Cannabinoids Inhibit the Vascular Endothelial Growth Factor Pathway in Gliomas

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ABSTRACT

Cannabinoids inhibit tumor angiogenesis in mice, but the mechanism of their antiangiogenic action is still unknown. Because the vascular endothelial growth factor (VEGF) pathway plays a critical role in tumor angiogenesis, here we studied whether cannabinoids affect it. As a first approach, cDNA array analysis showed that cannabinoid administration to mice bearing s.c. gliomas lowered the expression of various VEGF pathway-related genes. The use of other methods (ELISA, Western blotting, and confocal microscopy) provided additional evidence that cannabinoids depressed the VEGF pathway by decreasing the production of VEGF and the activation of VEGF receptor (VEGFR)-2, the most prominent VEGF receptor, in cultured glioma cells and in mouse gliomas. Cannabinoid-induced inhibition of VEGF production and VEGFR-2 activation was abrogated both in vitro and in vivo by pharmacological blockade of ceramide biosynthesis. These changes in the VEGF pathway were paralleled by changes in tumor size. Moreover, intratumoral administration of the cannabinoid Δ²-tetrahydrocannabinol to two patients with glioblastoma multiforme (grade IV astrocytoma) decreased VEGF levels and VEGFR-2 activation in the tumors. Because blockade of the VEGF pathway constitutes one of the most promising antitumoral approaches currently available, the present findings provide a novel pharmacological target for cannabinoid-based therapies.

INTRODUCTION

To grow beyond minimal size, tumors must generate a new vascular supply for purposes of gas exchange, cell nutrition, and waste disposal (1–4). They do so by secreting proangiogenic cytokines that promote the formation of blood vessels. Vascular endothelial growth factor (VEGF; also known as VEGF-A) is considered the most important proangiogenic molecule because it is expressed abundantly by a wide variety of animal and human tumors and because of its potency, selectivity, and ability to regulate most and perhaps all of the steps in the angiogenic cascade (1–4). The best characterized VEGF receptors are two related receptor tyrosine kinases termed VEGF receptor (VEGFR)-1 (also known as Flt-1) and VEGFR-2 (also known as kinase domain region or Flk-1). Although VEGF binds to VEGFR-2 with higher affinity, numerous studies in cultured cells and laboratory animals have provided evidence that VEGFR-2 is the major mediator of the mitogenic, antiapoptotic, angiogenic, and permeability-enhancing effects of VEGF (1–4). Because overexpression of VEGF and VEGFR-2 is causally involved in the progression of many solid tumors, several strategies to inhibit VEGF signaling have been translated into clinical trials in cancer patients, including anti-VEGF and anti-VEGFR-2 antibodies, small VEGFR-2 inhibitors, and a soluble decoy VEGFR (5–8). In addition, clinical trials are being performed with a number of promising anticancer compounds such as Iressa and Herceptin that block proteins involved in the induction of the VEGF pathway (5, 8).

Cannabinoids, the active components of Cannabis sativa L. (marijuana), and their derivatives exert a wide array of effects by activating their specific G protein-coupled receptors CB1 and CB2, which are normally engaged by a family of endogenous ligands—the endocannabinoids (9, 10). Marijuana and its derivatives have been used in medicine for many centuries, and there is currently a renaissance in the study of the therapeutic effects of cannabinoids. Today, cannabinoids are approved to palliate the wasting and emesis associated with cancer and AIDS chemotherapy (11), and ongoing clinical trials are determining whether cannabinoids are effective agents in the treatment of pain (12), neurodegenerative disorders such as multiple sclerosis (13), and traumatic brain injury (14). In addition, cannabinoid administration to mice and/or rats induces the regression of lung adenocarcinomas (15), gliomas (16), thyroid epitheliomas (17), lymphomas (18), and skin carcinomas (19). These studies have also evidenced that cannabinoids display a fair drug safety profile and do not produce the generalized cytotoxic effects of conventional chemotherapies, making them potential antitumoral agents (20, 21).

