through Gβγ. To further confirm that Gβγ mediates COX-2 induction by Δ9-THC, we treated mixed culture of hippocampal neurons and astroglial cells (~5%/~10%) with a membrane-permeable Gβγ-binding peptide mSIRK to disrupt the function of Gβγ (Delaney et al., 2007; Goubaea et al., 2003). As a negative control, we used a variant mSIRK with a point mutation of Leu9 to Ala (L9A-mSIRK). As shown in Figure 2B, disruption of Gβγ activity by mSIRK also blocked COX-2 induction by Δ9-THC, whereas it failed to block the suppression of COX-2 by 2-AG in response to LPS, a commonly used COX-2 inducer (Zhang and Chen, 2008). PTX treatment also blocked Δ9-THC-induced increase in COX-2. Interestingly, application of 2-AG failed to suppress Δ9-THC-induced increase in COX-2 (Figures 2B and S2I). To test the prediction that Gαi mediates COX-2 suppressive effect by 2-AG, we silenced Gαi using a lentiviral vector in mixed culture of neurons and astroglial cells (Figure S2C). As illustrated in Figures 2C and S2D, silencing Gαi1, but not Gαi2 or Gαi3, blocked the suppression of COX-2 by 2-AG in response to the LPS stimulus, and this blocking effect was rescued by concurrently expressing shRNA-resistant Gαi1 (Figures 2C and S2E). Knockdown of Gαi1, Gαi2, or Gαi3 did not block COX-2 induction by Δ9-THC (Figures 2C and S2D). These results indicate that COX-2 induction by Δ9-THC is likely mediated via Gβγ, whereas COX-2 suppression by 2-AG is likely mediated through Gαi1 (Figure S7).

**Akt, ERK, p38MAPK, and NF-κB Are Downstream Signaling of Gβγ**

To determine downstream signaling pathways of Gβγ, we detected phosphorylation of Akt, ERK, and p38MAPK by overexpression or knockdown of Gβγ in the presence and absence of Δ9-THC. As shown in Figures 2D and S2F, Δ9-THC-induced phosphorylation of these signaling molecules, and the phosphorylation was inhibited by knockdown or overexpression of Gβγ. Inhibition of phosphorylation of these mediators by shRNA was rescued by concurrently expressing shRNA-resistant Gβγ (Figure 2D). These data indicate that COX-2 induction by Δ9-THC is likely through signaling of these downstream molecules of Gβγ. To further characterize this signaling pathway that regulates COX-2 expression by Δ9-THC, we targeted NF-κB, which is a transcription factor regulating expression of genes, including the COX-2 gene (ptgs2). We observed that Δ9-THC-induced NF-κB phosphorylation in NG-108-15 cells, and this phosphorylation was inhibited by overexpression or knockdown of Gβγ and was rescued by concurrently expressing shRNA-resistant G βγ2 (Figures 2E and S2G). To determine regulation of COX-2 transcription by NF-κB, we performed a chromatin immunoprecipitation (ChIP) analysis in mixed culture of neurons and astroglial cells. As shown in Figure 2E, a binding activity of NF-κB p65 was detected in the promoter positions (~419 to ~428 bp) of ptgs2, and this interaction was enhanced by Δ9-THC and inhibited by SC-514, a specific IKKβ inhibitor that inhibits p65-associated transcriptional activation of the NF-κB pathway. To further confirm the involvement of NF-κB in Δ9-THC-induced increase in COX-2, COX-2 expression and NF-κB phosphorylation by Δ9-THC were determined in the absence and presence of SC-514. Inhibition of IKKβ blocked Δ9-THC-induced COX-2 and NF-κB phosphorylation (Figure 2E). Phosphorylation of Akt, ERK, p38MAPK, and NF-κB was confirmed in the hippocampus of animals that received Δ9-THC (Figure S2H).

