

Cannabinoid receptor ligands as potential anticancer agents – high hopes for new therapies?

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Abstract

Objectives The endocannabinoid system is an endogenous lipid signalling network comprising arachidonic-acid-derived ligands, cannabinoid (CB) receptors, transporters and endocannabinoid degrading enzymes. The CB₁ receptor is predominantly expressed in neurons but is also co-expressed with the CB₂ receptor in peripheral tissues. In recent years, CB receptor ligands, including Δ^9 -tetrahydrocannabinol, have been proposed as potential anticancer agents.

Key findings This review critically discusses the pharmacology of CB receptor activation as a novel therapeutic anticancer strategy in terms of ligand selectivity, tissue specificity and potency. Intriguingly, antitumour effects mediated by cannabinoids are not confined to inhibition of cancer cell proliferation; cannabinoids also reduce angiogenesis, cell migration and metastasis, inhibit carcinogenesis and attenuate inflammatory processes. In the last decade several new selective CB₁ and CB₂ receptor agents have been described, but most studies in the area of cancer research have used non-selective CB ligands. Moreover, many of these ligands exert prominent CB receptor-independent pharmacological effects, such as activation of the G-protein-coupled receptor GPR55, peroxisome proliferator-activated receptor gamma and the transient receptor potential vanilloid channels.

Summary The role of the endocannabinoid system in tumourigenesis is still poorly understood and the molecular mechanisms of cannabinoid anticancer action need to be elucidated. The development of CB₂-selective anticancer agents could be advantageous in light of the unwanted central effects exerted by CB₁ receptor ligands. Probably the most interesting question is whether cannabinoids could be useful in chemoprevention or in combination with established chemotherapeutic agents.

Keywords anticancer agent; cancer; cannabinoids; chemoprevention; endocannabinoid system

Introduction

The endocannabinoid system (ECS) comprises the two well-characterised G-protein-coupled receptors (GPCRs) CB₁ and CB₂,^[1–3] as well as the putative new GPCRs GPR55 and GPR119,^[4,5] former orphan receptors. While cannabinoid binding to GPR55 has been shown (*vide infra*), GPR119 appears to have little affinity for cannabinoids.^[6] There is also pharmacological evidence of other putative cannabinoid receptors that remain unknown.^[7,8]

The endogenous ligands that activate CB receptors are arachidonic acid derivatives, primarily arachidonoyl ethanolamide (anandamide) and 2-arachidonoyl glycerol (2-AG),^[9,10] which are directly released from cell membranes. Endocannabinoids are pleiotropic lipids and their actions are not restricted to cannabinoid receptors. Anandamide also activates transient receptor potential vanilloid 1 (TRPV1), peroxisome proliferator-activated receptors (PPARs), and potentially signals via serotonin 5HT(3) receptors.^[11–13] Moreover, 2-AG is an apparently potent ligand for GPR55 whose function is yet to be uncovered.^[5,14]

Among other effects, endocannabinoids have been reported to modulate cell differentiation, cell signalling, cell migration and cell fate.^[15–17]

The terpenophenolic phytocannabinoids from *Cannabis sativa*, with the prototype cannabinoid Δ^9 -tetrahydrocannabinol (Δ^9 -THC),^[18] were the first bioactive CB receptor

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ligands to be described and they have served as molecular scaffolds for the chemical development of analogous structures such as CP55,940.^[19] The use of CP55,940 as a radioligand has played a key role in the cloning of the CB receptors.

It is probably not an overstatement to claim that without cannabis research the ECS would not have been explored so extensively in the last two decades. It is becoming increasingly clear that the ECS is involved not only in central nervous system regulation (mainly via CB₁) and neuroimmunological processes (both via CB₁ and CB₂) but also in several peripheral physiological processes.^[20] It is important to highlight that many of the functions of the ECS that are currently proposed are not yet fully understood. Nonetheless, there is clinical evidence that CB₁ receptor antagonists (inverse agonists) such as rimonabant (SR141716A) are useful in the treatment of obesity and for the improvement of cardiovascular and metabolic risk factors. (Rimonabant was the first therapeutic CB₁ receptor blocker approved in Europe but was withdrawn in October 2008 because of psychiatric side effects.) CB₁ receptor antagonists also have good prospects in other therapeutic areas, including smoking cessation, alcohol addiction and cognitive impairment.^[21] CB₁ agonists are useful for the prevention of nausea and vomiting and to stimulate appetite.^[22] There is increasing evidence that CB receptors are involved in numerous immune mechanisms and are generally able to attenuate inflammatory processes.^[23,24] There are numerous reports on the anti-inflammatory action of CB receptor ligands from animal studies. Positive effects have been reported using CB ligands in models of liver inflammation,^[25] neuroinflammation,^[26] gut inflammation,^[27] skin inflammation^[28] and arthritis.^[29] Based on CB₂ receptor knockout studies, the involvement of this receptor has been suggested in immune cell function and development, infection, embryonic development, bone loss, liver disorders, pain, autoimmune inflammation, allergic dermatitis, atherosclerosis, apoptosis and chemotaxis.^[30] In particular, non-psychoactive CB₂ receptor ligands have been shown to be effective in bone degeneration,^[31–34] gut inflammation,^[35] neuroprotection^[36] and atherosclerosis.^[37,38] Given that cannabinoid pharmacology is exceptionally complex, it is difficult to provide a general picture. Overall, however, it seems that CB₂-selective agonists and inverse agonists and CB₁ inverse agonists could be promising therapeutic agents to target chronic inflammatory diseases. Moreover, indirect activation of the ECS via modulation of endocannabinoid tone, such as inhibition of fatty acid amide hydrolase (FAAH) and monoacyl glycerol lipase, may be a promising strategy to target pathological inflammatory processes.^[39] Different selective and non-selective CB₁/CB₂ receptor ligands have been described, which show potential for a wide range of diseases.^[20,21]

Evidence accumulated within the last decade suggests that CB receptor agonists may have antitumour properties in a variety of cancer types; this topic has been reviewed in several cancer-related journals.^[40–43] In this review, the recent developments and insights are discussed with respect to CB receptor signalling, ligand selectivity, specificity of effect in different tissues and potential therapeutic relevance.

In 1975, Munson and colleagues reported for the first time that cannabinoids can reduce tumour growth and viability of lung cancer cells *in vitro* as well as *in vivo*.^[44] After this initial observation another 20 years passed until more detailed investigations yielded further insights into the anticancer mechanisms of cannabinoids. However, the mechanism of action of CB receptor ligands has started to become uncovered only recently (*vide infra*). While some signalling events involved in the cytotoxic effects exerted by cannabinoids apply for all cellular models, other cellular mechanisms are restricted to only a few cell types. Thus, an important question is how CB receptor activation ultimately leads to inhibition of tumour growth and apoptosis of cancer cells. It is currently not clear whether these effects are specific for certain types of cancer cells, and whether the *in-vitro* data correlate with more physiological conditions, in particular with regard to the concentrations employed.

CB-receptor mediated signal transduction events leading to anticancer effects

Despite a growing amount of data on the cellular signalling events triggered by cannabinoids in non-neuronal cells, as yet there is no straightforward explanation for the molecular mechanism for their anticancer action. Pharmacological intervention in cancer therapy typically relies on well-defined molecular events that attenuate tumour growth, such as inhibition of microtubule dynamics, inhibition of topoisomerase or DNA intercalation. So far, GPCR signalling in cancer therapy is not a well-designed strategy and there are still many unanswered questions relating to signalling dynamics, limited prolongation of effect due to desensitisation, specificity of signals and potentially unwanted effects. However, with a change of paradigm from the ‘one selective drug acting on one target’ to network pharmacology,^[45] anticancer strategies involving GPCRs may become more interesting in the future. Fundamental to such developments is a better understanding of GPCR cellular signalling cascades, as cancer cells often hijack the normal physiological functions of GPCRs to survive.^[46] Targeting of dysregulated kinases in cancer cells could be accomplished via GPCR signalling, and modulation of the cancer kinome may drive tumour cells into apoptosis. As shown in the following sections, CB receptor signalling events that lead to antitumour effects are complex and largely depend on tissue type and physiological context (Figure 1). The major signalling molecules involved in cannabinoid-induced antitumour action are described in the following sections.

Ceramide

Ceramides are composed of sphingosine and fatty acid moieties and are commonly found at high concentrations within the cell membrane, where they are derived from sphingomyelin, one of the major membrane lipids. Ceramide is also a lipid messenger specifically triggered upon activation (e.g. via GPCR activation) and appears to play a key role in the cytoplasm, mediating different effects on cell survival following CB receptor activation.^[47] An acute rise of ceramide by sphingomyelin hydrolysis is observed in both glioma cells and normal primary astrocytes after cannabinoid challenge, presumably mediated through the

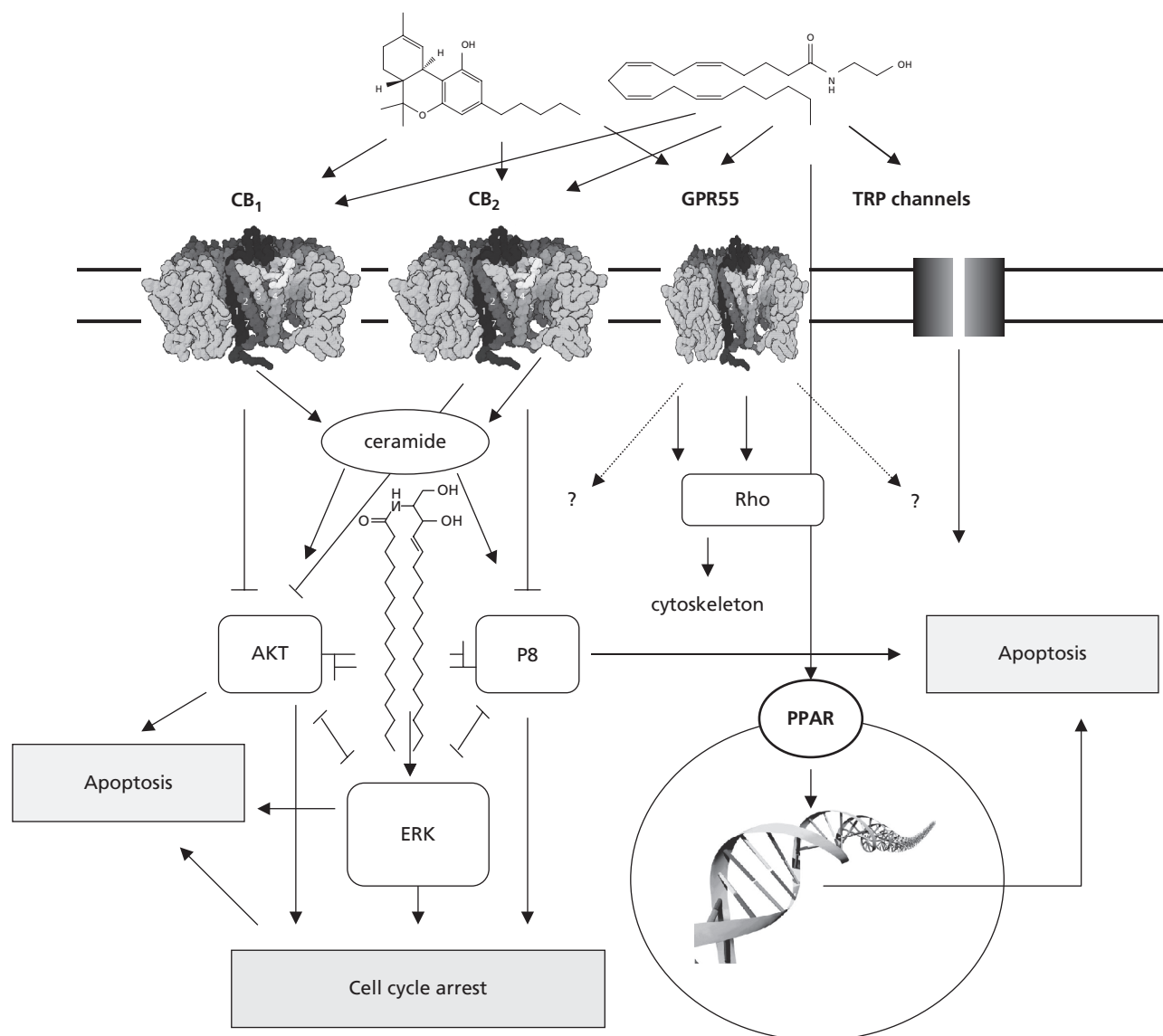


Figure 1 Major signalling pathways involved in the anticancer effects exerted by cannabinoids. The fact that most cannabinoids studied so far interact with more than one receptor adds to the complexity of the pharmacological effects. Ceramide, AKT and ERK are likely to be key mediators in the inhibition of cancer cell growth and induction of apoptosis. AKT, protein kinase B; ERK, extracellular signal-regulated kinase; GPR55, G-protein receptor 55, PPAR, peroxisome proliferator-activated receptor; TRP, transient receptor potential family of channels (including transient receptor potential vanilloid (TRPV)).