Little is known, however, about the mechanism of cannabinoid antitumoral action in vivo. By modulating key cell signaling pathways, cannabinoids directly induce apoptosis or cell cycle arrest in different transformed cells in vitro (20). However, the involvement of these events in their antitumoral action in vivo is as yet unknown. More recently, immunohistochemical and functional analyses of the vasculature of gliomas (22) and skin carcinomas (19) have shown that cannabinoid administration to mice inhibits tumor angiogenesis. These findings prompted us to explore the mechanism by which cannabinoids impair angiogenesis of gliomas and, particularly, the possible impact of cannabinoids on the VEGF pathway. Here, we report that cannabinoid administration inhibits the VEGF pathway in cultured glioma cells, in glioma-bearing mice, and in two patients with glioblastoma multiforme. In addition, this effect may be mediated by ceramide, a sphingolipid second messenger implicated previously in cannabinoid signaling in glioma cells (23).

MATERIALS AND METHODS

Cannabinoids. The Δ²-tetrahydrocannabinol was kindly given by Alfredo Dupetit (The Health Concept, Richelbach, Germany). JWH-133 was kindly given by Dr. John Huffman (Department of Chemistry, Clemson University, Clemson, SC; Ref. 24). WIN-55,212-2 and anandamide were from Sigma (St. Louis, MO). SR141716 and SR144528 were kindly given by Sanofi-Synthelabo (Montpellier, France). For in vitro incubations, cannabinoid agonists and antagonists were directly applied at a final DMSO concentration of 0.1–0.2% (v/v). For in vivo experiments, ligands were prepared at 1% (v/v) DMSO in 100 μl PBS supplemented with 5 mg/ml BSA. No significant influence of the vehicle was observed on any of the parameters determined.

Cell Culture. The rat C6 glioma (25), the human U373 MG astrocytoma (25), the mouse PDV-C57 epidermal carcinoma (19), and the human ECV304 bladder cancer epithelioma (22) were cultured as described previously. Human glioma cells were prepared from a glioblastoma multiforme (grade IV astrocytoma; Ref. 26). The biopsy was digested with collagenase (type Ia; Sigma) in DMEM at 37°C for 90 min, the supernatant was seeded in DMEM containing 15% FCS and 1 mM glutamine, cells were grown for 2 passages, and 24 h before the experiments, cells were transferred to 0.5%-serum DMEM. Cell viability was determined by trypan blue exclusion. Rat recombinant VEGF and N-acetylphosphoglycerine (C- ceramide) were from Sigma.

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Inhibition of the VEGF Pathway by Cannabinoids

Tumor Induction in Mice. Tumors were induced in mice deficient in recombination activating gene 2 by s.c. flank inoculation of 5 × 10^5 C6 glioma cells in 100 μl PBS supplemented with 0.1% glucose (16). When tumors had reached a volume of 350–450 mm^3, animals were assigned randomly to the various groups and injected intratumorally for up to 8 days with 50 μg/day JWH-133 and/or 60 μg/day fumonisins B1 (Alexis, San Diego, CA). Control animals were injected with vehicle. Tumors were measured with external caliper, and volume was calculated as (4π/3) × (width/2)^2 × (length/2).

Human Tumor Samples. Tumor biopsies were obtained from two of the patients enrolled in an ongoing Phase I/II clinical trial (at the Neurosurgery Department of Tenerife University Hospital, Spain) aimed at investigating the effect of Δ9-tetrahydrocannabinol administration on the growth of recurrent glioblastoma multiforme. The patients had failed standard therapy, which included surgery, radiotherapy (60 Gy), and temozolomide chemotherapy (4 cycles). Patients had clear evidence of tumor progression on sequential magnetic resonance scanning before enrollment in the study, had received no anticancer therapy for 1 year, and had a fair health status (Karnofsky performance score = 90). The patients provided written informed consent. The protocol was approved by the Clinical Trials Committee of Tenerife University Hospital and by the Spanish Ministry of Health.