**Inhibition of COX-2 Eliminates Impairments in Hippocampal Long-Term Synaptic Plasticity**

If sustained elevation of COX-2 expression and activity following repeated Δ9-THC exposure contribute to impairments in long-term synaptic plasticity and cognitive function, then inhibition of COX-2 should be able to eliminate or attenuate the impairments. To test this hypothesis, we recorded hippocampal LTP in mice receiving daily injections of Δ9-THC (10 mg/kg), the dosage used by other studies such as Fan et al. (2010), Hoffman et al. (2007), Puighermanal et al. (2009), and Tonini et al. (2006)), NS398, Δ9-THC+NS398, or vehicle for 7 consecutive days. We found that COX inhibition by NS398 rescued decreased hippocampal LTP induced by repeated in vivo exposure to Δ9-THC for 7 days both at CA3-CA1 synapses (Figure 3A) and perforant path synapses in the dentate gyrus (Figure S3A). Similarly, genetic inhibition of COX-2 also prevented LTP deterioration induced by Δ9-THC at both CA3-CA1 synapses (Figure 3B) and the perforant path (Figure S3B). To verify whether persistent overexpression of COX-2 impairs LTP, we recorded LTP in
animals repeatedly treated with LPS, which increases COX-2. As we expected, repeated injection of LPS significantly reduced LTP, and this decrease was prevented by inhibition of COX-2 (Figure S3C). These data suggest that persistent elevation of COX-2 in the brain will be detrimental to integrity of synaptic structure and plasticity. Because a single dose of Δ⁹-THC produced an increase in COX-2 expression, we wondered whether this increase alters synaptic function. To this end, we recorded long-term depression (LTD) induced by low-frequency stimulation (LFS) at hippocampal CA3-CA1 synapses and found that LTD is impaired by a single Δ⁹-THC exposure. However, LTD is normal in COX-2 knockout animals that received a single injection of Δ⁹-THC (Figure S4). This information suggests that a single Δ⁹-THC exposure induces a COX-2-associated impairment in LTD (Mato et al., 2004, 2005).

Impairments in Working and Fear Memory by Δ⁹-THC Are Occluded by COX-2 Inhibition

Administration of marijuana or Δ⁹-THC impairs learning and memory. If this impairment is associated with COX-2 induction, then inhibition of COX-2 would prevent or attenuate the deficits. To test this prediction, we determined the effect of COX-2 inhibition on spatial working memory using the Morris water maze test in mice that received repeated Δ⁹-THC exposure in wild-type (WT) and COX-2 KO mice. As shown in Figures 4B and 4C, pharmacological or genetic inhibition of COX-2 prevented Δ⁹-THC-impaired spatial working and retention memory. To further determine the role of COX-2 in Δ⁹-THC-impaired memory, hippocampus-dependent contextual memory was determined using the fear conditioning protocol (Chen et al., 2006a). As seen in Figure 4A, repeated Δ⁹-THC exposure impaired fear...
memory, and this impairment was attenuated by COX-2 inhibition. These results suggest that COX-2 plays a critical role in synaptic and cognitive function deterioration consequent to repeated in vivo Δ⁹-THC exposure (Figure S7).

Cataleptic effect and hypomotility are behavioral responses upon administering Δ⁹-THC (Burstein et al., 1989; Long et al., 2009). We observed that the cataleptic and locomotor depressive effects of Δ⁹-THC were attenuated or prevented by pharmacological or genetic inhibition of COX-2 (Figure S5). This means that cannabis-elicited catalepsy and locomotor depression are associated with the COX-2 induction.

Functional Synaptic Integrity in Δ⁹-THC-Treated Animals Is Maintained by COX-2 Inhibition

Impaired long-term synaptic plasticity and memory induced by Δ⁹-THC are largely associated with altered expression and function of glutamate receptors (Fan et al., 2010; Han et al., 2012). Recent evidence shows that adolescent chronic treatment with Δ⁹-THC results in reduced density of dendritic spines and lowered length and number of dendrites in the hippocampus (Rubino et al., 2009). We used Thy1-GFP-expressing transgenic mice to detect morphology of dendritic spines and locomotor depression are associated with the COX-2 induction.