CB₁ receptor.^[48,49] In addition, malignant glioma cells, as well as other cancer cells (e.g. pancreatic cancer), show sustained de-novo ceramide generation in a CB₁/CB₂-dependent manner, resulting in inhibition of AKT (see below),^[50,51] which among other cues will finally drive the cells into apoptosis. Two further studies have shown the role of ceramide as a key player in glioma anticancer action mediated via the CB₂ receptor.^[52,53] Interestingly, it was recently shown that either CB₁ or CB₂ receptor activation induces apoptosis through de-novo ceramide synthesis in colon cancer cells, with tumour necrosis factor (TNF)- α acting as a link between CB receptor activation and ceramide production.^[54] More strikingly, it appears that cannabinoids are able to protect astrocytes and other neuronal cells from

oxidative stress^[55] and other neurotoxic signals^[56] through ceramide signalling. Where the exact switch for this differential reaction to the apparently identical stimulus lies remains unknown, although in terms of known signalling events it should be concluded that AKT acts downstream of it.

AKT signalling

AKT1 (v-akt murine thymoma viral oncogene cellular homolog), also known as 'AKT' or protein kinase B, represents a group of three enzymes of the serine/threonine-specific protein kinase family and is involved in cellular survival pathways by inhibiting apoptotic processes.^[57] Independent of the ceramide-mediated effect on AKT described above, both CB₁ and CB₂ receptors are coupled to

Gi/Go proteins in different cell types and they inhibit adenylate cyclase and can activate phosphatidylinositol 3-kinase (PI3-K), which activates AKT via phosphatidylinositol (3,4,5)-triphosphate (PIP3).^[58,59] Along that line, cannabinoid stimulation of whole brain areas and of healthy non-transformed cells such as astrocytes and also of CB₁-positive Chinese hamster ovary cells causes AKT activation almost independently of drug concentration.^[60–62] In contrast, one of the general pro-apoptotic signalling events after cannabinoid treatment in cancer cells is the dephosphorylation of AKT1, occurring after both CB₁ and CB₂ receptor activation and probably involving dominant ceramide signalling. PI3-K-dependent AKT activation can be regulated through the tumour suppressor PTEN (phosphatase and tensin homolog), which works essentially as the opposite of PI3-K.^[63] PTEN acts as a phosphatase to dephosphorylate PIP3 back to phosphatidylinositol(4,5)P2. This removes the membrane-localisation factor from the AKT signalling pathway. Without this localisation, the rate of AKT activation decreases significantly, as do the all the downstream pathways that depend on AKT for activation. PIP3 can also be dephosphorylated at position 5 by the SH-2-containing inositol phosphatase (SHIP) family of inositol phosphatases, SHIP1 and SHIP2. These polyphosphate inositol phosphatases dephosphorylate PIP3 to form phosphatidylinositol(3,4)P2. An increasing amount of data suggests that AKT inhibition is one of the critical events after cannabinoid administration, determining the cellular downstream effects that ultimately lead to apoptosis (Figure 1). Interestingly, in transformed cancer cells, low nanomolar concentrations of CB agonists lead to AKT phosphorylation through transactivation by epidermal growth factor receptor (EGFR), followed by a pro-survival proliferative burst,^[64] whereas higher concentrations decrease the activation status of AKT, usually culminating in growth arrest or apoptosis.^[51,65,66] Importantly, overexpression of AKT could rescue cannabinoid-induced apoptosis in melanoma cells, reflecting its essential role in the mediation of cannabinoid-induced apoptosis.^[67] Therefore, the concentration range of cannabinoids and the cellular transformation status appear to critically influence the differential cytotoxic effects mediated via AKT signalling. Whether AKT is a molecular switch that determines the often biphasic effects exerted by cannabinoid treatment (*vide infra*) needs to be elucidated.

Extracellular signal-regulated kinase

Another well-known signalling molecule recruited upon treatment of cancer cells with CB receptor agonists is extracellular signal-regulated kinase (ERK). However, reports relating to its activation or inhibition by cannabinoids differ between cancer types, indicating an as yet unclear and maybe more complex role. After incubation with cannabinoids, cells derived from gliomas,^[68] prostate cancer^[66] and breast cancer^[69] display a sustained ERK activation; activation levels of ERK remain unchanged in melanoma cells,^[67] whereas in lung^[70] and colon cancer cells phosphorylation of ERK was reduced.^[65] While inhibition of the usually pro-proliferative signalling molecule ERK is in line with a pro-apoptotic signalling cascade,^[71] it is more difficult to understand the contribution of activated ERK to

the cannabinoid-induced inhibition of growth. There is evidence that ceramide induced by cannabinoid treatment and inhibition of protein kinase A by Gi-coupled CB receptor stimulation both can cause chronic ERK activation, which is reported to lead to cell cycle arrest and cell death.^[68,69] In leukaemia cells, ERK1/2 was induced more strongly by CB₂ receptor-selective agonists than in primary leucocytes.^[72] The same study showed that ERK phosphorylation was context dependent, as lipopolysaccharide-induced ERK1/2 activation could be partially blocked by CB₂ ligands.

P8 (Sp(G/C)F-1)

Transcription factor P8 (or candidate of metastasis 1, also referred to as Sp(G/C)F-1), is an endoplasmic-reticulum-associated stress protein able to bind to DNA and is similarly affected by CB-receptor stimulation.^[73] After treatment with cannabinoids, it is upregulated in different cancer cell lines, probably in response to de-novo synthesised ceramide, which subsequently leads to co-recruitment of the transcription factors activating transcription factor 4 (ATF4), TRB3 and C/EBP homologous protein (CHOP), all three of which are also critically involved in the cellular response to stress stimuli, probably via both CB₁ and CB₂ receptors.^[50,74] P8 seems to be a key factor for cellular sensitivity towards cannabinoids, as siRNA-mediated knock-down of P8 can abolish the cytotoxicity of Δ^9 -THC in glioma cells and breast cancer cells. Moreover, P8 is also implicated in the potential synergistic effect of chemotherapeutic agents with cannabinoids.^[50,75]

Cell cycle arrest and apoptosis

As classic anticancer agents directly inhibit tumour cell growth, the effects of cannabinoids on cancer cell cycle and apoptosis induction have been investigated in detail. However, no general picture is emerging as with, for example, the G2/M cell cycle arrest typically observed with tubulin-targeting antimetabolic agents, probably because different cell types react differently to distinct concentrations of cannabinoids and there are different stress-related mechanisms of action.^[42] Moreover, cannabinoids are only moderately cytotoxic and typically exert their effects in the upper-nanomolar and micromolar concentration ranges, depending on the initial cell number and experiment. For example, in U373MG glioma cells expressing CB receptors, Δ^9 -THC induced apoptosis at concentrations greater than 5 μM *in vitro*,^[76] which appears to be a typical cytotoxic concentration. While some CB-receptor-expressing cancer cells survive treatment with higher micromolar concentrations (e.g. HL60 cells) (Gertsch *et al.*, unpublished data), other cancer cells (e.g. Jurkat T-cells^[77]) undergo cell cycle arrest and apoptosis, in part coupled to the signalling pathways described above. Interestingly, R(+)-methanandamide, WIN-55,212-2 and Δ^9 -THC lead to up-regulation of tumour suppressor genes such as p16 (INK4A), p27 and p53,^[66,78,79] and the oncogene RB is hypophosphorylated,^[67,80] which could be due to altered activation levels of either AKT or ERK. Further down this cascade, different cyclins such as D1 and D2, as well as the transcription factor E2F1, are down-regulated, followed by lower activity of cyclin-dependent kinases cdk2, 4 and 6^[66] and cdc2,^[81] finally causing cell cycle arrest at different cell

cycle check points. These events can either reduce proliferation of cells or prime them for apoptosis. Additionally, cannabinoid challenge with Δ^9 -THC and WIN-55,212-2 can prompt cancer cells to undergo apoptosis through the mitochondrial apoptosis pathway, where AKT inhibition classically leads to activation of the pro-apoptotic BCL2-family member BCL2 antagonist of cell death (BAD).^[65,82] Upon BAD activation, mitochondrial cytochrome c is released, leading to activation of caspase-3 and cleavage of poly(ADP-ribose) polymerase,^[81] which will finally drive cells into apoptosis. This putative mechanism may account for cell cycle arrest and induction of apoptosis in some adherent cells, but the mechanism may be significantly different in other cell types (*vide infra*).

Anti-angiogenesis effects

All of the growth inhibitory mechanisms of cannabinoids discussed so far are direct cellular effects. However, cannabinoids can modulate intercellular signalling, leading to modulation of important regulatory factors involved in inflammation and cellular activation and thereby influence tumour development indirectly. In this regard, the effect of cannabinoid treatment on tumour angiogenesis ranks most prominently.^[83] Different cannabinoid compounds with varying CB₁ and CB₂ receptor affinities decrease the formation of new blood vessels in tumours of different origins (e.g. non-melanoma skin cancer and glioma) by downregulating essential proangiogenic factors such as vascular endothelial growth factor (VEGF), placental growth factor and angiotensin II accompanied by dephosphorylation of VEGF receptors 1 and 2.^[79,84,85] These events could also partially account for a lower rate of metastasis, as this process is crucially linked to peri- and intratumoural vascularisation.^[86]

It is not only cancer cells that are influenced by cannabinoids; endothelial cell sprouting and vessel formation were blocked in various angiogenesis assays by application of R(+)-methanandamide.^[87] Both the CB₁ receptor agonist ACEA and the CB₂ receptor agonist JWH-015 decreased the weight and vascularisation of carrageenan-induced granulomas in rats and reduced mast cell number and activation in granulomatous tissue.^[88] Interestingly, in this study ACEA and JWH-015 prevented the transcription and expression of rMCP-5, a protein involved in sprouting and advance of new blood vessels. Currently, it is unclear whether these effects are actually mediated via CB receptor signalling or whether other as-yet unknown mechanisms are involved. However, the effectiveness of the CB₂-receptor-selective agonists JWH-015 and JWH-133 in blocking monocyte migration^[89] suggests that CB₂ activation may generally inhibit cell migration and vessel formation. In fact, cell migration is a key event in tumour metastasis and angiogenesis. Various studies have shown that cannabinoids affect cell migration through both CB₁ and CB₂ receptors, as well as through mechanisms related to elusive cannabinoid targets.^[17,90] Overall, the evolving picture is rather complex, as apparently anandamide and 2-AG produce opposite effects and only 2-AG signals via CB receptors.^[17] Endocannabinoids now join the list of factors involved in bone marrow cell

proliferation and differentiation, the ECS being a part of a highly complex lipid network that is still poorly understood.

