Inhibition of skin tumor growth and angiogenesis in vivo by activation of cannabinoid receptors

M. Llanos Casanova, Cristina Blázquez, Jesús Martínez-Palacio, Concepción Villanueva, M. Jesús Fernández-Aceñero, John W. Huffman, José L. Jorcano, and Manuel Guzmán

Nonstandard abbreviations used:
PIGF; angiopoietin 1 (Ang1); squamous cell carcinoma (SCC).

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The authors have declared that no conflict of interest exists.

E-mail: mgp@bbm1.ucm.es.
Phone: 34-913944668; Fax: 34-913944672;
Complutense University, 28040 Madrid, Spain.

Introduction
The epidermis is a stratified squamous epithelium composed mainly of keratinocytes, whose proliferation and differentiation must be tightly regulated and coordinated. Basal keratinocytes, which are attached to the basement membrane, are undifferentiated and have proliferative potential. Before entering the differentiation program, they withdraw from the cell cycle and migrate toward the surface of the epidermis, leading to the formation of the outermost layer of the epidermis composed of enucleated dead squames, which are continuously shed from the surface of the skin (1). The incidence of both benign and malignant skin neoplasms has been rising at an alarming rate for the past several years. Thus, nonmelanoma skin cancer is one of the most common malignancies in humans: basal cell carcinomas and squamous cell carcinomas represent the vast majority of the malignant tumors diagnosed (2). These tumors are believed to arise mainly from stem cells of hair follicles (3), and their growth and development seems to rely on an early burst of neovascularization (4) in which VEGF (5–7) and EGF-R (8, 9) are essential components. The skin is also a major site for metastasis of internal disease (2, 10). Early recognition, biopsy confirmation, and treatment selection can reduce patient morbidity. Different types of strategies are currently being investigated as therapies for the treatment of these tumors, including cryotherapy, topical chemotherapeutic agents such as 5-fluorouracil, and photodynamics, the success of which is hampered by limitations such as the poor penetration of molecules into the skin and the difficulty to gain access to the whole tumor (10–12).

Cannabinoids, the active components of Cannabis sativa Linnæus (marijuana) and their derivatives, exert a wide array of effects on the CNS as well as on peripheral sites such as the immune, cardiovascular, digestive, reproductive, and ocular systems (13–15). Nowadays, it is widely accepted that most of these effects are mediated by the activation of specific G protein–coupled receptors that are normally bound by a family of endogenous ligands — the endocannabinoids (14, 16, 17). Two different cannabinoid receptors have been characterized and cloned from mammalian tissues: the
“central” CB1 receptor, mostly expressed in brain and responsible for cannabinoid psychoactivity (18), and the “peripheral” CB2 receptor, mostly expressed in the immune system and unrelated to cannabinoid psychoactivity (19). Marijuana and its derivatives have been used in medicine for many centuries, and currently there is a renaissance in the study of the therapeutic effects of cannabinoids, which constitutes a widely debated issue with ample scientific and social relevance. Ongoing research is determining whether cannabinoid ligands may be effective agents in the treatment of, for example, pain and inflammation, neurodegenerative disorders such as multiple sclerosis and Parkinson’s disease, and the wasting and emesis associated with AIDS and cancer chemotherapy (13–15). In addition, cannabinoids may be potential antitumoral agents owing to their ability to induce the regression of various types of tumors, including lung adenocarcinoma (20), glioma (21, 22), and thyroid epithelioma (23) in animal models. Although cannabinoids directly induce apoptosis or cell cycle arrest in different transformed cells in vitro (24), the involvement of this and other potential mechanisms (e.g., inhibition of tumor angiogenesis) in their antitumoral action in vivo is as yet unknown.

This background prompted us to explore whether (a) the skin and skin tumors express cannabinoid receptors; (b) cannabinoid receptor activation exerts a growth-inhibiting action on skin tumors in vivo; and (c) inhibition of angiogenesis is implicated in the antitumoral effect of cannabinoids. Our data show that (a) CB1 and CB2 receptors are present in the skin and skin tumors; (b) local cannabinoid receptor activation induces the regression of skin tumors in vivo; and (c) at least two mechanisms may be involved in this action: direct apoptosis of tumor cells and inhibition of tumor angiogenesis.

