Cannabinoid Administration Attenuates the Progression of Simian Immunodeficiency Virus

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Abstract

Δ9-Tetrahydrocannabinol (Δ9-THC), the primary psychoactive component in marijuana, is FDA approved to ameliorate AIDS-associated wasting. Because cannabinoid receptors are expressed on cells of the immune system, chronic Δ9-THC use may impact HIV disease progression. We examined the impact of chronic Δ9-THC administration (0.32 mg/kg im, 2×daily), starting 28 days prior to inoculation with simian immunodeficiency virus (SIVmac251; 100 TCID50/ml, iv), on immune and metabolic indicators of disease during the initial 6 month asymptomatic phase of infection in rhesus macaques. SIVmac251 inoculation resulted in measurable viral load, decreased lymphocyte CD4+/CD8+ ratio, and increased CD8+ proliferation. Δ9-THC treatment of SIV-infected animals produced minor to no effects in these parameters. However, chronic Δ9-THC administration decreased early mortality from SIV infection (p = 0.039), and this was associated with attenuation of plasma and CSF viral load and retention of body mass (p = NS). In vitro, Δ9-THC (10 μm) decreased SIV (10 TCID50) viral replication in MT4-R5 cells. These results indicate that chronic Δ9-THC does not increase viral load or aggravate morbidity and may actually ameliorate SIV disease progression. We speculate that reduced levels of SIV, retention of body mass, and attenuation of inflammation are likely mechanisms for Δ9-THC-mediated modulation of disease progression that warrant further study.

The cannabinoids including cannabidiol, cannabinol, and Δ9-tetrahydrocannabinol (Δ9-THC) exert their effects by binding to two major subtypes of cannabinoid receptor, CB1 and CB2.1 The CB1 receptor is preferentially expressed in the brain where it mediates neurobehavioral effects. The CB2 receptor is expressed primarily in peripheral tissues, particularly in immune cells where they have been shown to affect cytokine production, lymphocyte phenotype, function and survival, cell-mediated immunity, and balance of Th1/Th2 cells.2 With the advent of highly active antiretroviral therapy (HAART), human immunodeficiency virus (HIV) infection has become a chronic disease frequently coexisting with chronic use of drugs of abuse, including marijuana.3 In addition, Dronabinol (Δ9-THC; Marinol) is approved by the Food and Drug Administration for treatment of HIV-associated anorexia.4 Although this approval has gained strong support from the lay public, little scientific evidence exists to support the efficacy of such an intervention. To date, no clinical studies have rigorously addressed the impact of chronic Δ9-THC use on the course and progression of HIV infection. Only one study has examined the impact of short-term (21 day) Δ9-THC administration (3 daily 0.9 g marijuana cigarettes; 3.95% Δ9-THC) on HIV viral load. The results from that study did not show substantial elevation in viral load in HIV-infected individuals receiving stable antiretroviral regimens containing nelfinavir or indinavir,5 and, thus, were considered to reflect the relative safety of short-term Δ9-THC use in this patient population. The long-term effects of cannabinoid administration on progression of HIV infection had not been previously examined.

Using a well-established nonhuman primate model of HIV disease, we examined the impact of chronic intramuscular Δ9-THC (provided by the National Institute on Drug Abuse, Research Technical Branch, Rockville, MD) administration on the early phase of simian immunodeficiency virus (SIV) infection in age-matched (4–6 years old) and body weight-matched healthy male Indian-derived rhesus macaques. Chronic administration of Δ9-THC [or 0.05 ml/kg vehicle (VEH)] was initiated prior to SIV with 0.18 mg/kg, a dose that eliminated responding in a complex operant behavioral task in almost all of the subjects. The dose was subsequently increased for each subject to 0.32 mg/kg, over...
a period of approximately 2 weeks, and maintained for the duration of the study. Almost all of the animals demonstrated tolerance to the behavioral effects of this dose prior to SIV inoculation (reported elsewhere). Approximately 1 month after initiating chronic Δ9-THC administration, eight animals were inoculated intravenously with 100 times the TCID50 (50% tissue culture infective dose) of SIVmac251. The pathogenicity of this SIV isolate is similar to HIV. The progression of SIV disease was monitored through clinical and biochemical parameters, and viral load in plasma and cerebrospinal fluid (CSF).