The CB₂ receptor – a proto-oncogene?

It has been shown that cannabinoids stimulate proliferation of neural stem/precursor cells acting via both CB₁ and CB₂ receptors, leading to activation of the PI3-K/AKT pathway.^[91] Both the anti- and pro-proliferative effects exerted via CB receptor activation are intriguing and clearly deserve further investigation. In leukaemia cells, the CB₂ receptor has been suggested to act as a proto-oncogene, which under certain circumstances may turn into an oncogene that promotes carcinogenesis. Valk and colleagues have identified the new common virus integration site Evi11 and demonstrated that the gene encoding the CB₂ receptor (*Cnr2*) is its potential target, thus suggesting that *Cnr2* could be a proto-oncogene.^[92] Subsequent research by the same group demonstrated that the CB₂ receptor can act as an oncoprotein that blocks neutrophilic differentiation when overexpressed in myeloid precursor cells and that haematopoietic precursor cells expressing high levels of CB₂ have increased susceptibility for leukaemia development, thus suggesting that CB₂ and Evi1/Evi11 might collaborate in leukemogenesis.^[93] Moreover, the CB₂ receptor appears to mediate this activity through mitogen-activated protein kinase ERK/(MEK) and PI3-K pathways.^[94] This would suggest that blocking rather than activating the CB₂ receptor should be beneficial in the treatment of leukaemia. Alternatively, stabilising the CB₂ receptor in its inactive state using inverse agonists could counteract leukemogenesis. High CB₂ receptor expression in myeloid precursors is also associated with different immunomodulatory effects, such as inhibition of immune cell migration^[90] and inhibition of TNF- α expression.^[20,24] Since both CB₂-selective agonists and inverse agonists are anti-inflammatory *in vivo* and, paradoxically, apparently both via CB₂ interaction,^[20,24,95,96] it is currently not clear whether CB₂-selective agonists or inverse agonists should be developed for therapeutic intervention. Moreover, the effects of these ligands may differ substantially *in vitro* and *in vivo*, and an agonist *in vitro* may act as an antagonist *in vivo* and vice versa.^[96] However, it is still not clear whether the CB₂ receptor actually becomes an oncoprotein and whether this relates to mutations or increased receptor expression. On the other hand, it is already clear that the CB₂ receptor regulates cell growth and differentiation in promyelotic human cells, being a regulator of signal transduction via the oncogenic Erk1/2 pathways and execution of mitogenic signals that are relevant to cell differentiation (*vide supra*). In light of the fact that healthy humans have a high surface expression of functional CB₂ receptors in monocytes and B cells but a low surface expression in T cells (Gertsch *et al.*, unpublished data), it is possible that *Cnr2* is a proto-oncogene in T cells but not in promyelocytic cells (precursors of monocytes/macrophages and dendritic cells). This would be confirmed by the fact that cannabinoids induce apoptosis in Jurkat T cells but not HL60 cells. Another factor that complicates studies with the CB₂ receptor is that *Cnr2* has undergone more rapid evolution than *Cnr1*, leading to pronounced species differences in ligand-receptor interactions (receptor affinities and G-protein recruiting)^[97] and therefore efficacy

in animal studies cannot always be extrapolated to humans. There are still too many uncertainties to draw any conclusion regarding cannabinoid treatment of lymphomas, despite studies showing overexpression of the CB₂ receptor.

Intriguingly, CB₁ agonists can induce apoptosis in mantle cell lymphoma via CB₁ receptor activation,^[98] although this was under conditions where the CB₂ receptor is also activated, as non-selective cannabinoids were used in this study (Table 1; Figure 2). Moreover, CB₂ receptor activation leads to anticancer effects in other tissues. CB₂ receptor overexpression may contribute to the regression of human anaplastic thyroid tumour in nude mice following interleukin-12 gene transfer,^[139] suggesting an inhibitory role of CB₂ in thyroid carcinogenesis. *In vitro*, Met-F-AEA was shown to reduce thyroid tumour growth^[79] and to induce apoptosis in thyroid carcinoma cells.^[140] Interestingly, 3,3'-diindolmethane (DIM), which is an anticarcinogenic metabolite generated by ingestion of indole-3-carbinol commonly found in *Brassica* vegetables, has recently been shown to be a weak partial CB₂ receptor agonist.^[141] However, DIM has other targets that may explain its anticancer effects, including elastase.^[142] Nonetheless, it is tempting to speculate that dietary CB₂ ligands such as beta-caryophyllene^[72] and DIM may exert potentially chemopreventive effects and inhibit carcinogenesis via CB₂ receptor interaction.

Anticancer effects of cannabinoids independent of CB receptors

Not all effects of cannabinoids are mediated through classic CB receptors, and there is an increasing amount of data showing that many ligands are not specific for CB receptors. Often well-designed protein-selective ligands are specific for a certain target until their non-specificity is shown, rendering erroneous initial conclusions drawn from pharmacological experiments. This may also be true for CB receptor inverse agonists (i.e. antagonists). Recently, it was shown that the CB₁ selective agonist SR141716A (rimonabant) also binds to GPR55^[143] and can act as GPR55 receptor antagonist.^[144] A recent report using a beta-arrestin Pathhunter assay showed that SR141716A and AM251 induced significant effects via GPR55, while endocannabinoids were only weakly active.^[141] While the number of CB₁- and CB₂-selective agonists and antagonists is increasing, it is not clear whether these compounds exert other cellular actions at the often high concentrations/doses used (Table 1). Moreover, studies like the one performed on the murine lymphomas L-4, LSA and P815 with Δ^9 -THC treatment may be hard to interpret, as Δ^9 -THC apparently more strongly activates GPR55 than CB receptors,^[143] the role of which in cancer remains to be elucidated. Recently, it was shown that GPR55 signals via Rho and activates nuclear factor of activated T cells (NF-AT).^[145] Because NF-AT signalling plays a potential role in cancer growth (e.g. in Burkitt's lymphoma),^[146] this certainly complicates the interpretation of studies performed with cannabinoids without using knockout mice as controls. In fact, the new cannabinoid-like receptor GPR55 with signalling distinct from CB₁ and CB₂ may be a hitherto neglected receptor with regard to the anticancer effects of several cannabinoids. Many cannabinoids interact with GPR55 and the receptor appears to be present in numerous cell

types.^[4,14,143] GPR55 is activated by a whole range of plant, synthetic and endogenous cannabinoids and is blocked by cannabidiol, a non-psychoactive phytocannabinoid,^[5,143] and SR141716A.^[144] Cannabidiol induces a concentration-dependent increase in FAAH activity and 5-lipoxygenase activity in U87 glioma cells, reducing the growth rate.^[147] The most striking difference reported so far is the agonist activity of the CB₁ receptor antagonists AM251 and AM281 at GPR55,^[5,141] rendering elucidative studies of CB receptor specificities a challenging task. To date, nothing has been published about its expression in cancer cells and therefore putative effects of cannabinoids through GPR55 cannot be ruled out and deserve further attention. Activation of GPR55 by AM251^[125] could also explain the observation that this drug exerts antiproliferative effects on pancreatic cancer cells in the low micromolar range. Similarly, another article reported cell cycle arrest in breast cancer cells treated with the CB₁ antagonist SR141716A,^[148] an effect that could, at least in part, also be mediated by interaction with GPR55.

TRPV channels, PPAR γ and 5HT(3) receptor are also non-cannabinoid targets of cannabinoids.^[13,149,150] Anandamide and similar cannabinoid structures activate the vanilloid receptor (VR1 or TRPV1), which can be blocked with the TRPV1 antagonist capsaizepine. In cervical cancer cells with aberrant TRPV1 expression, the stimulation of TRPV1 rather than CB₁ or CB₂ receptors accounts for the apoptosis-inducing effects of anandamide,^[101] whereas the migration-reducing effects of R(+)-methanandamide could be blocked by antagonists to TRPV1, CB₁ and CB₂, highlighting the complexity of cannabinoid-evoked signal generation.^[151] Recently, De Petrocellis and colleagues suggested that phytocannabinoids and cannabis extracts exert some of their pharmacological actions by interacting with TRPA1 and TRPM8 channels, with potential implications for the treatment of pain and cancer.^[152]

Another well-described mechanism for CB-independent action of certain CB receptor agonists is their binding to some members of the nuclear receptor transcription factor superfamily PPARs,^[12,150] although the extent to which this mechanism is involved in the effects of cannabinoids as anti-tumour agents remains poorly described. Intriguingly, in the HepG2 hepatoma cell line, PPAR γ may play a key role in WIN 55,212-2-induced apoptosis.^[138] The non-psychoactive Δ^9 -THC analogue ajulemic acid, which binds to the CB₂ receptor, has been shown to exert antitumour effects in glioma cells.^[107] Interestingly, ajulemic acid is also an activator of PPAR γ .^[153]

In hormone-dependent breast and prostate carcinoma, cannabinoid treatment can decrease expression levels of receptors involved in their pro-proliferative response to the cytokines prolactin, nerve growth factor (NGF) and androgen.^[69,129,154] Namely, in prolactin-dependent breast cancer, 2-AG and anandamide downregulate the prolactin receptor and the trkNGF receptor, whereas in prostate cancer, 2-AG, anandamide and WIN-55,212-2 reduce levels of prolactin and androgen receptors. In addition to these indirect proliferation-inhibiting effects, certain plant-derived and synthetic cannabinoids inhibit the multidrug-transporter ABCG2 and p-glycoprotein in mouse embryonic fibroblasts (MEF), immortalised renal cells, Caco-2 cells and rat brain microvessel cells,

Table 1 Effects of cannabinoid receptor ligands on cancer cells *in vitro* and *in vivo*