Patient 1 (a 48-year-old man) had a right-occipital-lobe tumor (7.5 × 6 cm maximum diameters), and Patient 2 (a 57-year-old man) had a right-temporal-lobe tumor (6 × 5 cm maximum diameters). Both tumors were diagnosed by the Pathology Department of Tenerife University Hospital as glioblastoma multiforme and showed the hallmarks of this type of tumor (high vascularization, necrotic areas, abundant palisading and mitotic cells, and so on). The tumors were removed extensively by surgery, biopsies were taken, and the tip (−5 cm) of a silastic infusion catheter (9.6 French; 3.2 mm diameter) was placed into the resection cavity. The infusion catheter was connected to a Nuport subclavicular s.c. reservoir. Each day 0.5 ml of physiological saline solution supplemented with 0.5% (w/v) human serum albumin, and the resulting solution was filtered and subsequently stored at −20°C. Patient 1 started the treatment 4 days after the surgery and received a total amount of 24.5 mg of Δ9-tetrahydrocannabinol for 19 days. The posttreatment biopsy was taken 19 days after the cessation of Δ9-tetrahydrocannabinol administration. Patient 2 started the treatment 4 days after the surgery and received a total amount of 13.5 mg of Δ9-tetrahydrocannabinol for 16 days. The posttreatment biopsy was taken 43 days after the cessation of Δ9-tetrahydrocannabinol administration. Samples were either transferred to DMEM containing 15% FCS and 1 mM glutamine (for tumor-cell isolation, see above; Fig. 2B) and frozen (for VEGF determination, Patients 1 and 2; and for VEGF ELISA Western blotting, Patient 1; Fig. 6A and C) or fixed in formalin and embedded in paraffin (for VEGF-2 confocal microscopy, Patients 1 and 2; Fig. 6B).

The CDNA Arrays. Total RNA was extracted (27) from tumors of vehicle- or JWH-133-treated mice (see above), and poly(A) RNA was isolated with oligotex resin (Qiagen Inc., Valencia, CA) and reverse-transcribed with Moloney murine leukemia virus reverse transcriptase in the presence of 50 μCi [α-32P]dATP for the generation of radiolabeled cDNA probes. Purified radio-labeled probes were hybridized to angiogenesis, hypoxia, and metastasis gene array membranes (GEArray Q Series; Superarray Bioscience Corporation, Frederick, MD) according to the manufacturer’s instructions. Hybridization signals were detected by phorourimag and analyzed by Phoretix housekeeping genes in the blots as internal controls for normalization. The selection criteria were set conservatively throughout the process, and the genes selected were required to exhibit at least a 2-fold change of expression and a P < 0.01.

ELISA. VEGF levels were determined in cell culture media and in tumor extracts, obtained by homogenization as described previously (16), by solid-phase ELISA using the Quantikine mouse VEGF Immunoassay (R&D Systems, Abingdon, United Kingdom; 70% cross-reactivity with rat VEGF) for rat and mouse samples and the Quantikine human VEGF Immunoassay (R&D Systems) for human samples.

Western Blot. Particulate cell or tissue fractions were subjected to SDS-PAGE, and proteins were transferred from the gels onto polyvinylidene fluo-

See Internet address http://www.superarray.com for a detailed list of the genes analyzed.
etin-2 [a prominent proangiogenic factor that cooperates with VEGF (3, 19, 22)], and Tie-1 [an angiopoietin receptor (34)]. In addition, cannabinoi

d treatment increased the expression of the gene encoding type I procollagen α1 chain (a metalloproteinase substrate related to matrix remodeling during angiogenesis; Ref. 35).