Methods

Cannabinoids. JWH-133 was prepared in J.W. Huffman’s laboratory (25). WIN-55,212-2 was from Sigma-Aldrich (St. Louis, Missouri, USA). SR141716 and SR144528 were kindly given by Sanofi-Synthelabo (Montpellier, France).

Cell culture. The mouse tumorigenic epidermal cell lines PDV.C57 and HaCa4, and the nontransformed epidermal cell lines MCA3D (mouse) and HaCat (human), were routinely maintained in DMEM supplemented with 10% FCS. Twenty-four hours before the experiments, cells were transferred to low serum (0.5%) DMEM supplemented with 5 mg/ml BSA and operated at a flux of 0.52 µl/h for 11 days. Cannabinoid treatment did not affect animal weight gain (data not shown).

Viability and apoptosis in vitro. Cell viability in the cultures was determined by the 3-(4,5-dimethylthiazol-2,5-diphenyltetrazolium bromide thiazol blue test. Apoptosis was determined by both TUNEL staining (21) and oligonucleosomal DNA fragmentation (26) according to kit manufacturer’s instructions (Boehringer Mannheim GmbH, Mannheim, Germany).

Proliferation and apoptosis in vivo. For proliferation assays, mice received an intraperitoneal injection of BrdU (120 mg/kg body weight) (Boehringer Mannheim GmbH) 2 hours before tumor harvesting. Detection of BrdU-positive cells was performed using an anti-BrdU mouse mAb (Boehringer Mannheim GmbH) as described (9). Apoptosis was determined by TUNEL

| Table 1 Quantification of apoptotic and proliferative cells in vehicle- and cannabinoid-treated skin carcinomas |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Control | JWH | WIN |
| TUNEL (positive cells/field) | 2.6 ± 1.1 | 7.2 ± 3.6 | 5.6 ± 2.5 |
| BrdU (positive cells/section) | 15.0 ± 8.7 | 23.8 ± 15.2 | 10.3 ± 4.7 |

Tumor-bearing mice were treated with vehicle (Control), WIN-55,212-2 (WIN), or JWH-133 (JWH) for 11 days, and then tumors were dissected. Several sections of five different tumors were analyzed per group. *Positive cells per ten high-power fields. Significantly different (P < 0.05) from control mice.

Human tumor samples. Formalin-fixed, paraffin-embedded, human tumor samples were obtained from the files of the Department of Pathology, Hospital General de Móstoles (Madrid, Spain). Six-micrometer tumor sections were stained with either hematoxylin-eosin or used for immunohistochemistry (see below). The normal skin sample (Figures 1 and 3, skin) came from the face of a 70-year-old man. The slowly growing tumor sample (Figure 3, BCC) came from the face of a 69-year-old woman. The histological analysis revealed the growth of basaloid cell solid nests at the dermoepidermal junction with diagnostic characteristics of basal cell carcinoma. The highly malignant tumor sample (Figures 1 and 3, SCC) came from the retroauricular skin of a 73-year-old man. The histological analysis showed the neoplastic growth of epithelial cells, with squamous differentiation and focal areas of acantholysis.

Tumor induction in mice. Malignant skin tumors were induced in nude (NMRI nu) mice by subcutaneous flank inoculation of 10^6 PDV.C57 epidermal tumor cells. When tumors had reached an average volume of 500 mm^3 (range, 400–600 mm^3), a continuous flow pump (Alzet 2002; Alza Corporation, Palo Alto, California, USA) was surgically implanted on the flank of every mouse near the site of tumor inoculation. The pump was filled witheither vehicle, 1,580 µg of WIN-55,212-2, or 1,580 µg of JWH-133 in 236 µl PBS supplemented with 5 mg/ml BSA and operated at a flux of 0.52 µl/h for 11 days. Tumors were measured with an external caliper and their volume calculated as (4π/3) × (width/2)^2 × (length/2). Cannabinoid treatment did not affect animal weight gain (data not shown).