Cancer	Cell lines	Effects	Compound	Reversible by CB ₁ /CB ₂ antagonists?	<i>In vivo</i> ?	Reference
Glioblastoma multiforme	U251-MG and U87-MG	Cell cycle inhibition	Δ9-THC	?	no	Galanti <i>et al.</i> 2007 ^[78]
	SF126, U87, U251, U373-MG, SF188, GBM primary cells	Cell death, reduced proliferation	WIN-55,212-2, Δ9-THC	SR1, SR2	no	McAllister <i>et al.</i> 2005 ^[99]
Glioma	U87	ROS, apoptosis	Cannabidiol	no	yes	Massi <i>et al.</i> 2006 ^[100]
	C6, U87mg	Apoptosis	Δ9-THC	SR1, SR2	yes	Carracedo <i>et al.</i> 2006 ^[50]
	?	Apoptosis	AEA	no?	no	Contassot <i>et al.</i> 2004 ^[101]
	C6	Cell death by oxidative stress	Δ9-THC	SR1	no	Goncharov <i>et al.</i> 2005 ^[102]
	C6	Apoptosis	WIN-55,212-2	no	no	Ellert-Miklaszewska <i>et al.</i> 2005 ^[82]
	U87, U373	Anti-proliferative	Cannabidiol	SR2	no	Massi <i>et al.</i> 2004 ^[103]
	H4 neuroglioma cells	Apoptosis	R-methanandamide	no	no	Hinz <i>et al.</i> 2004 ^[104]
	C6	Anti-proliferative	1-AG, phosphate esters of anandamide	no	no	Fowler <i>et al.</i> 2003 ^[105]
	C6	Apoptosis	Δ9-THC	no	no	Gomez del Pulgar <i>et al.</i> 2002 ^[51]
	C6	Anti-proliferative	AEA, 2-AG, JWH-015, CP55,940	SR1/2, AM251, AM630, capsazepine	no	Jacobsson <i>et al.</i> 2001 ^[106]
	C6, U87mg	Reduced viability	Ajulemic acid	SR2	yes	Recht <i>et al.</i> 2001 ^[107]
	C6	Apoptosis	Δ9-THC	SR1 & SR2 combination	yes	Galve-Roperh <i>et al.</i> 2000 ^[68]
	C6	Apoptosis	Δ9-THC	SR1	no	Sanchez <i>et al.</i> 1998 ^[48]
	C6	Apoptosis	JWH-33	SR2	yes	Sanchez <i>et al.</i> 2001 ^[108]
	C6	Inhibition of invasion, down-regulation of MMP-2	Δ9-THC, JWH-133	no	yes	Blazquez <i>et al.</i> 2008 ^[52]
Neuroblastoma	U87-mg, T98G, LN-229, MT310	Reduced viability	C1'-phenyl-substituted Δ(8)-THC	no	no	Krishnamurthy <i>et al.</i> 2008 ^[109]
	B102	Growth-inhibition	Δ9-THC	no	no	Cabral <i>et al.</i> 1987 ^[110]
	NB2A, (C6)	Anti-proliferative	Δ9-THC	no	no	End <i>et al.</i> 1977 ^[111]
Leukaemia	Jurkat	Apoptosis	Δ9-THC	SR1 & SR2	no	Jia <i>et al.</i> 2006 ^[77]
	Jurkat, MOLT-4	Apoptosis	Cannabidiol	SR2	yes	McKallip <i>et al.</i> 2006 ^[112]
	Jurkat	Apoptosis	Δ9-THC	SR2	no	Herrera <i>et al.</i> 2005 ^[113]
	Jurkat	Apoptosis	Δ9-THC	no	no	Lombard <i>et al.</i> 2005 ^[114]
	EL-4, LSA, P815, Jurkat, Molt4	Apoptosis	Δ9-THC, HU210, anandamide, JWH-015	SR2	yes	McKallip <i>et al.</i> 2002 ^[115]
	K562	Anti-proliferative	Δ9-THC	no	no	Dvilansky <i>et al.</i> 1984 ^[116]
Lymphoma	L1210 murine leukemia	Anti-proliferative	Δ8-THC	no	yes	Tucker & Friedman 1977 ^[117]
	L1210 murine leukemia, Lewis lung carcinoma	Inhibition of DNA synthesis	Δ9-THC, Δ8-THC	no	yes	Carchman <i>et al.</i> 1976 ^[118]
	Rec1, Jeko, JVM-2	Apoptosis	WIN-55,212-2, R(+)-methanandamide	SR1 & SR2	no	Gustafsson <i>et al.</i> 2006 ^[98]
Lung cancer	MCL cells from biopsies	Apoptosis	WIN-55,212-2, anandamide	no	no	Flygare <i>et al.</i> 2005 ^[119]
	Rec-1, MEL1, MEL2, Raji, Namalwa, JEKO-1	Apoptosis	R(+)-methandandamide	SR1 & SR2	yes	Gustafsson <i>et al.</i> 2008 ^[120]
	A549 and SW-1573	Growth inhibition, anti-angiogenic, anti-migration	Δ9-THC	no	yes	Preet <i>et al.</i> 2008 ^[70]

(Continued)

Table 1 (Continued)

Cancer	Cell lines	Effects	Compound	Reversible by CB ₁ /CB ₂ antagonists?	In vivo?	Reference
	Lewis lung carcinoma	Anti-proliferative	Δ9-THC, Δ8-THC, cannabidiol	no	no	Friedmann 1977 ^[121]
	Lewis lung adenocarcinoma cells	Anti-proliferative	Δ9-THC	no	no	White <i>et al.</i> 1976 ^[122]
	L1210 murine leukemia, Lewis lung carcinoma	Inhibition of DNA synthesis	Δ9-THC, Δ8-THC	no	yes	Carchman <i>et al.</i> 1976 ^[118]
Colon cancer	Lewis lung adenocarcinoma cells	Reduced tumour growth	Δ9-THC, Δ8-THC, cannabinol	no	yes	Munson <i>et al.</i> 1975 ^[44]
	SW480, HCT15	Apoptosis	Δ9-THC	AM251	no	Greenhough <i>et al.</i> 2007 ^[65]
	?	Cell death	Anandamide	no	no	Patsos <i>et al.</i> 2005 ^[123]
	CaCo-2, DLD-1	Anti-proliferative	2-AG, anandamide, HU210	SR1 & SR2	no	Ligresti <i>et al.</i> 2003 ^[124]
	DLD-1, HT29, primary human tumor	Apoptosis via ceramide	ACEA, CB13	no	no	Cianchi <i>et al.</i> 2008 ^[54]
	CaCo-2	Anti-proliferative, reduced viability	HU-210, anandamide, NAGly	no	no	Gustafsson <i>et al.</i> 2008 ^[120]
Pancreatic cancer	MiaPaCa, Panc-1	Apoptosis	Δ9-THC, WIN-55,212-2, JWH-133	SR2	yes	Carracedo <i>et al.</i> 2006 ^[74]
	MiaPaCa2	Apoptosis	ACEA, AM251, JWH-015, AM630	no	no	Fogli <i>et al.</i> 2006 ^[125]
Breast cancer	MDA-MB-231, T47D and MCF-7	Cell cycle arrest, lipid rafts critically involved	SR141716	no	no	Sarnataro <i>et al.</i> 2006 ^[126]
	EVSA-T, MCF-7, MDA-MB-468, MDA-MB-231, SKBr3, T47D	Cell cycle block, apoptosis	Δ9-THC	SR1, better SR2	no	Caffarel <i>et al.</i> 2006 ^[84]
	HBcc	Anti-proliferative	Anandamide	no	no	De Petrocellis <i>et al.</i> 2002 ^[127]
	HBcc	Anti-proliferative	PEA + anandamide	SR2	no	Di Marzo <i>et al.</i> 2001 ^[128]
	HBCC, DU145	Anti-proliferative, PRL/NGF receptors↓	Anandamide, 2-AG, HU210	SR1	no	Melck <i>et al.</i> 2000 ^[129]
	MCF-7	Anti-proliferative, PRL/NGF receptors↓	Anandamide	SR1	no	Melck <i>et al.</i> 1999 ^[69]
Prostate cancer	EFM-19	Anti-proliferative	Anandamide	SR1	no	Bisogno <i>et al.</i> 1998 ^[130]
	EFM-19, MCF7	Anti-proliferative	Anandamide, 2-AG, HU210	SR1	no	De Petrocellis <i>et al.</i> 1998 ^[131]
	LNCaP	Apoptosis	WIN-55,212-2	SR1 SR2	yes	Sarfaraz <i>et al.</i> 2006 ^[66]
	DU145, LNCaP, PC-3	Apoptosis	WIN-55,212-2	SR1, SR2	yes	Sarfaraz <i>et al.</i> 2005 ^[132]
	DU145, LNCaP, PC-4	Cell death	Anandamide	SR1	no	Mimeault <i>et al.</i> 2003 ^[133]
	PC-3	Cell death	Anandamide	no	no	Sarker <i>et al.</i> 2003 ^[134]
	HBCC, DU145	Anti-proliferative, PRL/NGF receptors↓	Anandamide, 2-AG, HU210	SR1	no	Melck <i>et al.</i> 2000 ^[129]
Cervix carcinoma	PC3	Apoptosis	Δ9-THC	no	no	Ruiz <i>et al.</i> 1999 ^[135]
	CC299, Caski, HeLa	Apoptosis	Anandamide	VR1 inhibition	no	Contassot <i>et al.</i> 2004 ^[101]
Melanoma	B16, A375	Apoptosis, anti-angiogenic	WIN-55,212-2, Δ9-THC, JWH-133	SR2	yes	Blazquez <i>et al.</i> 2006 ^[67]
Skin tumour	PDV.C57, HaCa4	Apoptosis, anti-angiogenic	WIN-55,212-2, JWH-133, Δ9-THC	SR1 & SR2	yes	Casanova <i>et al.</i> 2003 ^[85]
Thyroid cancer	KiMol, TK-6	Growth inhibition	Met-F-anandamide	SR1	yes	Portella <i>et al.</i> 2003 ^[79]
Thymoma	?	ROS, apoptosis	Cannabidiol	no	no	Lee <i>et al.</i> 2008 ^[136]
Cholangiocarcinoma	Mz-ChA-1, HuH28, HuCC-T1, SG231	Apoptosis (FAS to lipid raft)	Anandamide	no	no	DeMorrow <i>et al.</i> 2007 ^[137]
Hepatoma	HepG2	Apoptosis	WIN-55,212-2	GW9662 & T00709007 (PPAR γ)	no	Giuliano <i>et al.</i> 2009 ^[138]

GBM, glioblastoma multiforme; NGF, nerve growth factor; PPAR, peroxisome proliferator-activated receptor; PRL, prolactin; ROS, reactive oxygen species; SR1, SR141716A (selective CB₁ receptor antagonist/inverse agonist); SR2, SR144528 (selective CB₂ receptor antagonist/inverse agonist); THC, tetrahydrocannabinol.