Inhibition of VEGF Production in Cultured Glioma Cells and in Mouse Gliomas. We focused next on the two main components of the VEGF pathway, namely VEGF and VEGFR-2, in both cultured glioma cells and gliomas in vivo. Incubation of C6 glioma cells with the synthetic cannabinoid WIN-55,212-2 (100 nM), a mixed CB1/CB2

Fig. 2. Inhibition of VEGF production by cannabinoids in cultured glioma cells and in mouse gliomas. A, C6 glioma cells were cultured for the times indicated with vehicle (Control) or 100 nM WIN-55,212-2 (WIN), and VEGF levels in the medium were determined (n = 4). B, U373 MG astrocytoma cells, tumor cells obtained from a patient with glioblastoma multiforme (GBM), PDV.C57 epidermal carcinoma cells, and ECV304 bladder cancer epithelioma cells were cultured for 48 h with vehicle (Control) or 100 nM WIN-55,212-2 (WIN), and VEGF levels in the medium were determined (n = 3–4). C, C6 glioma cells were cultured for 48 h with vehicle (Control), 100 nM WIN-55,212-2 (WIN), 1 µM C2-ceramide (CER), and/or 0.5 µM fumonisin B1 (FB1), and VEGF levels in the medium were determined (n = 4). D, animals bearing gliomas were treated with either vehicle (Control), JWH-133 (JWH), fumonisin B1 (FB1), or JWH-133 plus fumonisin B1 for 8 days as described in “Materials and Methods,” and VEGF levels in the tumors were determined (n = 4–6 for each experimental group). Significantly different (*, P < 0.01; **, P < 0.001) from control incubations or control animals. Bars, ±SD.
receptor agonist, inhibited VEGF release into the medium in a time-
dependent manner (Fig. 2A). The cannabinoid did not affect cell
viability throughout the time interval in which VEGF determinations
were performed (up to 48 h; data not shown). Cannabinoid-induced
attenuation of VEGF production was evident in another glioma cell
line (the human astrocytoma U373 MG) and, more importantly, in
tumor cells obtained directly from a human glioblastoma multiforme
biopsy (Fig. 2B). The cannabinoid effect was also observed in the
mouse skin carcinoma PDV.C57 and in the human bladder cancer
epithelioma ECV304 (Fig. 2B).

To prove the specificity of WIN-55,212-2 action on VEGF release,
we used other cannabinoid receptor agonists as well as selective
cannabinoid receptor antagonists (Fig. 2C). The inhibitory effect of
WIN-55,212-2 was mimicked by the endocannabinoid anandamide (2
μM), another mixed CB1/CB2 agonist, and by the synthetic cannabi-
noid JWH-133 (100 nM), a selective CB2 agonist. In addition, the CB1
agonist SR141716 (0.5 μM) and the CB2 antagonist SR144528 (0.5
μM) prevented WIN-55,212-2 action, pointing to the involvement of
CB receptors in cannabinoid-induced inhibition of VEGF production.

The sphingolipid messenger ceramide has been implicated in the
regulation of tumor cell function by cannabinoids (16, 23, 36). The
involvement of ceramide in cannabinoid-induced inhibition of VEGF
production was tested by the use of N-acetylspingosine (C2-,
ceramide), a cell-permeable ceramide analog, and fumonisin B1, a
selective inhibitor of ceramide synthesis de novo. In line with our previous data
in primary cultures of rat astrocytes (28), fumonisin B1 was able to
prevent cannabinoid-induced ceramide biosynthesis (relative values of [14C]serine incorporation into ceramide, n = 3: vehicle, 100; 100
nM WIN-55,212-2, 140 ± 1; 100 nM WIN-55,212-2 plus 0.5 μM
fumonisin B1, 86 ± 9). C2-ceramide (1 μM) depressed VEGF pro-
duction, whereas pharmacological blockade of ceramide synthesis de novo
with fumonisin B1 (0.5 μM) prevented the inhibitory effect of
WIN-55,212-2 (Fig. 2D). We subsequently evaluated whether fumo-
nisin B1 action was also evident in vivo. The decrease in tumor VEGF
levels induced by cannabinoid administration (19, 22, 37) was pre-
vented by cotreatment of the animals with fumonisin B1 (Fig. 2E).