Figure 3. Inhibition of COX-2 Eliminates Deficits in LTP by Repeated Δ⁹-THC Exposure

(A) Top: representative field excitatory postsynaptic potentials (fEPSPs) recorded at hippocampal CA3-CA1 synapses from WT animals repeatedly injected with vehicle, Δ⁹-THC (10 mg/kg), NS398 (10 mg/kg), or Δ⁹-THC+NS398 once daily for 7 consecutive days. LTP was measured 24 hr after cessation of the last injection. Left: time courses of changes in fEPSP slope under different treatment. Right: mean values of the potentiation of fEPSPs averaged from 56 to 60 min following TBS (n = 6–8 slices/5–6 animals). Error bars represent ± SEM; **p < 0.01 compared with vehicle controls; ##p < 0.01 compared with Δ⁹-THC (ANOVA with Bonferroni post hoc test). Scale bars in (A1) and (B1), 0.3 mV/10 ms. See also Figures S3 and S4.

(B) Top: representative fEPSPs recorded from COX-2 knockout (KO) mice injected with vehicle or Δ⁹-THC (10 mg/kg) once daily for 7 consecutive days. Left: time courses of changes in fEPSP slope induced by Δ⁹-THC. Right: mean values of the potentiation of fEPSPs averaged from 56 to 60 min following TBS (n = 8–12 slices/6–8 animals). Error bars represent ± SEM; *p < 0.01 compared with vehicle controls; #p < 0.01 compared with Δ⁹-THC (ANOVA with Bonferroni post hoc test). Scale bars in (A1) and (B1), 0.3 mV/10 ms. See also Figures S3 and S4.

As seen in Figure 5A, repeated Δ⁹-THC exposure significantly reduced density of dendritic spines of CA1 pyramidal neurons, especially mushroom spines in which AMPA and NMDA receptors are expressed. We found that the reduction in spines was prevented by pharmacological or genetic inhibition of COX-2. (We should mention here that the comparatively low number of mushroom-type spines in Figure 5A may be due to the scoring criteria.) Meanwhile, Δ⁹-THC-reduced expression of PSD-95, an important postsynaptic marker, was rescued by COX-2 inhibition (Figure 5B). However, Δ⁹-THC did not alter expression of synaptophysin (Syn), a presynaptic marker. This information indicates that increased COX-2 by repeated Δ⁹-THC exposure decreases dendritic spines and postsynaptic density. We show previously that repeated Δ⁹-THC exposure for 7 days induces CB1R-dependent decreases in functional and surface expression of AMPA and NMDA receptor subunits (Fan et al., 2010). We speculated that reduced expression of glutamate receptor subunits in the hippocampus of animals that received repeated in vivo Δ⁹-THC exposure is likely regulated by a homeostatic mechanism. Δ⁹-THC increased synthesis of COX-2 and its reaction product PGE₂, which stimulates glutamate released from presynaptic nerve terminals and astroglial cells, resulting in an extracellular accumulation of glutamate (Figure S6A). The increased extracellular glutamate may also result from the reduced uptake of glutamate by glutamate transporters because expression of these transporters was downregulated by repeated exposure to Δ⁹-THC (Figure S6B). To this end, we used immunostaining to determine expressions of synaptic and extrasynaptic GluA1, GluN2A, and GluN2B in the hippocampal CA1 area. As shown in Figures 5C and 5D, hippocampal expressions of both synaptic and extrasynaptic GluA1, GluN2A, and GluN2B were significantly reduced by repeated Δ⁹-THC exposure, and the reduction was attenuated or prevented by COX-2 inhibition. This was consistent with the observations where total and surface expressions of GluA1, GluN2A, and GluN2B detected by immunoblot in WT mice were significantly decreased following...
exposure to Δ⁹-THC for 7 days, but the decreases were not seen in COX-2 knockout mice (Figure 6). These results indicate that reduced expression of glutamate receptor subunits and density of dendritic spines are associated with the COX-2 induction effect of Δ⁹-THC (Figure S7).