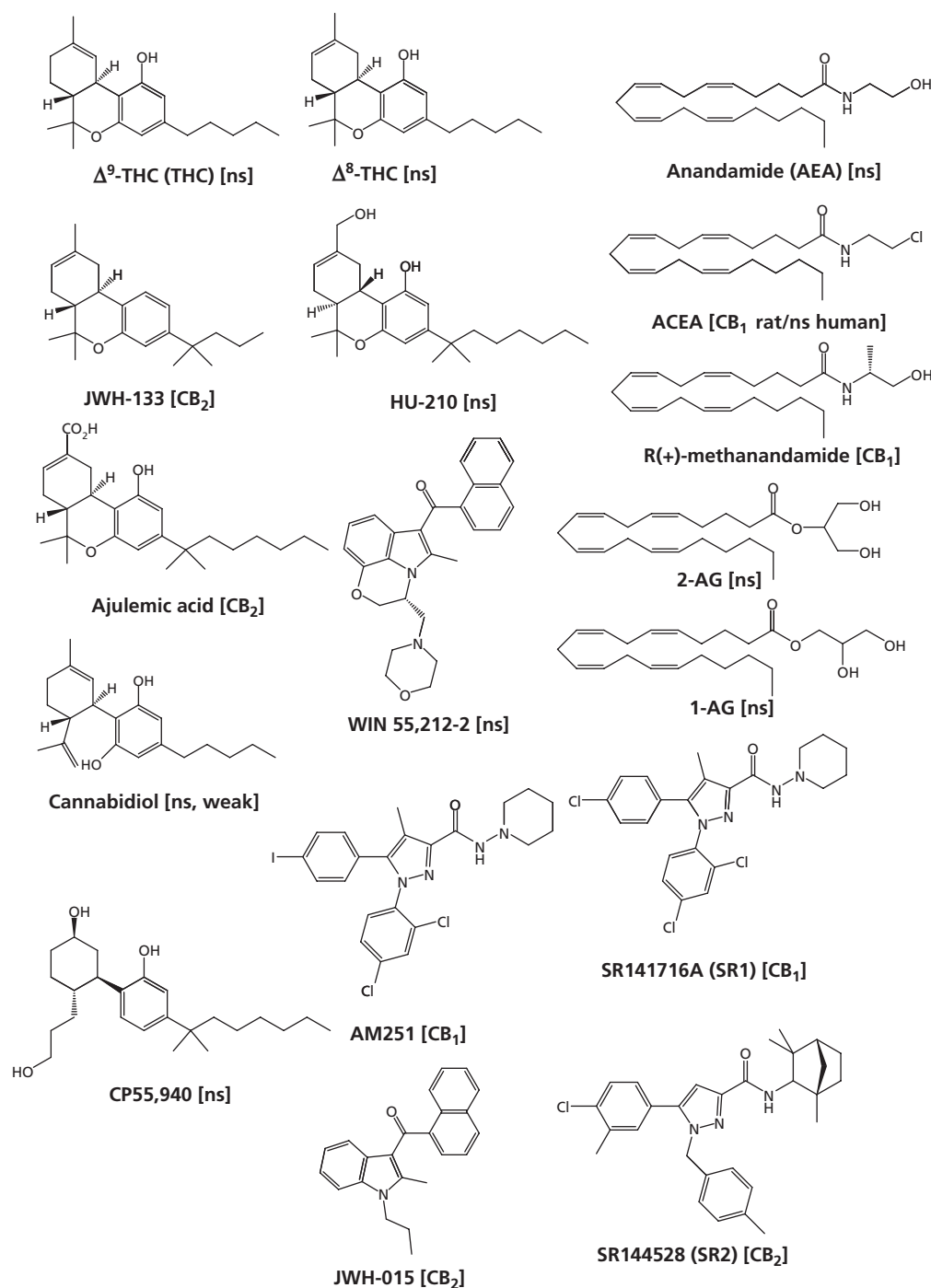


Figure 2 Cannabinoid receptor ligands commonly used in the study of the anticancer effects. The binding selectivity towards CB₁ and CB₂ receptors is indicated in square brackets. ns, non-selective; THC, tetrahydrocannabinol.

which potentially contribute to sensitisation to and accumulation of chemotherapeutic agents such as topotecan and doxorubicin.^[155–159]

Is elevation of endocannabinoid levels in tumours good or bad?

There is good evidence that certain tumour cells overexpress endocannabinoids, which are typically released during cellular

stress (e.g. upon activation of Toll-like receptor pathways). For example, in colon tissue anandamide levels are significantly upregulated after malignant transformation.^[160] Since endocannabinoids activate both CB₁ and CB₂ receptors, they could initiate the anticancer signalling pathways described above. This leads to the obvious question of why a growing tumour should kill itself by such a mechanism? It has previously been postulated that endocannabinoid tone may be

a means of controlling endogenous tumour growth (reviewed by Flygare & Sander^[42]). However, despite data from several studies showing anticancer effects mediated by the endogenous ligands anandamide and 2-AG (either directly or by increasing their levels by blocking degradation or transport), it is still not clear whether the ECS is an endogenous anticancer or a procarcinogenic system. The latter was proposed in a study using knockout mice, in which CB₁/CB₂ receptors were suggested to play a positive role in UV-induced inflammation and development of skin cancer; the study showed that in the skin UVB activates nuclear factor κ B via CB receptors, leading to increased TNF- α expression.^[161] As cannabinoids at low concentrations typically inhibit TNF- α expression from immune cells,^[20,24] this seems to be rather contradictory. However, several lines of evidence suggest that the ECS in the skin is different from the ECS in the rest of the body, and that CB₂ receptor agonists seem to be pro-inflammatory in the skin.^[20,28] Somewhat contradictorily, CB receptor activation in melanoma has been shown to reduce tumour growth via AKT signalling.^[67] A report by Aguado and colleagues on glioma stem-like cells showed that cannabinoids such as HU210 and JWH-133 cause higher expression of glial differentiation markers in a CB₁ and CB₂-dependent manner, respectively.^[162] Upon engraftment of these more differentiated cells into mice, a lower rate of gliomagenesis was observed than in engrafted control cells, suggesting a potential inhibitory role for CB receptor agonists in cancer stem cell differentiation. The CB₂ receptor agonists JWH133 and Δ^9 -THC were able to inhibit glioma cell invasion in mice, probably due to down-regulation of metalloproteinase-2 expression.^[52] A recent study suggests that high CB₁ receptor expression is associated with severity of prostate cancer and outcome.^[163] Obviously, the role of the ECS system is not clear, and it is likely that different tissues employ the ECS differently. While for many tissues (central nervous system, liver, gut, arteries, etc.) it may be beneficial to activate the ECS, other tissues may develop pathologies (adipose tissue, skin). As pointed out in a recent review by Di Marzo,^[20] endocannabinoids may be able to act in opposite directions depending on the physiological context. Furthermore, physiological processes are dynamic whereas experiments often look at single time points rather than the overall kinetics. This makes the development of new cannabinoid therapeutics a challenging task. With regard to cancer, it needs to be emphasised that CB receptor expression in cancer cells has largely been determined at the level of mRNA expression and by Western blots,^[67,120,154] which does not allow for the fact that surface expression may vary and may not correlate with gene expression. Unpublished data from our laboratory clearly indicate that many cancer cells lack CB surface expression despite being positive in RT-PCR and Western blot analyses. Thus, studies ignoring the fact that CB receptors are probably not coupled to G-proteins in many cancer cell lines may lead to potentially erroneous conclusions.

In spite of the vast number of publications supporting the use of cannabinoids as anticancer agents, it should be noted that there are some potential not insignificant drawbacks, such as the apparently prosurvival effects of cannabinoids at low concentrations in cancer cells and their potential immunosuppressive action (*vide supra*). Apparently,

nanomolar concentrations of Δ^9 -THC, comparable with those detected in the serum of patients after administration of Δ^9 -THC, accelerate proliferation of cancer cells instead of inducing apoptosis.^[64] The same observation also holds true for the in-vitro incubation of several cancer cell types with WIN55,212-2 and HU210, an effect that was attributed to transactivation of the EGFR, leading to activation of the AKT and MAPK signalling pathways.^[64] In this regard, the use of cannabis as it is already approved as an adjuvant to chemotherapeutic treatment regimens^[164,165] could potentially boost tumour growth, although clinical evidence for this hypothesis is lacking.

The second critical point relates to the fact that Δ^9 -THC potentially alters the immune status by suppressing the cell-mediated TH₁ response, which is of particular relevance in the battle against tumour cells.^[166] Since TNF- α expression is typically inhibited by low cannabinoid concentrations and TNF- α itself inhibits tumour growth,^[167] it is not clear what the effect of cannabinoids on physiological tumour development is. On the other hand, a pro-inflammatory environment can lead to carcinogenesis^[167,168] and cannabinoids may be able to prevent this. Two recent studies have shown that loss of CB₁ led to an increase in carcinogenesis in colon cancer^[169] and enhanced endocannabinoid tone prevented colon cancer,^[170] thus pointing to a suppression of colon carcinogenesis by the ECS and CB₁ receptor. Moreover, the CB₂ receptor has been suggested to exert beneficial regulatory effects in the gut, such as attenuation of inflammation and probably colon cancer.^[35] With the commonly used xenograft animal models, where human cancer cells are grafted into immunodeficient mice, it is impossible to predict the impact of the cannabinoid treatment on the immune surveillance of the tumour; data from a melanoma allograft model suggest that the inhibitory effects on tumour growth and formation may be independent of immune status of the mice and site of drug injection.^[67]

Conclusions and outlook

Cannabinoids may have anticancer effects in the appropriate context but their effects may not be sufficiently radical for chemotherapy. Currently, Δ^9 -THC (Marinol) and the synthetic derivative Nabilone are successfully used as adjuvants to chemotherapeutic treatment because they prevent nausea and vomiting and stimulate appetite.^[22,165] Moreover, the Δ^9 -THC- and cannabidiol-containing *C. sativa* extract Sativex is used for the symptomatic relief of neuropathic pain in adults with multiple sclerosis and as an adjunctive analgesic treatment for adults with advanced cancer.^[164,171] Currently, there are no clinical data indicating that co-treatment with these cannabinoids improves or reduces the anticancer efficacy of the actual chemotherapeutic agents. Such clinical comparisons would be very interesting. Based on current knowledge, the ECS may be a system that, under the appropriate conditions, produces synergy with established chemotherapeutic agents. *In vitro*, subcytotoxic concentrations of Δ^9 -THC were shown to sensitise leukaemia cells to chemotherapeutic agents such as doxorubicin and vincristine.^[172] Several other reports have dealt with the potential synergism of cannabinoids with chemotherapeutic

agents such as topotecan and doxorubicin.^[50,75,155–159] Clearly, more research should be directed towards the potential synergism and antagonism of cannabinoids in chemotherapy. Despite several promising reports from studies with cannabinoids in animal xenograft models, data relating to humans are limited and therapeutic benefits therefore remain speculative. Moreover, there are numerous apparently non-toxic natural products that potentially exert chemopreventive or antitumour effects, many of which have been confirmed in animal models,^[173] but few have been tested in a clinical setting. This is largely because of limited financial resources and the high risk for a pharmaceutical company to become involved in clinical studies with known natural products in general and cannabinoids in particular.

While data obtained in different cellular and animal models suggest that cannabinoid ligands could be useful to treat certain forms of cancer, the abundance of CB receptors in different tissues could clearly be a problem with regard to potentially unwanted effects. However, based on a recent review,^[174] cannabinoids appear to be selective antitumour agents that kill glioma cells without affecting the viability of non-transformed counterparts. Intriguingly, they mention a pilot clinical trial on patients with glioblastoma multiforme which showed remarkable antitumour effects of cannabinoids and a good safety profile, thus setting the basis for further studies.

Interestingly and somewhat surprisingly, most studies to date have been carried out with ligands that target both CB₁ and CB₂ receptors in a non-selective manner. In terms of a potential therapeutic application the unwanted psychotropic effects mediated via CB₁ could be problematic. However, there is still a limited amount of data on CB₂-receptor-selective anticancer effects (by agonists, silent antagonists or inverse agonists) and the potential therapeutic relevance remains unclear. Given that the CB₂ receptor mediates several of the effects reported for CB₁ without being psychotropic, more research should be directed to the role of CB₂ in cancer. Future studies using CB₁- and CB₂-selective ligands in combination with animal models in which CB receptors have been genetically deleted should be useful. Importantly, conclusions drawn from experiments with CB receptor antagonists may be misleading because these ligands potentially interact with other targets, such as the CB₁ receptor inverse agonists (antagonists) SR141716A and AM251 with GPR55 (*vide supra*).