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Western blot analysis. Particulate cell or tissue fractions were subjected to SDS-PAGE, and proteins were transferred from the gels onto polyvinylidene fluoride membranes. To determine cannabinoid receptor expression the blots were incubated with polyclonal Ab’s raised in rabbits against residues 1–14 of the human/mouse CB1 receptor (1:500; kindly given by A. Howlett, North Carolina Central University, Durham, North Carolina, USA) or residues 20–33 of the human/mouse CB2 receptor (1:2,000; Cayman Chemical, Ann Arbor, Michigan, USA) as described (21). Antigen preabsorption experiments were performed by preincubating (37°C, 1 hour) 1 µl (= 0.5 µg) of the anti-CB1 or anti-CB2 Ab and 100 µl PBS with or without 20 µl (= 20 µg) of the corresponding immune peptide (Cayman Chemical). Western blots were subsequently done with the aforementioned Ab dilutions. To determine EGF-R phosphorylation the blots were incubated with anti-phosphotyrosine (1:500; 4G10 mAb; Upstate Biotechnology Inc., Lake Placid, New York, USA) or anti-keratin 5 (1:1,000; Berkeley Antibody Co., Richmond, California, USA) Ab’s, the latter used as a loading control. In all cases, samples were subjected to luminography with an enhanced chemiluminescence detection kit (Amersham Life Sciences, Arlington Heights, Illinois, USA). Densitometric analysis of the blots was performed with the Molecular Analyst software package (Bio-Rad Laboratories Inc., Hercules, California, USA).

Immunohistochemistry. Tissues were fixed in 10% buffered formalin and embedded in paraffin. Sections of mouse and human skin and tumors were stained with the aforementioned Ab’s against CB1 (1:300) and CB2 (1:300) receptors. Control immunostainings using the secondary Ab in the absence of the primary Ab were routinely performed. In addition, antigen preabsorption experiments were carried out with the corresponding immune peptide as described above. Immunodetection of blood vessels in cryosections of mouse tumors was performed with an anti-CD31 Ab (1:40; PharMingen, San Diego, California, USA). Sections were incubated with a biotinylated anti-rabbit (CB1 and CB2) or anti-rat Ab (CD31) and then with peroxidase-conjugated streptavidin (LSAB Kit Peroxidase; DAKO A/S, Glostrup, Denmark). Ab localization was determined using 3,3′-diaminobenzidine (Vector Laboratories, Burlingame, California, USA). Morphometric values were obtained by examination of six 0.11-mm² sections per tumor with the image analysis system Leica Qwin (Leica Microsystems Inc., Chantilly, Virginia, USA).

Northern blot analysis. Total RNA was extracted from the tumor samples by the acid guanidinium method (27). The VEGF probe has been described previously (7). The placental growth factor (PIGF) probe was kindly given by G. Persico (Istituto Internazionale di Genetica e Biofisica, Naples, Italy). Probes for angiopoietin 1 (Ang1) and angiopoietin 2 (Ang2) detection were kindly provided by G.D. Yancopoulos (Regeneron Pharmaceuticals, Tarrytown, New York, USA). A 1-kb fragment of the 5′ region of the hEGF-R cDNA was used as probe for EGF-R detection (9). Ribosomal 7S RNA was used as a loading control. Densitometric analysis of the blots was performed with a PhosphorImager using Quantity One software (Bio-Rad Laboratories Inc.).

Statistics. Results shown represent means ± SD. Statistical analysis was performed by ANOVA with a post hoc analysis by the Student-Neuman-Keuls test. Data in Table 1, Figure 5a, and Figure 6c were analyzed by the Mann-Whitney (Wilcoxon) W test to compare medians for nonparametric data.