The Beneficial Effects of Decreasing Aβ and Neurodegeneration by Δ⁹-THC Are Preserved in the Presence of COX-2 Inhibition

A critical issue is whether COX-2 inhibition would eliminate the beneficial effects of marijuana. To answer this question, we used 5XFAD APP transgenic mice, an animal model of Alzheimer’s disease (AD) as described previously (Chen et al., 2012), to determine whether Δ⁹-THC is capable of reducing Aβ and neurodegeneration and whether these effects are retained when COX-2 is inhibited. As shown Figures 7A and 7B, treatment of Δ⁹-THC once daily for 4 weeks significantly reduced the numbers of Aβ plaques and degenerated neurons in the absence and presence of Celebrex in AD animals. This information indicates that the beneficial effects of Δ⁹-THC are preserved when COX-2 is inhibited. Meanwhile, we revealed that the reduction of Aβ by Δ⁹-THC is not through inhibiting expression of β-site amyloid precursor protein cleaving enzyme 1 (BACE1), an enzyme responsible for synthesis of Aβ, but is likely through elevating nephrilysin, an important endopeptidase that degrades Aβ (Figure 7C).

**DISCUSSION**

The results presented here demonstrate that impaired synaptic and cognitive function induced by repeated Δ⁹-THC exposure is associated with a previously unrevealed CB1R-Gβγ-Akt-ERK/MAPK-NF-κB-COX-2 signaling pathway. It has been long known that use of marijuana induces neuropsychiatric and cognitive deficits, which greatly limit medical use of marijuana. Synaptic and memory impairments are also the consequence of cannabis abuse. However, the molecular mechanisms underlying undesirable effects by cannabis are largely unknown. We discovered in this study that pharmacological or genetic inhibition of COX-2 eliminates or attenuates synaptic and memory impairments elicited by repeated Δ⁹-THC exposure, suggesting that these major adverse effects of cannabis on synaptic and cognitive function can be eliminated by COX-2 inhibition, which would broaden the use of medical marijuana.

CB1R is the primary target of cannabinoid exposures causing synaptic and memory impairments (Lichtman and Martin, 1996; Hoffman et al., 2007; Puighermanal et al., 2009; Fan et al., 2010; Han et al., 2012). Previous studies show that the endocannabinoid 2-AG suppresses COX-2 via a CB1R-dependent mechanism in response to proinflammatory and excitotoxic insults (Zhang and Chen, 2008). Surprisingly, we found in the present study that the exogenous cannabinoid Δ⁹-THC increases COX-2 activity and expression, which are also mediated via CB1R. We demonstrate that COX-2 induction by Δ⁹-THC is mediated via Gβγ subunits, whereas COX-2 suppression by 2-AG is mediated via the Gxi1 subunit, suggesting that activation of the same CB1 receptor may induce opposite biological effects. Indeed, previous studies showed that endogenous cannabinoids and exogenous Δ⁹-THC exhibit different behavioral responses via CB1R (Long et al., 2009). However, it is still not clear how activation of CB1R and its coupled Gβγ by the endogenous cannabinoid 2-AG results in Gxi-mediated suppression of COX-2 in response to proinflammatory insults but the exogenous cannabinoid Δ⁹-THC leads to Gβγ-mediated induction of COX-2. Activation of CB1R/Gβγ either by 2-AG or Δ⁹-THC should induce both Gxi- and Gβγ-mediated effector responses through different downstream signaling events. For example, inhibition of N type calcium channel currents by 2-AG appears to be mediated via Gβγ (Guo and Ikeda, 2004), suggesting that 2-AG is also capable of triggering Gβγ-mediated responses in...
addition to Gαi-mediated responses. In the case of COX-2 induction, the Gbg-mediated COX-2 induction by Δ9-THC may be predominant, which may mask Gαi-mediated COX-2 suppression. In addition, our results showing that the beneficial effects of Δ9-THC are retained in the presence of COX-2 inhibition further suggest that activation of CB1R by Δ9-THC may have both Gαi- and Gbg-mediated effector responses. It is likely that COX-2 induction by Δ9-THC may be just one of several Gbg-mediated effects, and we cannot exclude the possibility that other biological effects are mediated via Gbg. The divergent roles of G protein subunits in mediating endogenous and exogenous cannabinoids may be a consequence the intrinsic mechanisms of CB1R/G protein coupling, such as the agonist binding sites in the receptor, the efficacy of binding, or different conformational changes in the receptor/G protein upon binding with different agonists.