Contrary to what we expected, chronic cannabinoid administration did not significantly increase viral load or exacerbate immune dysfunction. Mean viral load in VEH/SIV+ animals was 6.56 ± 0.16 log copies at 7 days and 6.04 ± 0.6 log copies/ml at 2 months postinfection (Fig. 1A). Viral load remained elevated (6.35 ± 0.76 and 5.8 ± 0.06 log copies/ml at 3 and 6 months, respectively) throughout the duration of the study. Viral load in THC/SIV+ was lower (4.83 ± 0.56 log copies/ml) as compared to VEH/SIV+ beginning at 2 months post-SIV infection (p = NS). Viral mRNA in CSF peaked at day 14 postinfection and remained elevated up to 2 months postinfection in the VEH/SIV+ and THC/SIV+ animals (Fig. 1B). Thereafter, CSF viral load fluctuated between levels below the limit of detection and low counts in both SIV-infected groups. Across all time points, 60% of VEH/SIV+...
CSF samples were above the limit of detection for the assay. In contrast, only 40% of CSF samples from THC/SIV+ animals had viral loads above the limit of detection.

Complete and differential blood counts were performed using a Beckman Coulter LH755 for total leukocyte counts and Wright-Giemsa staining of blood smears for leukocyte differentials. Blood lymphocyte subsets were determined by flow cytometry as previously described. The CD4+ to CD8+ ratio decreased significantly from preinfection values ($p = 0.0001$) in both VEH- and THC-treated animals (Fig. 2B). The marked decrease in CD4+ lymphocyte counts reached statistical significance ($p = 0.023$) at 0.5 and 1 months post-SIV infection in VEH/SIV+ animals, and beginning at 2 months in THC/SIV+ ($p = 0.037$). In contrast, CD8+ counts showed a short-lived increase at 2 weeks postinfection, which reached statistical significance only in THC/SIV+ animals ($p = 0.029$) (Fig. 2D). CD4+ and CD8+ lymphocyte expressions of Ki67 and caspase 3 (Cas3) were measured as indices of proliferation and apoptosis. No significant changes were noted in the percent of either Ki67+ or Cas3+ on CD4+ lymphocytes in either of the experimental groups (data not shown). In contrast, both markers were increased significantly in CD8+ lymphocytes at 2 weeks postinfection, suggesting increased activation of these cells during the acute response to infection (Fig. 3A). The CD8+ Ki67 expression was increased 10-fold at this time point, and was significantly higher in THC/SIV+ animals when compared to the VEH/SIV+-infected animals ($p = 0.049$). This rise in

![FIG. 2](https://example.com/fig2.png) (A) Lymphocyte count (cells x 10^3/μl), (B) CD4+/CD8+ lymphocyte ratio, and (C) CD4+ and (D) CD8+ counts determined by flow cytometry in vehicle-treated uninfected (VEH/SIV−), THC-treated uninfected (THC/SIV−), vehicle-treated infected (VEH/SIV+), and THC-treated infected (THC/SIV+) rhesus macaques expressed as means over time post-SIV infection. Change from baseline was analyzed by a model that included baseline value, as a covariate, and factor effects for Study Period (SPno), THC (+/−), SIV (+/−), and all SPno, THC, and SIV interaction effects. The PROC MIXED procedure in SAS (version 9.1) was selected to perform the analyses. As these are repeated measures on the same subjects over the eight study periods, the within-subjects covariance structure was modeled as compound symmetry; the Kenward-Roger approximation was used to compute $p$-values for tests of significance. Values for experimental groups $N = 3$ in VEH/SIV− and $N = 4$ in all others. *$p < 0.05$ vs. time- and treatment-matched uninfected controls.
CD8⁺ lymphocyte proliferation was transient in both groups with only values for THC/SIV⁺ animals remaining higher (p = 0.05) than controls at 1 month post-SIV infection. Values for the VEH/SIV⁺ and THC/SIV⁺ groups were not different from control beyond 1 month postinfection. The changes in the number of Ki67⁺ CD8⁺ lymphocytes were paralleled by those in number of Cas3⁺ CD8⁺ lymphocytes. Cas3⁺ CD8⁺ lymphocytes showed a transient and significant (p = 0.001) 7- to 8-fold increase that peaked at 2 weeks post-SIV infection in both VEH/SIV⁺ and THC/SIV⁺ animals (Fig. 3B). Although a similar pattern of higher levels of Cas3⁺ CD8⁺ lymphocytes was observed in the THC/SIV⁺ animals, this difference failed to reach statistical significance in comparison to the VEH/SIV⁺ animals (p = 0.06). This rise in CD8⁺ lymphocyte apoptosis was short-lived, and values after 1 month post-SIV infection were not different from uninfected control values.