**Inhibition of VEGFR-2 in Cultured Glioma Cells and in Mouse
Gliomas.** VEGFR-2 activation was determined by measuring the
extent of phosphorylation of two of its essential tyrosine autophos-
phorylation residues, namely 996 and 1214 (3, 4). Western blot
experiments showed that C6 glioma cells express highly phosphory-
lated VEGFR-2 in the absence of ligand, indicating that the receptor
may be constitutively active. Incubation of C6 glioma cells with
WIN-55,212-2 or JWH-133 decreased VEGFR-2 activation without
affecting total VEGFR-2 levels (Fig. 3A). Confocal microscopy ex-
periments confirmed the decrease in VEGFR-2 immunoreactivity by
cannabinoid challenge when fluorescence was expressed per cell
nucleus (Fig. 3B) or per total-VEGFR-2 fluorescence (data not
shown). Moreover, fumonisin B1 prevented cannabinoid inhibitory
action, and C2-ceramide reduced VEGFR-2 activation (Fig. 3, A and
B). Interestingly, on cannabinoid exposure the receptor seemed to be
preferentially condensed in the perinuclear region, and this relocal-
ization was prevented by fumonisin B1 (Fig. 3B). The functional
impact of VEGF on C6 glioma cells was supported by the finding that
VEGF induced a prosurvival action by preventing the loss of cell
viability on prolonged (72 h) cannabinoid or C2-ceramide challenge
(Fig. 3C).

The effect of cannabinoid administration on VEGFR-2 activation
was subsequently tested in tumor-bearing mice. The ceramide-
dependent cannabinoid-induced inhibition of VEGFR-2 activation
found in cultured cells was also observed by Western blot (Fig. 4A)
and confocal microscopy (Fig. 4B) in mouse gliomas. Like in the
cultured-cell experiments and in line with the cDNA array experi-
ments (data not shown), total VEGFR-2 expression in the tumors was
unaffected by cannabinoid treatment (Fig. 4, A and B).

Phosphorylated VEGFR-2 has been found previously in the cell
nucleus, and it has been postulated that this translocation process
might play a role in VEGFR-2 signaling (38–40). However, by
confocal microscopy, we found a rather variable fraction of phospho-
rylated VEGFR-2 in the nuclei of C6 glioma cells in culture and on
inoculation in mice, and this fraction of nuclear VEGFR-2 was un-
altered after treatment with cannabinoids and/or fumonisin B1 in vitro
and in vivo (data not shown).
Changes in the Size of Mouse Gliomas. To test whether the aforementioned ceramide-dependent changes in the VEGF pathway are functionally relevant, we measured tumor size along cannabinoid and fumonisin B1 treatment. In agreement with previous observations (26), JWH-133 administration blocked the growth of s.c. gliomas in mice. Of importance, cotreatment of the animals with fumonisin B1 prevented cannabinoid antitumoral action (Fig. 5).

Inhibition of the VEGF Pathway in Two Patients with Glioblastoma Multiforme. To obtain additional support for the potential therapeutic implication of cannabinoid-induced inhibition of the VEGF pathway, we analyzed the tumors of two patients enrolled in a clinical trial aimed at investigating the effect of Δ⁹-tetrahydrocannabinol, a mixed CB₁/CB₂ agonist, on recurrent glioblastoma multiforme. The patients were subjected to local Δ⁹-tetrahydrocannabinol administration, and biopsies were taken before and after the treatment. In both patients, VEGF levels in tumor extracts were lower after cannabinoid inoculation (Fig. 6A). The Δ⁹-tetrahydrocannabinol also lowered the expression of phosphorylated VEGFR-2 in the tumors of the two patients, and this was accompanied (in contrast to the mouse glioma experiments shown above) by a decrease in total VEGFR-2 levels (Fig. 6B). This was confirmed by Western blot analysis in Patient 1 (Fig. 6C). Unfortunately, we were unable to obtain appropriate samples for Western blot from Patient 2.