Results

Cannabinoid receptors are expressed in skin and skin tumors. The expression of cannabinoid receptors in epidermal cell lines, normal skin, and skin tumors of mice and humans was examined by Western blot analysis and immunohistochemistry. Western blot experiments showed that CB1 and CB2 receptors were expressed in a number of tumorigenic and nontransformed epidermal cell lines of murine and human origin (Figure 1a). In addition, the two receptors were present in normal mouse skin as well as in benign (papillomas) and malignant (squamous cell carcinomas) mouse skin tumors. Likewise, CB1 and CB2 receptors were expressed in human skin, keratinocytes, and carcinomas (Figure 1a). To ascertain the specificity of the cannabinoid receptor Ab’s used in the blotting experi-

![Figure 1](https://example.com/figure1.png)
ments, antigen preabsorption experiments were carried out with the corresponding blocking peptides. As shown in Figure 1b, the peptides blocked anti-CB1 and anti-CB2 Ab binding, not only in skin-derived samples but also in other cell types used as well-established controls for the presence of CB1 (rat cortical neurons) (18), CB2 (human promyelocytic HL60 cells) (19), and CB1 plus CB2 (rat C6 glioma cells) (21).

Immunocytochemical analyses showed that in mouse (Figure 2a) and human (Figure 3a) normal skin CB1 and CB2 receptors were mostly present in suprabasal layers of the epidermis and hair follicles. Basal staining was also observed in some sporadic regions. CB1 and CB2 receptor immunoreactivity was also evident in both papillomas and squamous cell carcinomas of mouse origin (Figure 2a), as well as in human basal cell carcinomas and squamous cell carcinomas (Figure 3a). The specificity of the immunolabeling was shown by experiments in which the primary Ab was omitted and—as mentioned above for Western blots—by antigen preabsorption experiments carried out with the corresponding blocking peptides (Figures 2b and 3b).

Cannabinoid receptor activation induces skin tumor cell apoptosis. We tested the functionality of cannabinoid receptors in the induction of apoptosis in skin tumor cells. The mixed CB1/CB2 agonist WIN-55,212-2 decreased the viability of the tumorigenic epidermal cell lines PDV.C57 and HaCa4 (Figure 4a). Values of cell viability after WIN-55,212-2 treatment (as percentage of the corresponding incubations with no additions) were 74 ± 10 (day 3) and 62 ± 7 (day 4) for PDV.C57 cells, and 75 ± 7 (day 3) and 71 ± 4 (day 4) for HaCa4 cells. Of interest, the cannabinoid was unable to induce any statistically significant change in the viability of MCA3D and HaCat cells, two nontransformed epidermal cell lines, and of primary human keratinoctyes (Figure 4b). The mixed CB1/CB2 agonist HU-210 and the selective CB2 agonist JWH-133 (Kᵢ = 677 nM for CB1 and 3.4 nM for CB2; ref, 25) (both at 25 nM) also induced PDV.C57 death to an extent similar to that of WIN-55,212-2 (data not shown). WIN-55,212-2–induced death of PDV.C57 cells occurred by a process of apoptosis, as determined by oligonucleosomal DNA fragmentation (Figure 4c) and TUNEL staining (Figure 4d).

To evaluate the possible implication of the CB1 and CB2 receptors in cannabinoid-induced apoptosis, the
The effect of selective receptor antagonists was studied. Thus, the CB₁ antagonist SR141716 and the CB₂ antagonist SR144528 prevented WIN-55,212-2–induced apoptosis of PDV.C57 cells (Figures 4, a, c, and d), pointing to the involvement of both receptors in the apoptotic action of cannabinoids.

Cannabinoids inhibit skin tumor growth in vivo. Given the inhibition of tumorigenic epidermal cell survival in culture by cannabinoids, we evaluated the effect of cannabinoid treatment on skin tumor growth in vivo. Tumors generated by inoculation of the highly malignant PDV.C57 cell line were treated with vehicle or WIN-55,212-2. As shown in Figure 5, a–c, cannabinoid administration blocked the growth of tumor cells in vivo (in ≈75% of the mice treated).

Because cannabinoid-based therapeutic strategies should be as devoid as possible of psychotropic side effects and PDV.C57 express functional CB₂ receptors, we administered to mice the selective CB2 agonist JWH-133. Previously, we have provided pharmacological, biochemical, and behavioral evidence that JWH-133 activates selectively the CB₂ receptor and does not elicit psychotropic effects in mice (22). As shown in Figure 5, a–c, tumors from JWH-133–treated animals were significantly smaller than those from vehicle-treated controls (in ≈70% of the mice treated).