No deaths were noted during the first 5 months post-SIV infection in VEH/SIV⁺ or THC/SIV⁺ animals (Fig. 4). Two of the VEH/SIV⁺ animals succumbed to SIV infection shortly after 5 months, and a third reached end stage at 7 months. Among the THC/SIV⁺ animals, the first animal did not reach end stage until 11 months post-SIV inoculation. A summary of the clinical indications for euthanasia and the most salient necropsy findings is presented in Table 1.

Notably different patterns in weight gain were observed between the initial 3 month post-SIV infection period and the subsequent 3- to 6-month post-SIV period (Fig. 5). This was particularly true for the VEH/SIV⁺ animals, which showed a tendency for greater (p = NS) weight loss than the THC/SIV⁺ animals. Echocardiography (Toshiba Aplio at 8.5 MHz) performed prior to (baseline) and 3 and/or 6 months after SIV infection in the two SIV-infected groups (VEH and THC) failed to show significant alterations in cardiac systolic or diastolic function (data not shown). Cannabinoids, including Δ⁹-THC, have been shown to have immunomodulatory effects on cytokine production and lymphocyte phenotype, function, and survival as well as cell-mediated immunity. Similar immunosuppressive effects on lymphocyte and alveolar macrophage function have been reported in nonhuman primates. Furthermore, the potential of cannabinoids to regulate the activation and balance of human Th1/Th2 cells by a CB2 receptor-dependent pathway has been supported by findings from several studies. More recent studies have provided evidence that the synthetic cannabinoid WIN 55,212-2 can potently inhibit HIV-1 expression in CD4⁺ lymphocytes and microglial cell cultures in a time- and concentration-dependent manner. Moreover, Rock et al. demonstrated the involvement of CB2 receptors in cannabinoid antiviral activity in microglial cells. To examine the possibility that the improved survival of SIV-infected rhesus could have been...
due to direct suppression of viral replication, we examined the in vitro effects of 1 and 10 μM Δ2-THC on viral replication in MT4-R5 cells (human T cell line)\textsuperscript{21} infected with SIV\textsubscript{MAC251} (10 TCID\textsubscript{50}). Pretreatment with 10 μM Δ2-THC (3.2 μg/ml) resulted in a significant decrease in cell-associated viral load in cells collected at 3 and 6 days post-SIV inoculation (Fig. 6). Several possible mechanisms could be involved in this suppression of viral replication, including effects on cell cycle, interaction of cannabinoids with viral coreceptor, and viral integration into the host genome. Moreover, the contribution of the specific cannabinoid receptor subtypes to the overall effects also remains to be examined.

In summary, this study is the first to report in vivo experimental data demonstrating that chronic Δ2-THC initiated prior to, and continued throughout the asymptomatic phase of SIV infection, does not impair the host’s ability to control viral load, and does not increase morbidity and mortality from the infection. Although the small groups and natural variation in SIV disease are limitations of the study, the vehicle-treated group is representative of typical rhesus infections with SIV\textsubscript{mac251}. Δ2-THC treatment clearly did not increase disease progression, and indeed resulted in generalized attenuation of the classic markers of SIV disease (set point viral load/viral level in general). The mechanisms underlying the decreased mortality in cannabinoid-treated SIV-infected animals remain to be elucidated. However, based on our results and reports in the literature, we speculate that retention of body mass, attenuation of viral replication, and an overall immunosuppressant effect of cannabinoids may contribute to the amelioration of SIV disease progression seen in our study. The cellular mechanisms, including the potential role of the recently identified interaction between the HIV coreceptor CXCR4 and the cannabinoid system\textsuperscript{22} as potential sites of pharmacoimmunomodulation, remain to be determined.

Acknowledgments

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**Table 1. Clinical Indications for Euthanasia and Necropsy Findings\textsuperscript{a}**