DISCUSSION

Angiogenesis is a prerequisite for the progression of most solid tumors. In particular, gliomas first acquire their blood supply by co-opting existing normal brain vessels to form a well-vascularized tumor mass without the necessity to initiate angiogenesis (41–43). When gliomas progress, they become hypoxic as the co-opted vasculature regresses and malignant cells rapidly proliferate. These hypoxic conditions, in turn, induce robust angiogenesis via the VEGF pathway and angiopoietin-2, and in fact, this angiogenic sprouting distinguishes a grade IV astrocytoma (glioblastoma multiforme) from lower-grade astrocytomas (41–43). Here, we show that cannabinoid treatment impairs the VEGF pathway in mouse gliomas by blunting VEGF production and signaling. Cannabinoid-induced inhibition of VEGF expression and VEGFR-2 activation also occurred in cultured glioma cells, indicating that the changes observed in vivo may reflect the direct impact of cannabinoids on tumor cells. Moreover, a depression of the VEGF pathway was also evident in two patients with glioblastoma multiforme. Although the changes in VEGF-2 expression observed in these two patients...
do not fully mirror the cultured-cell and mouse data, they clearly follow the same direction. The molecular basis of this discrepancy is, however, unknown.

Our observations do not exclude that cannabinoids may also blunt tumor VEGF signaling indirectly by targeting other receptor-mediated processes that stimulate the VEGF pathway. For example, it is known that engagement of epidermal growth factor (44) and nerve growth factor (45) receptors induces the VEGF pathway, and cannabinoids have been reported to inhibit the epidermal growth factor receptor in skin carcinoma (19) and prostate carcinoma cells (46) as well as the TrkA neurotrophin receptor in breast carcinoma (47) and pheochromocytoma cells (20). However, the molecular mechanisms by which cannabinoid receptor activation impact these growth factor receptors remain obscure.

Recent work has shown that cannabinoids can modulate sphingolipid-metabolizing pathways by increasing the intracellular levels of ceramide (23), a lipid second messenger that controls cell fate in lipid-metabolizing pathways by increasing the intracellular levels of sphingosine 1-phosphate (48). The findings reported here expand the role of de novo-synthesized ceramide in cannabinoid action. Moreover, as far as we know, this is also the first report showing that ceramide depresses the VEGF pathway by interfering with VEGF production and VEGFR-2 activation, a notion that is in line with the observation that ceramide analogs prevent VEGF-induced cell survival (51, 52). In the context of the sphingolipid rheostat theory (48, 49), the mitogenic sphingolipid sphingosine 1-phosphate would shift the balance toward angiogenesis and tumorigenesis (5, 53), whereas the antiproliferative sphingolipid ceramide would blunt angiogenesis and tumorigenesis (present study).

The use of cannabinoids in medicine is limited by their psychoactive effects mediated by neuronal CB₁ receptors (9, 10). Although these adverse effects are within the range of those accepted for other medications, especially in cancer treatment, and tend to disappear with tolerance on continuous use (20), it is obvious that cannabinoid-based therapies devoid of side-effects would be desirable. As glioma cells express functional CB₂ receptors (26), we used a selective CB₂ ligand to target the VEGF pathway. Selective CB₂ receptor activation in mice also inhibits the growth and angiogenesis of skin carcinomas (19). Unfortunately, very little is known about the pharmacokinetics and toxicology of the selective CB₂ ligands synthesized to date, making them as yet unavailable for clinical trials.

Gliomas are one of the most malignant forms of cancer, resulting in the death of affected patients within 1–2 years after diagnosis. Current therapies for glioma treatment are usually ineffective or just palliative. Therefore, it is essential to develop new therapeutic strategies for the management of glioblastoma multiforme, which will most likely require a combination of therapies to obtain significant clinical results. In line with the idea that anti-VEGF treatments constitute one of the most promising antitumoral approaches currently available (5–7), the present laboratory and clinical findings provide a novel pharmacological target for cannabinoid-based therapies.

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