Maybe more promising is the potential of the ECS in the suppression of cancer development. It is tempting to speculate that the ECS is involved in carcinogenesis and tumourigenesis in certain tissues, as it potentially modulates the biochemical microenvironment, probably leading to modulation of cytokines and growth factors. To provide stronger evidence, future research will have to uncover potential ways of chemoprevention by cannabinoids. Given that the ECS regulates immune processes, it is tempting to believe that the ECS can directly affect carcinogenesis by modulating inflammatory stress that leads to carcinogenesis. More than 10 years ago, Sidney and colleagues^[175] concluded that not only is the evidence linking cannabis smoking to cancer negative, but the largest human studies cited indicated that cannabis users had lower rates of cancer than non-users. Moreover, those who smoked both cannabis

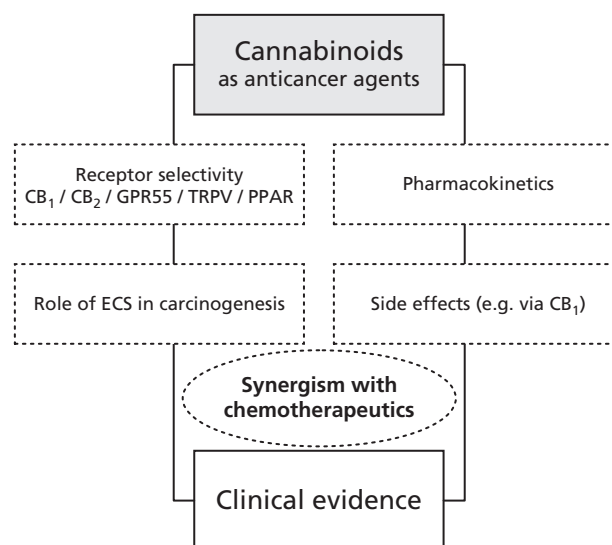


Figure 3 Important issues that need to be addressed (shown in dotted boxes) prior to the development of cannabinoid-type anticancer agents in a clinical setup. ECS, endocannabinoid system; GPR55, G-protein receptor 55; PPAR, peroxisome proliferator-activated receptor; TRPV, transient receptor potential vanilloid.

and tobacco had lower rates of lung cancer than those who smoked only tobacco – a strong indication of chemoprevention. However, this statement was recently challenged by a study performed by Aldington and colleagues,^[176] which showed that cannabis smoking increased the risk for lung cancer, but it is not certain that cannabinoids are responsible for this correlation.^[177] Along the same lines, it is not clear whether chronic marijuana use is correlated with an increased incidence of testicular germ cell tumours^[178] because of cannabinoid action. An increasing amount of data shows attenuation of tumour growth by both orally and locally administered cannabinoids in different animal models, raising high hopes for potentially new treatments, in particular in combination with established chemotherapeutic agents (*vide supra*). Future research along that line will have to show whether cannabinoids or cannabinomimetic agents may reduce tumour growth *in vivo* synergistically when used with chemotherapeutic agents. Meanwhile, the exact mode of action of cannabinoids, the role of classic CB receptors, and the potential involvement of GPR55 and the other non-cannabinoid targets remain to be elucidated. In conclusion, a better understanding of the underlying physiological processes of the ECS in malignancy is needed before anticancer agents that act via the ECS can be developed (Figure 3).

References

1. Mackie K. Cannabinoid receptors as therapeutic targets. *Annu Rev Pharmacol Toxicol* 2006; 46: 101–122.
2. Matsuda LA *et al.* Structure of a cannabinoid receptor and functional expression of the cloned cDNA. *Nature* 1990; 346: 561–564.
3. Munro S *et al.* Molecular characterization of a peripheral receptor for cannabinoids. *Nature* 1993; 365: 61–65.

4. Brown AJ. Novel cannabinoid receptors. *Br J Pharmacol* 152: 567–575.
5. Ryberg E *et al.* The orphan receptor GPR55 is a novel cannabinoid receptor. *Br J Pharmacol* 2007; 152: 1092–1101.
6. Overton *et al.* GPR119, a novel G protein-coupled receptor target for the treatment of type 2 diabetes and obesity. *Br J Pharmacol* 2008; 153: 76–81.
7. Mackie K, Stella N. Cannabinoid receptors and endocannabinoids: evidence for new players. *AAPS J* 2006; 8: E298–E306.
8. Kreitzer FR, Stella N. The therapeutic potential of novel cannabinoid receptors. *Pharmacol Ther* 2009; 122: 83–96.
9. Di Marzo V. Endocannabinoids: synthesis and degradation. *Rev Physiol Biochem Pharmacol* 2008; 160: 1–24.
10. Hanus LO. Discovery and isolation of anandamide and other endocannabinoids. *Chem Biodivers* 2007; 4: 1828–1841.
11. Ross RA. Anandamide and vanilloid TRPV1 receptors. *Br J Pharmacol* 2003; 140: 790–801.
12. Lenman A, Fowler CJ. Interaction of ligands for the peroxisome proliferator-activated receptor gamma with the endocannabinoid system. *Br J Pharmacol* 2007; 151: 1343–1351.
13. Racz I *et al.* Anandamide effects on 5-HT(3) receptors *in vivo*. *Eur J Pharmacol* 2008; 596: 98–101.
14. Ross RA. The enigmatic pharmacology of GPR55. *Trends Pharmacol Sci* 2009; 30: 156–163.
15. Bab I *et al.* Endocannabinoids and the regulation of bone metabolism. *J Neuroendocrinol* 2008; 20(Suppl 1): 69–74.
16. Maccarrone M, Finazzi-Agro A. The endocannabinoid system, anandamide and the regulation of mammalian cell apoptosis. *Cell Death Differ* 2003; 10: 946–955.
17. Patinkin D *et al.* Endocannabinoids as positive or negative factors in hematopoietic cell migration and differentiation. *Eur J Pharmacol* 2008; 595: 1–6.
18. Mechoulam R, Gaoni Y, Hashish IV. The isolation and structure of cannabinolic cannabidiol and cannabigerolic acids. *Tetrahedron* 1965; 21: 1223–1229.
19. Devane WA *et al.* Determination and characterization of a cannabinoid receptor in rat brain. *Mol Pharmacol* 1988; 34: 605–613.
20. Di Marzo V. Targeting the endocannabinoid system: to enhance or reduce? *Nat Rev Drug Discov* 2008; 7: 438–455.
21. Lange JH, Kruse CG. Cannabinoid CB1 receptor antagonists in therapeutic and structural perspectives. *Chem Rec* 2008; 8: 156–168.
22. Machado Rocha FC *et al.* Therapeutic use of Cannabis sativa on chemotherapy-induced nausea and vomiting among cancer patients: systematic review and meta-analysis. *Eur J Cancer Care (Engl)* 2008; 17: 431–443.
23. Klein TW. Cannabinoid-based drugs as anti-inflammatory therapeutics. *Nat Rev Immunol* 2005; 5: 400–411.
24. Ashton JC. Cannabinoids for the treatment of inflammation. *Curr Opin Investig Drugs* 2007; 8: 373–384.
25. Parfienuk A *et al.* Role of cannabinoids in chronic liver disease. *World J Gastroenterol* 2008; 14: 6109–6114.
26. Wolf SA *et al.* CNS immune surveillance and neuroinflammation: endocannabinoids keep control. *Curr Pharm Des* 2008; 14: 2266–2278.
27. Di Marzo V, Izzo AA. Endocannabinoid overactivity and intestinal inflammation. *Gut* 2006; 55: 1371–1376.
28. Karsak M *et al.* Attenuation of allergic contact dermatitis through the endocannabinoid system. *Science* 2007; 316: 1494–1497.
29. Lunn CA *et al.* Biology and therapeutic potential of cannabinoid CB2 receptor inverse agonists. *Br J Pharmacol* 2008; 153: 226–239.
30. Buckley NE. The peripheral cannabinoid receptor knockout mice: an update. *Br J Pharmacol* 2008; 153: 309–318.
31. Idris AI *et al.* Regulation of bone mass, bone loss and osteoclast activity by cannabinoid receptors. *Nat Med* 2005; 11: 774–779.
32. Karsak M *et al.* Cannabinoid receptor type 2 gene is associated with human osteoporosis. *Hum Mol Genet* 2005; 14: 3389–3396.
33. Ofek O *et al.* Peripheral cannabinoid receptor, CB2, regulates bone mass. *Proc Natl Acad Sci USA* 2006; 103: 696–701.
34. Bab I, Zimmer A. Cannabinoid receptors and the regulation of bone mass. *Br J Pharmacol* 2008; 153: 182–188.
35. Izzo AA. The cannabinoid CB(2) receptor: a good friend in the gut. *Neurogastroenterol Motil* 2007; 19: 704–708.
36. Ashton JC, Glass M. The cannabinoid CB2 receptor as a target for inflammation-dependent neurodegeneration. *Curr Neuropharmacol* 2007; 5: 73–80.
37. Steffens S *et al.* Low dose oral cannabinoid therapy reduces progression of atherosclerosis in mice. *Nature* 2005; 434: 782–786.
38. Mach F, Steffens S. The role of the endocannabinoid system in atherosclerosis. *J Neuroendocrinol* 2008; 20(Suppl 1): 53–57.
39. Jhaveri MD *et al.* Endocannabinoid metabolism and uptake: novel targets for neuropathic and inflammatory pain. *Br J Pharmacol* 2007; 152: 624–632.
40. Bifulco M, Di Marzo V. [The endocannabinoid system as a target for the development of new drugs for cancer therapy]. *Recenti Prog Med* 2003; 94: 194–198.
41. Bifulco M *et al.* Cannabinoids and cancer: pros and cons of an antitumour strategy. *Br J Pharmacol* 2006; 148: 123–135.
42. Flygare J, Sander B. The endocannabinoid system in cancer-potential therapeutic target? *Semin Cancer Biol* 2008; 18: 176–189.
43. Sarfaraz S *et al.* Cannabinoids for cancer treatment: progress and promise. *Cancer Res* 2008; 68: 339–342.
44. Munson AE *et al.* Antineoplastic activity of cannabinoids. *J Natl Cancer Inst* 1975; 55: 597–602.
45. Hopkins AL. Network pharmacology: the next paradigm in drug discovery. *Nat Chem Biol* 2008; 4: 682–690.
46. Dorsam RT, Gutkind JS. G-protein-coupled receptors and cancer. *Nat Rev Cancer* 2007; 7: 79–94.
47. Velasco G *et al.* Cannabinoids and ceramide: two lipids acting hand-by-hand. *Life Sci* 2005; 77: 1723–1731.
48. Sanchez C *et al.* Delta9-tetrahydrocannabinol induces apoptosis in C6 glioma cells. *FEBS Lett* 1998; 436: 6–10.
49. Sanchez C *et al.* Involvement of sphingomyelin hydrolysis and the mitogen-activated protein kinase cascade in the Delta9-tetrahydrocannabinol-induced stimulation of glucose metabolism in primary astrocytes. *Mol Pharmacol* 1998; 54: 834–843.
50. Carracedo A *et al.* The stress-regulated protein p8 mediates cannabinoid-induced apoptosis of tumor cells. *Cancer Cell* 2000; 9: 301–312.
51. Gomez del Pulgar T *et al.* De novo-synthesized ceramide is involved in cannabinoid-induced apoptosis. *Biochem J* 2002; 363: 183–188.
52. Blazquez C *et al.* Cannabinoids inhibit glioma cell invasion by down-regulating matrix metalloproteinase-2 expression. *Cancer Res* 2008; 68: 1945–1952.
53. Blazquez C *et al.* Down-regulation of tissue inhibitor of metalloproteinases-1 in gliomas: a new marker of cannabinoid antitumoral activity? *Neuropharmacology* 2008; 54: 235–243.
54. Cianchi F *et al.* Cannabinoid receptor activation induces apoptosis through tumor necrosis factor alpha-mediated ceramide de novo synthesis in colon cancer cells. *Clin Cancer Res* 2008; 14: 7691–7700.
55. Carracedo A *et al.* Ceramide sensitizes astrocytes to oxidative stress: protective role of cannabinoids. *Biochem J* 2004; 380: 435–440.
56. Sarne Y, Mechoulam R. Cannabinoids: between neuroprotection and neurotoxicity. *Curr Drug Targets CNS Neurol Disord* 2005; 4: 677–684.