Synaptic and cognitive impairments by Δ9-THC are apparently associated with alterations in glutamatergic synaptic transmission and functional expression of glutamate receptor subunits (Fan et al., 2010; Han et al., 2012; Monory et al., 2007; Tonini et al., 2006). It has been demonstrated that cannabinoid exposure leads to downregulation, internalization, and endocytosis of glutamate receptor subunits (Fan et al., 2010; Han et al., 2012; Suárez et al., 2004). In this...
study, we also demonstrate that density of dendritic spines in hippocampal neurons is reduced in animals that received Δ⁹-THC for 7 days. The reduced expressions of synaptic and extrasynaptic of glutamate receptor subunits as well as PSD-95 by Δ⁹-THC are likely associated with elevated extracellular glutamate levels. Indeed, it has been shown that cannabinoids elevate extracellular glutamate levels, which may result from increased synaptic and astrocytic release of glutamate or reduced uptake of glutamate by glutamate transporters (Fan et al., 2010; Ferraro et al., 2001; Han et al., 2012; Navarrete and Araque, 2008; Tomasini et al., 2002; Suárez et al., 2004; Tonini et al., 2006). We detected that expression of glutamate transporters is significantly decreased in Δ⁹-THC exposed animals, and this decrease is attenuated by COX-2 inhibition (Figure S6). These previous studies, together with our results, suggest that accumulation of glutamate in the extracellular space contributes to reductions in total and surface expression of the glutamate receptors and the density of dendritic spines.

Earlier studies showed that the levels of the eicosanoid PGE₂ in circulation and the brain are elevated in humans and animals exposed to marijuana or Δ⁹-THC, and the elevation could be antagonized by indomethacin, a nonsteroidal anti-inflammatory drug (NSAID) (Burstein et al., 1989; Fairbairn and Pickens, 1979, 1980; Perez-Reyes et al., 1991). NSAIDs are nonselective inhibitors for both COX-1 and COX-2. This suggests that COX-1 and/or COX-2 may be involved in marijuana- or Δ⁹-THC-induced elevation of PGE₂. Our data showing that Δ⁹-THC increases PGE₂ in the brain and that this increase is blocked by COX-2 inhibition support this speculation. Interestingly, Δ⁹-THC-induced cataleptic response can be eliminated by NSAIDs and mimicked by direct administration of PGE₂ (Burstein et al., 1989; Sang et al., 2005). We also provide convincing evidence that pharmacological or genetic inhibition of COX-2 prevents or attenuates cataleptic and locomotor depressive responses by Δ⁹-THC. Importantly, synaptic and cognitive deficits following repeated Δ⁹-THC exposure are eliminated or attenuated by COX-2 inhibition.