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Time days post-SIV</th>
<th>Clinical findings</th>
<th>Necropsy findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEH/SIV\textsuperscript{+}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2L046</td>
<td>148</td>
<td>Head pressing, ataxia, inactivity, lack of a pupillary light reflex in the right eye, serum albumin &lt;3 mg/dl, and dehydration, unresponsive to treatment</td>
<td>Cytomegalovirus meningitis with cerebral edema and uncal herniation</td>
</tr>
<tr>
<td>A1R047</td>
<td>166</td>
<td>Unilateral right facial nerve paralysis, lethargy, ventral recumbence, dyspnea</td>
<td>Acute bilateral bronchopneumonia and pulmonary edema</td>
</tr>
<tr>
<td>A1R058</td>
<td>220</td>
<td>Decreased platelet count, hematuria, hematochezia, pyuria; collapsed and did not respond to CPR</td>
<td>Giant cell pneumonia with <em>Mycobacterium sp.</em>, <em>Pneumocystis jiroveci</em>, meningoencephalitis, and cerebral vasculitis</td>
</tr>
<tr>
<td>A2R065</td>
<td>503</td>
<td>None</td>
<td>Pulmonary thromboembolism</td>
</tr>
<tr>
<td>THC/SIV\textsuperscript{+}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1R044</td>
<td>343</td>
<td>Chronic progressive intermittent diarrhea, nonresponsive to treatment, chronic intermittent rectal prolapse, gradual body weight loss (&gt;25%), serum albumin &lt;3 mg/dl</td>
<td><em>Mycobacterium sp.</em> involving lungs, liver, spleen, kidneys, gastrointestinal tract, and mesenteric lymph nodes with granulomatous inflammation</td>
</tr>
<tr>
<td>A1R022</td>
<td>351</td>
<td>None</td>
<td>Pulmonary edema, congestion, mild hepatic microsteatosis</td>
</tr>
<tr>
<td>A1R005</td>
<td>461</td>
<td>None</td>
<td>Steatohepatitis, pulmonary granulomatus inflammation, chronic pancreatitis</td>
</tr>
<tr>
<td>A2L094</td>
<td>503</td>
<td>None</td>
<td>Mild cerebral edema, mild acute steatohepatitis</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Animals were studied during the pretreatment period (prior to initiating the Δ\textsuperscript{2-THC administration) and following SIV infection during the "asymptomatic phase of infection" prior to any of them reaching criteria for euthanasia. This period was defined as the period of time following SIV infection during which none of the animals showed clinical signs of disease including weight loss greater than 5% of basal, secondary infections that required antibiotic treatment, neurological manifestations of disease, severe diarrhea, and dehydration. Animals were sacrificed and necropsy performed when they met predefined clinical indications including the presence of three or more of the following: weight loss greater than 15%, hypoalbuminemia (<3 mg/dl) in the presence of edema, anemia and thrombocytopenia, 3 days of complete anorexia, major organ failure or medical conditions unresponsive to treatment (including respiratory distress, intractable diarrhea, or persistent vomiting, secondary infections that required antibiotic treatment), neurological manifestations of disease, severe diarrhea, and dehydration. Survival was tracked throughout the first year postinfection, at which time all animals still on study were euthanized and necropsy was performed.
FIG. 5. Body weight change (kg) during the initial 3 months post-SIV infection (left panels) and during the subsequent 3- to 6-month period of infection. Top panels depict change in body weight in vehicle-treated uninfected (VEH/SIV−), THC-treated uninfected (THC/SIV−), vehicle-treated infected (VEH/SIV+), and THC-treated infected (THC/SIV+) rhesus macaques expressed as means ± SEM over time post-SIV infection. Because of the individual variability, data are shown for each animal during the initial 3 months post-SIV infection and during the later 3–6 months post-SIV infection in the lower panels, showing the trends in body weight changes. The symbols in the line graphs represent individual animals in the specified treatment group and carry over across time.
MT4-R5 cells (human T cell line) were seeded at a cell density of 5 × 10^5/ml in RPMI 1640 containing 10% heat-inactivated fetal calf serum, 2 mM glutamine, 100 U/ml penicillin, 100 µg/ml streptomycin, and 1 µg/ml puromycin in T25 flasks and maintained at 37°C with 5% CO2 in the presence of Δ^2-THC (1 or 10 µM) or vehicle for 11 days. Culture media was replaced at 3–4 day intervals. After 11 days, 1.5 × 10^6 MT4-R5 cells from each treatment group were inoculated with 10 TCID50 SIVmac in fresh media containing Δ^2-THC or vehicle, plated in 96-well dishes at a density of 1 × 10^4 cells/well, and maintained at 37°C with 5% CO2. Uninfected cultures of Δ^2-THC- and vehicle-treated cells were maintained identically for use as controls. One-half of the replicate cultures were harvested 3 days post-SIV-infection, with the remainder harvested 6 days after infection. Supernatant and cell pellets were fractionated by centrifugation at 700×g for 5 min at room temperature. Cell viability was monitored through cell counts using Trypan blue. DNA was prepared and the quantity of proviral SIV DNA in the cell pellets was determined by real-time PCR. DNA viral load (log SIV DNA copies/well) was quantified in cells harvested at 3 and 6 days postinoculation. Expression of CB1 and CB2 receptors was confirmed in these cells prior to using them in the study. Values are mean ± SEM of eight replicate wells. Results were analyzed with two-way ANOVA followed by pairwise multiple comparison procedures (Holm–Sidak method) *p ≤ 0.008.

**Author Disclosure Statement**

No competing financial interests exist.

**References**


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