57. Parcellier A *et al.* PKB and the mitochondria: AKTing on apoptosis. *Cell Signal* 2008; 20: 21–30.
58. Andrews S *et al.* PI3K class IB pathway. *Sci STKE* 2007; cm2.
59. Stephens L *et al.* A novel phosphoinositide 3 kinase activity in myeloid-derived cells is activated by G protein beta gamma subunits. *Cell* 1994; 77: 83–93.
60. Gomez Del Pulgar T *et al.* Cannabinoids protect astrocytes from ceramide-induced apoptosis through the phosphatidylinositol 3-kinase/protein kinase B pathway. *J Biol Chem* 2002; 277: 36527–36533.
61. Gomez del Pulgar T *et al.* The CB1 cannabinoid receptor is coupled to the activation of protein kinase B/Akt. *Biochem J* 2000; 347: 369–373.
62. Ozaita A *et al.* Regulation of PI3K/Akt/GSK-3 pathway by cannabinoids in the brain. *J Neurochem* 2007; 102: 1105–1114.
63. Fang J *et al.* PI3K/PTEEN/AKT signaling regulates prostate tumor angiogenesis. *Cell Signal* 2007; 19: 2487–2497.
64. Hart S *et al.* Cannabinoids induce cancer cell proliferation via tumor necrosis factor alpha-converting enzyme (TACE/ADAM17)-mediated transactivation of the epidermal growth factor receptor. *Cancer Res* 2004; 64: 1943–1950.
65. Greenhough A *et al.* The cannabinoid delta(9)-tetrahydrocannabinol inhibits RAS-MAPK and PI3K-AKT survival signalling and induces BAD-mediated apoptosis in colorectal cancer cells. *Int J Cancer* 2007; 121: 2172–2180.
66. Sarfaraz S *et al.* Cannabinoid receptor agonist-induced apoptosis of human prostate cancer cells LNCaP proceeds through sustained activation of ERK1/2 leading to G1 cell cycle arrest. *J Biol Chem* 2006; 281: 39480–39491.
67. Blazquez C *et al.* Cannabinoid receptors as novel targets for the treatment of melanoma. *FASEB J* 2006; 20: 2633–2635.
68. Galve-Roperh I *et al.* Anti-tumoral action of cannabinoids: involvement of sustained ceramide accumulation and extracellular signal-regulated kinase activation. *Nat Med* 2000; 6: 313–319.
69. Melck D *et al.* Involvement of the cAMP/protein kinase A pathway and of mitogen-activated protein kinase in the anti-proliferative effects of anandamide in human breast cancer cells. *FEBS Lett* 1999; 463: 235–240.
70. Preet A *et al.* Delta9-Tetrahydrocannabinol inhibits epithelial growth factor-induced lung cancer cell migration *in vitro* as well as its growth and metastasis *in vivo*. *Oncogene* 2008; 27: 339–346.
71. Krishna M, Narang H. The complexity of mitogen-activated protein kinases (MAPKs) made simple. *Cell Mol Life Sci* 2008; 65: 3525–3544.
72. Gertsch J *et al.* Beta-caryophyllene is a dietary cannabinoid. *Proc Natl Acad Sci USA* 2008; 105: 9099–9104.
73. Encinar JA *et al.* Human p8 is a HMG-I/Y-like protein with DNA binding activity enhanced by phosphorylation. *J Biol Chem* 2001; 276: 2742–2751.
74. Carracedo A *et al.* Cannabinoids induce apoptosis of pancreatic tumor cells via endoplasmic reticulum stress-related genes. *Cancer Res* 2006; 66: 6748–6755.
75. Caffarel MM *et al.* JunD is involved in the antiproliferative effect of Delta9-tetrahydrocannabinol on human breast cancer cells. *Oncogene* 2008; 27: 5033–5044.
76. Widmer M *et al.* High concentrations of cannabinoids activate apoptosis in human U373MG glioma cells. *J Neurosci Res* 2008; 86: 3212–3220.
77. Jia W *et al.* Delta9-tetrahydrocannabinol-induced apoptosis in Jurkat leukemia T cells is regulated by translocation of Bad to mitochondria. *Mol Cancer Res* 2006; 4: 549–562.
78. Galanti G *et al.* Delta 9-tetrahydrocannabinol inhibits cell cycle progression by downregulation of E2F1 in human glioblastoma multiforme cells. *Acta Oncol* 2008; 47: 1062–1070.
79. Portella G *et al.* Inhibitory effects of cannabinoid CB1 receptor stimulation on tumor growth and metastatic spreading: actions on signals involved in angiogenesis and metastasis. *FASEB J* 2003; 17: 1771–1773.
80. Laezza C *et al.* Anandamide inhibits Cdk2 and activates Chk1 leading to cell cycle arrest in human breast cancer cells. *FEBS Lett* 2006; 580: 6076–6082.
81. Caffarel MM *et al.* Delta9-tetrahydrocannabinol inhibits cell cycle progression in human breast cancer cells through Cdc2 regulation. *Cancer Res* 2006; 66: 6615–6621.
82. Ellert-Miklaszewska A *et al.* Cannabinoids down-regulate PI3K/Akt and Erk signalling pathways and activate proapoptotic function of Bad protein. *Cell Signal* 2005; 17: 25–37.
83. Bifulco M *et al.* Endocannabinoids as emerging suppressors of angiogenesis and tumor invasion (review). *Oncol Rep* 2007; 17: 813–816.
84. Blazquez C *et al.* Inhibition of tumor angiogenesis by cannabinoids. *FASEB J* 2003; 17: 529–531.
85. Casanova ML *et al.* Inhibition of skin tumor growth and angiogenesis *in vivo* by activation of cannabinoid receptors. *J Clin Invest* 2003; 111: 43–50.
86. Nyberg P *et al.* Tumor microenvironment and angiogenesis. *Front Biosci* 2008; 13: 6537–6553.
87. Pisanti S *et al.* Antiangiogenic activity of the endocannabinoid anandamide: correlation to its tumor-suppressor efficacy. *J Cell Physiol* 2007; 211: 495–503.
88. De Filippis D *et al.* Cannabinoids reduce granuloma-associated angiogenesis in rats by controlling transcription and expression of mast cell protease-5. *Br J Pharmacol* 2008; 154: 1672–1679.
89. Montecucco F. *et al.* CB₂ cannabinoid receptor agonist JWH-015 modulates human monocyte migration through defined intracellular signaling pathways. *Am J Physiol Heart Circ Physiol* 2008; 294: H1145–H1155.
90. Miller AM, Stella N. CB2 receptor-mediated migration of immune cells: it can go either way. *Br J Pharmacol* 2008; 153: 299–308.
91. Molina-Holgado F *et al.* CB2 cannabinoid receptors promote mouse neural stem cell proliferation. *Eur J Neurosci* 2007; 25: 629–634.
92. Valk PJ *et al.* Retroviral insertions in Evi12, a novel common virus integration site upstream of Tral/Grp94, frequently coincide with insertions in the gene encoding the peripheral cannabinoid receptor Cnr2. *J Virol* 1999; 73: 3595–3602.
93. Joosten M *et al.* Leukemic predisposition of pSca-1/Cb2 transgenic mice. *Exp Hematol* 2002; 30: 142–149.
94. Jorda MA *et al.* Identification, characterization, and function of a novel oncogene: the peripheral cannabinoid receptor Cb2. *Ann NY Acad Sci* 2003; 996: 10–16.
95. Gertsch J. Antiinflammatory cannabinoids in diet – towards a better understanding of CB2 receptor action? *Commun Integr Biol* 2008; 1: 26–28.
96. Smith SR *et al.* Effects of cannabinoid receptor agonist and antagonist ligands on production of inflammatory cytokines and anti-inflammatory interleukin-10 in endotoxemic mice. *J Pharmacol Exp Ther* 2000; 293: 136–150.
97. Ashton JC *et al.* Cannabinoid CB1 and CB2 receptor ligand specificity and the development of CB2-selective agonists. *Curr Med Chem* 2008; 15: 1428–1443.
98. Gustafsson K *et al.* Cannabinoid receptor-mediated apoptosis induced by R(+)-methanandamide and Win55,212-2 is associated with ceramide accumulation and p38 activation in mantle cell lymphoma. *Mol Pharmacol* 2006; 70: 1612–1620.
99. McAllister SD *et al.* Cannabinoids selectively inhibit proliferation and induce death of cultured human glioblastoma multiforme cells. *J Neurooncol* 2005; 74: 31–40.