The elevated levels of extracellular glutamate by Δ⁹-THC result likely from induction of COX-2, which makes PGE₂. It has been shown that PGE₂ stimulates or facilitates both synaptic and astrocytic release of glutamate (Bezzi et al., 1998; Chen et al., 2002; Dave et al., 2010; Sang et al., 2005; Sanzgiri et al., 1999). In fact, COX-2 and PGE₂ signaling have been shown to regulate glutamatergic synaptic transmission and plasticity via EP2 or EP3 receptors (Akaneya and Tsumoto, 2006; Chen et al., 2002; Cowley et al., 2008; Sang et al., 2005). It is possible that Δ⁹-THC exposure stimulates COX-2 expression and activity through CB1R-coupled Gβ subunits and the downstream Akt-ERK/MAPK-NF-κB signaling pathway, resulting in increase of COX-2 transcription, expression, and activity, which in turn enhance the release of PGE₂ from neurons and astroglial cells. Our results show that Δ⁹-THC-induced COX-2 expression in
Astroglial cells are more pronounced than in neurons. A recent study also shows that CB1R expressed in astroglial cells is responsible for LTD and working memory impairment in animals exposed to cannabinoids (Han et al., 2012). This suggests that glutamate released from astroglial cells triggered by COX-2-derived PGE2 and reduced uptake of glutamate by glutamate transporters in astrocytes resulting from repeated Δ⁹-THC exposure may play an important role in extracellular glutamate accumulation. Sustained elevation and accumulation of extracellular glutamate upon repeated exposure to Δ⁹-THC induce downregulation and internalization of glutamate receptor subunits and reduction in the density of dendritic spines in hippocampal neurons, leading to the deficits in long-term synaptic plasticity and cognitive function (Figure S7).

It has been well recognized that cannabinoids possess antioxidant, anti-inflammatory, and neuroprotective properties (Bahr et al., 2006; Campbell and Gowran, 2007; Centonze et al., 2007; Chen et al., 2011; Du et al., 2011; Gowran et al., 2011; Marchalant et al., 2008; Marsicano et al., 2003; Zhang and Chen, 2008). Also, cannabis has been used for thousands of years as medical treatments. However, neuropsychiatric and cognitive side effects limit medical use of marijuana, especially for a long-term treatment. The results presented here suggest that the unwanted side effects of cannabis could be eliminated or reduced—while retaining its beneficial effects—by administering a COX-2 inhibitor or NSAID along with Δ⁹-THC for treatments of intractable medical conditions such as AD. In the present study, we did observe that brain Aβ and neurodegeneration in 5XFAD transgenic mice are significantly reduced by Δ⁹-THC, and these beneficial effects are preserved in the presence of COX-2 inhibition. We also discovered that Δ⁹-THC significantly elevates expression of neprilysin, an important endopeptidase for Aβ degradation. This suggests that Δ⁹-THC is capable of reducing Aβ and neurodegeneration in an animal model of AD and that the Aβ-reducing effect is likely through elevating expression of neprilysin. This suggests that Δ⁹-THC (brand name: Marinol) may have therapeutic potential for prevention and treatment of AD if its undesirable side effects (e.g., synaptic and cognitive impairments) can be eliminated by COX-2 inhibition. In particular, there are no effective medications currently available for preventing and treating AD or halting disease progression. Our results also suggest that selective COX-2 inhibitors or NSAIDs may be useful for treating the neuropsychological and cognitive side effects of cannabis abuse.

**EXPERIMENTAL PROCEDURES**

**Animals**

C57BL/6, CB1 knockout, Thy1-EGFP transgenic, COX-2 knockout, and 5XFAD APP transgenic mice were used in the present study.

**Cell Culture**

Relative pure hippocampal neurons (astroglial cells < 2%), mixed neurons and astroglial cells (astroglial cells ~10%), astroglial cell-enriched (astroglial
cells > 95%), and NG108-15 cell cultures were made as described previously (Sang et al., 2005; Zhang and Chen, 2008).

Electrophysiological Recordings
Hippocampal LTP both at CA3-CA1 and perforant path synapses were recorded in acutely hippocampal slices and induced by a theta-burst stimulation (TBS) as described previously (Hoffman et al., 2007).