We next examined whether, as occurs in cultured skin tumor cell lines, cannabinoids induce apoptosis of malignant cells in vivo. As shown in Table 1, quantification of apoptotic cells in tumor sections revealed that treatment with WIN-55,212-2 or JWH-133 increased the number of apoptotic cells. In contrast, the proliferation index did not significantly differ between control and cannabinoid-treated carcinomas.

Cannabinoids inhibit skin tumor angiogenesis in vivo. Tumors require an adequate supply of oxygen and nutrients to grow more than a few millimeters. For that purpose they produce proangiogenic factors that promote the formation of new blood vessels (28, 29). We therefore analyzed whether the vascularization of growth-arrested cannabinoid-treated tumors was affected. Northern blot analyses showed that the
expression of major proangiogenic factors, namely VEGF, PI GF, and Ang2, was strongly depressed by treatment with WIN-55,212-2 or JWH-133 (Figure 6a). The mRNA expression of Ang1 and the two antiangiogenic factors, thrombospondin 1 and thrombospondin 2, was not significantly affected by cannabinoid administration (data not shown). Furthermore, although immunostaining of CD31, a marker of endothelial cells, revealed no significant differences in vascular density (number of blood vessels per unit area) between control and WIN-55,212-2– or JWH-133–treated tumors (Figures 6, b and c), important differences were observed when vessel morphology was examined: while control carcinomas showed a network of dilated vessels, cannabinoid-treated tumors displayed a pattern of blood vessels characterized predominantly by narrow capillaries (Figure 6b). Morphometric analyses confirmed that cannabinoid treatment induced a statistically significant decrease in blood vessel size, as determined by the total area occupied by vessels, the area per vessel, and the vessel larger diameter length (Figure 6c).

Cannabinoids decrease EGF-R activation in skin tumors in vivo. We have recently found that in skin carcinomas EGF-R plays an important role in triggering the angiogenic switch necessary for skin tumor growth (9). Thus, we measured the expression levels and activation state of EGF-R in control and cannabinoid-treated skin tumors. While EGF-R mRNA was highly expressed in vehicle-treated tumors, in line with its known overexpression in skin carcinomas (30, 31), the levels of EGF-R mRNA in cannabinoid-treated tumors were very low (Figure 7a). In addition, the degree of EGF-R activation (autophosphorylation) was markedly reduced in cannabinoid-treated tumors (Figure 7b). Moreover, exposure of cul-
tured PDV.C57 cells to WIN-55,212-2 or JWH-133 blunt-ed EGF-R phosphorylation (Figure 7c), supporting the direct impact of cannabinoids on skin tumor cells.

Discussion

Here we report that CB1 and CB2 cannabinoid receptors are expressed in normal epidermis and in skin tumors and that both receptors are functional in the induction of apoptosis of skin tumor cells and the regression of skin carcinomas. It is therefore plausible that apoptosis of tumor cells and tumor regression are two causally related events. Nonetheless, our data indicate that cannabinoid antitumoral action may also rely on the inhibition of tumor angiogenesis. It has been shown that mouse skin tumor growth and progression depends on critical events leading to epithelial and stromal changes, including the establishment of an active angiogenesis (4). Here, we report that blood vessels developed by cannabinoid-treated carcinomas are small, in line with the finding that blood vessel enlargement constitutes a prominent feature of skin tumor progression (4, 32). Moreover, we show that in cannabinoid-treated carcinomas the expression of proangiogenic factors is depressed and that of antiangiogenic factors is unchanged, which fits well with the observations that link skin carcinoma development with a small, in line with the finding that blood vessel enlargement constitutes a prominent feature of skin tumor progression (4) and that cannabinoid-induced glioma cell apoptosis (21, 22). In any event, the present report, together with the implication of CB2 or CB2-like receptors in the control of peripheral pain (40–42) and inflammation (41), opens the attractive possibility of finding cannabinoid-based therapeutic strategies for diseases of the skin and other tissues devoid of nondesired CB1-mediated psychotropic side effects.

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