Immunoblot
Western blot assay was conducted using specific antibodies (Table S1) to determine expressions of COX-2, glutamate receptor subunits, PSD-95, G protein subunits, phosphoproteins, BACE1, and nephrilysin in hippocampal tissue and/or in cultured cells as described previously (Che et al., 2012). Surface biotinylation assays were performed to determine surface expression of glutamate receptor subunits in hippocampal slices as described previously (Fan et al., 2010).

Transfection of Plasmid and Lentiviral Vectors
NG108-15 cells were used for transfection of the pcDNA3.1 plasmid encoding Gβ1 and Gγ2 subunits or the pLL3.7 vector expressing scramble, Gβ1 and Gγ2 shRNA, and shRNA-resistant Gβ1γ2. Mixed culture of neurons and astroglial cells was used for transfection of the pLL3.7 lentiviral vector expressing scramble, Gβ1 shRNA, and shRNA-resistant Gβ1.

qRT-PCR
The iScript complementary (cDNA) synthesis kit (BioRad) was used for the reverse transcription reaction. Real-time RT-PCR specific primers for COX-2, Gβ1, Gγ2, and GAPDH were synthesized by IDT. Samples were compared using the relative CT method as described previously (Zhang and Chen, 2009).

ChIP Analysis
ChIP analysis was performed to determine the binding activity of NF-κB in the promoter of the COX-2 gene.

PGE2 Assay
PGE2 in hippocampal tissue was detected using PGE2 enzyme immunoassay kit (Cayman Chemical) according to the procedure described by the manufacturer (Zhang and Chen, 2008).

Immunostaining and Histochemistry
Aβ plaques, degenerated neurons, and glutamate receptor subunits in cryostat sectioning brain slices were performed as described previously (Chen et al., 2012; Li et al., 2011).

Two-Photon Imaging
Morphology of dendritic spines in hippocampal CA1 pyramidal neurons was determined in GFP-expressing transgenic mice using a two-photon laser scanning microscope as described previously (Chen et al., 2012). Shape, size, and density of spines were measured from the three-dimensional reconstructions using NeuronStudio version 0.9.92.

Behavioral Tests
The classic Morris water maze and fear conditioning tests were performed to determine spatial working and fear memory as described previously (Chen et al., 2006a, 2012). The “open field” test was conducted to detect the locomotor activity, and the bar test was used to detect catalepsy (Egas et al., 2007).

SUPPLEMENTAL INFORMATION
Supplemental Information includes Extended Experimental Procedures, seven figures, and one table and can be found with this article online at http://dx.doi.org/10.1016/j.cell.2013.10.042.

AUTHOR CONTRIBUTIONS
R.C. designed and performed the following experiments and analyzed the data: (1) LTP recordings in the hippocampal CA1 region; (2) two-photon imaging of dendritic spines in WT animals; and (3) water maze behavioral tests. J.Z. designed and performed the following experiments and analyzed the data: (1) immunoblot and qPCR; (2) immunohistochemistry; (3) overexpression of Gβγ subunits, shRNA knockdown, and rescue; (4) behavioral tests; and (5) cell culture, genotyping, and animal care. N.F. designed and performed the following experiments and analyzed the data: (1) LTP recordings in the hippocampal dentate gyrus area; (2) LTP recordings in animals treated with LPS; and (3) PGE2 assay. Z.T. designed and performed the following experiments and analyzed the data: (1) ChIP; (2) shRNA-resistant rescue; (3) immunohistochemistry; and (4) fear conditioning behavioral tests. Y.W. designed and performed the following experiments and analyzed the data: (1) two-photon imaging of dendritic spines in COX-2 knockout mice; (2) cataleptic and open field behavior tests; and (3) immunoblot. H.Y., H.S., and Y.S. performed some experiments; Y.T. provided the behavioral testing setups; and C.C. conceived the project and wrote the manuscript.

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