100. Massi P *et al.* The non-psychoactive cannabidiol triggers caspase activation and oxidative stress in human glioma cells. *Cell Mol Life Sci* 2006; 63: 2057–2066.
101. Contassot E *et al.* Arachidonyl ethanolamide induces apoptosis of uterine cervix cancer cells via aberrantly expressed vanilloid receptor-1. *Gynecol Oncol* 2004; 93: 182–188.
102. Goncharov I *et al.* Delta9-tetrahydrocannabinol increases C6 glioma cell death produced by oxidative stress. *Neuroscience* 2005; 134: 567–574.
103. Massi P *et al.* Antitumor effects of cannabidiol, a non-psychoactive cannabinoid, on human glioma cell lines. *J Pharmacol Exp Ther* 2004; 308: 838–845.
104. Hinz B *et al.* Up-regulation of cyclooxygenase-2 expression is involved in R(+)-methanandamide-induced apoptotic death of human neuroglioma cells. *Mol Pharmacol* 2004; 66: 1643–1651.
105. Fowler CJ *et al.* Inhibition of C6 glioma cell proliferation by anandamide, 1-arachidonoylglycerol, and by a water soluble phosphate ester of anandamide: variability in response and involvement of arachidonic acid. *Biochem Pharmacol* 2003; 66: 757–767.
106. Jacobsson SO *et al.* Inhibition of rat C6 glioma cell proliferation by endogenous and synthetic cannabinoids. Relative involvement of cannabinoid and vanilloid receptors. *J Pharmacol Exp Ther* 2001; 299: 951–959.
107. Recht LD *et al.* Antitumor effects of ajulemic acid (CT3), a synthetic non-psychoactive cannabinoid. *Biochem Pharmacol* 2001; 62: 755–763.
108. Sanchez C *et al.* Inhibition of glioma growth *in vivo* by selective activation of the CB(2) cannabinoid receptor. *Cancer Res* 2001; 61: 5784–5789.
109. Krishnamurthy M *et al.* Exploring the substituent effects on a novel series of C1'-dimethyl-aryl Delta8-tetrahydrocannabinol analogs. *Bioorg Med Chem* 2008; 16: 6489–6500.
110. Cabral GA *et al.* Interaction of delta-9-tetrahydrocannabinol with rat B103 neuroblastoma cells. *Arch Toxicol* 1987; 60: 438–449.
111. End DW *et al.* A comparative study of the disposition of (–)-delta 9-tetrahydrocannabinol in neuroblastoma and glioma cells in tissue culture: relation cellular impairment. *Mol Pharmacol* 1977; 13: 864–871.
112. McKallip RJ *et al.* Cannabidiol-induced apoptosis in human leukemia cells: a novel role of cannabidiol in the regulation of p22phox and Nox4 expression. *Mol Pharmacol* 2006; 70: 897–908.
113. Herrera B *et al.* p38 MAPK is involved in CB2 receptor induced apoptosis of human leukaemia cells. *FEBS Lett* 2005; 579: 5084–5088.
114. Lombard C *et al.* Targeting cannabinoid receptors to treat leukemia: role of cross-talk between extrinsic and intrinsic pathways in Delta9-tetrahydrocannabinol (THC)-induced apoptosis of Jurkat cells. *Leuk Res* 2005; 29: 915–922.
115. McKallip RJ *et al.* Targeting CB2 cannabinoid receptors as a novel therapy to treat malignant lymphoblastic disease. *Blood* 2002; 100: 627–634.
116. Dvilansky A *et al.* Effects of ethanol, CBD and delta THC on proliferation of K-562 cells. *Int J Tissue React* 1984; 6: 409–412.
117. Tucker AN, Friedman MA. Effects of cannabinoids on L1210 murine leukemia. 1. Inhibition of DNA synthesis. *Res Commun Chem Pathol Pharmacol* 1977; 17: 703–714.
118. Carchman RA *et al.* The inhibition of DNA synthesis by cannabinoids. *Cancer Res* 1976; 36: 95–100.
119. Flygare J *et al.* Cannabinoid receptor ligands mediate growth inhibition and cell death in mantle cell lymphoma. *FEBS Lett* 2005; 579: 6885–6889.
120. Gustafsson SB *et al.* Cannabinoid receptor-independent cytotoxic effects of cannabinoids in human colorectal carcinoma cells: synergism with 5-fluorouracil. *Cancer Chemother Pharmacol* 2008; 63: 691–701.
121. Friedmann MA. *In vivo* effects of cannabinoids on macromolecular biosynthesis in Lewis lung carcinomas. *Cancer Biochem Biophys* 1977; 2: 51–54.
122. White AC *et al.* Effects of delta9-tetrahydrocannabinol in Lewis lung adenocarcinoma cells in tissue culture. *J Natl Cancer Inst* 1976; 56: 655–658.
123. Patsos HA *et al.* The endogenous cannabinoid, anandamide, induces cell death in colorectal carcinoma cells: a possible role for cyclooxygenase 2. *Gut* 2005; 54: 1741–1750.
124. Ligresti A *et al.* Possible endocannabinoid control of colorectal cancer growth. *Gastroenterology* 2003; 125: 677–687.
125. Fogli S *et al.* Cannabinoid derivatives induce cell death in pancreatic MIA PaCa-2 cells via a receptor-independent mechanism. *FEBS Lett* 2006; 580: 1733–1739.
126. Sarnataro D *et al.* The cannabinoid CB1 receptor antagonist rimonabant (SR141716) inhibits human breast cancer cell proliferation through a lipid raft-mediated mechanism. *Mol Pharmacol* 2006; 70: 1298–1306.
127. De Petrocellis L *et al.* Effect on cancer cell proliferation of palmitoylethanolamide, a fatty acid amide interacting with both the cannabinoid and vanilloid signalling systems. *Fundam Clin Pharmacol* 2002; 16: 297–302.
128. Di Marzo V *et al.* Palmitoylethanolamide inhibits the expression of fatty acid amide hydrolase and enhances the anti-proliferative effect of anandamide in human breast cancer cells. *Biochem J* 2001; 358: 249–255.
129. Melck D *et al.* Suppression of nerve growth factor Trk receptors and prolactin receptors by endocannabinoids leads to inhibition of human breast and prostate cancer cell proliferation. *Endocrinology* 2000; 141: 118–126.
130. Bisogno T *et al.* Biosynthesis and degradation of bioactive fatty acid amides in human breast cancer and rat pheochromocytoma cells—implications for cell proliferation and differentiation. *Eur J Biochem* 1998; 254: 634–642.
131. De Petrocellis L *et al.* The endogenous cannabinoid anandamide inhibits human breast cancer cell proliferation. *Proc Natl Acad Sci USA* 1998; 95: 8375–8380.
132. Sarfaraz S *et al.* Cannabinoid receptor as a novel target for the treatment of prostate cancer. *Cancer Res* 2005; 65: 1635–1641.
133. Mimeault M *et al.* Anti-proliferative and apoptotic effects of anandamide in human prostatic cancer cell lines: implication of epidermal growth factor receptor down-regulation and ceramide production. *Prostate* 2003; 56: 1–2.
134. Sarker KP *et al.* ASK1-p38 MAPK/JNK signaling cascade mediates anandamide-induced PC12 cell death. *J Neurochem* 2003; 85: 50–51.
135. Ruiz L *et al.* Delta9-tetrahydrocannabinol induces apoptosis in human prostate PC-3 cells via a receptor-independent mechanism. *FEBS Lett* 1999; 458: 400–404.
136. Lee CY *et al.* A comparative study on cannabidiol-induced apoptosis in murine thymocytes and EL-4 thymoma cells. *Int Immunopharmacol* 2008; 8: 732–740.
137. De Morrow S *et al.* Opposing actions of endocannabinoids on cholangiocarcinoma growth: recruitment of Fas and Fas ligand to lipid rafts. *J Biol Chem* 2007; 282: 13098–13113.
138. Giuliano M *et al.* Apoptosis induced in HepG2 cells by the synthetic cannabinoid WIN: involvement of the transcription factor PPARgamma. *Biochimie* 2009; 91: 457–465.
139. Shi Y *et al.* Cannabinoid 2 receptor induction by IL-12 and its potential as a therapeutic target for the treatment of anaplastic thyroid carcinoma. *Cancer Gene Ther* 2008; 15: 101–107.

140. Cozzolino R *et al.* A metabolically stable analogue of anandamide, Met-F-AEA, inhibits human thyroid carcinoma cell lines by activation of apoptosis. *Invest New Drugs* 2009; Feb 3 (Epub ahead of print).
141. Yin H *et al.* Lipid G-protein-coupled receptor ligand identification using beta-arrestin pathhunter assay. *J Biol Chem* 2009; 284: 12328–12338.
142. Nguyen *et al.* The dietary phytochemical indole-3-carbinol is a natural elastase enzymatic inhibitor that disrupts cyclin E protein processing. *Proc Natl Acad Sci USA* 2008; 105: 19750–19755.
143. Pertwee RG. GPR55: a new member of the cannabinoid receptor clan? *Br J Pharmacol* 2007; 152: 984–986.
144. Lauckner JE *et al.* GPR55 is a cannabinoid receptor that increases intracellular calcium and inhibits M current. *Proc Natl Acad Sci USA* 2008; 105: 2699–2704.
145. Henstridge CM *et al.* The GPR55 ligand L-alpha-lysophosphatidylinositol promotes RhoA-dependent Ca²⁺ signaling and NFAT activation. *FASEB J* 2009; 23: 183–193.
146. Kondo E *et al.* NF-ATc induces apoptosis in Burkitt's lymphoma cells through signaling via the B cell antigen receptor. *Eur J Immunol* 2003; 33: 1–11.
147. Massi P *et al.* 5-Lipoxygenase and anandamide hydrolase (FAAH) mediate the antitumor activity of cannabidiol, a non-psychoactive cannabinoid. *J Neurochem* 2008; 104: 1091–1100.
148. Sarnataro D *et al.* Plasma membrane and lysosomal localization of CB1 cannabinoid receptor are dependent on lipid rafts and regulated by anandamide in human breast cancer cells. *FEBS Lett* 2005; 579: 6343–6349.
149. Starowicz K *et al.* Biochemistry and pharmacology of endovanilloids. *Pharmacol Ther* 2007; 114: 13–33.
150. Burstein S. PPAR-gamma: a nuclear receptor with affinity for cannabinoids. *Life Sci* 2005; 77: 1674–1684.
151. Ramer R, Hinz B. Inhibition of cancer cell invasion by cannabinoids via increased expression of tissue inhibitor of matrix metalloproteinases-1. *J Natl Cancer Inst* 2008; 100: 59–69.
152. De Petrocellis L *et al.* Plant-derived cannabinoids modulate the activity of transient receptor potential channels of ankyrin type-1 and melastatin type-8. *J Pharmacol Exp Ther* 2008; 325: 1007–1015.
153. Ambrosio AI *et al.* Ajulemic acid, a synthetic nonpsychoactive cannabinoid acid, bound to the ligand binding domain of the human peroxisome proliferator-activated receptor gamma. *J Biol Chem* 2007; 282: 18625–18633.
154. Sarfaraz S *et al.* Cannabinoid receptor as a novel target for the treatment of prostate cancer. *Cancer Res* 2005; 65: 1635–1641.
155. Holland ML *et al.* Interaction of plant cannabinoids with the multidrug transporter ABCB1 (MRP1). *Eur J Pharmacol* 2008; 591: 128–131.
156. Holland ML *et al.* The multidrug transporter ABCG2 (BCRP) is inhibited by plant-derived cannabinoids. *Br J Pharmacol* 2007; 152: 815–824.
157. Holland ML *et al.* The effects of cannabinoids on P-glycoprotein transport and expression in multidrug resistant cells. *Biochem Pharmacol* 2006; 71: 1146–1154.
158. Nieri P *et al.* Modulation of P-glycoprotein activity by cannabinoid molecules in HK-2 renal cells. *Br J Pharmacol* 2006; 148: 682–687.
159. Zhu HJ *et al.* Characterization of P-glycoprotein inhibition by major cannabinoids from marijuana. *J Pharmacol Exp Ther* 2006; 317: 850–857.
160. Ligresti A *et al.* Antitumor activity of plant cannabinoids with emphasis on the effect of cannabidiol on human breast carcinoma. *J Pharmacol Exp Ther* 2006; 318: 1375–1387.
161. Zheng D *et al.* The cannabinoid receptors are required for ultraviolet-induced inflammation and skin cancer development. *Cancer Res* 2008; 68: 3992–3998.
162. Aguado T *et al.* Cannabinoids induce glioma stem-like cell differentiation and inhibit gliomagenesis. *J Biol Chem* 2007; 282: 6854–6862.
163. Chung SC *et al.* A high cannabinoid CB(1) receptor immunoreactivity is associated with disease severity and outcome in prostate cancer. *Eur J Cancer* 2009; 45: 174–182.
164. Russo EB. Cannabinoids in the management of difficult to treat pain. *Ther Clin Risk Manag* 2008; 4: 245–259.
165. Slatkin NE. Cannabinoids in the treatment of chemotherapy-induced nausea and vomiting: beyond prevention of acute emesis. *J Support Oncol* 2007; 5: 1–9.
166. McKallip RJ *et al.* Delta-9-tetrahydrocannabinol enhances breast cancer growth and metastasis by suppression of the antitumor immune response. *J Immunol* 2005; 174: 3281–3289.
167. Mocellin S, Nitti D. TNF and cancer: the two sides of the coin. *Front Biosci* 2008; 13: 2774–2783.
168. Sethi G *et al.* TNF: a master switch for inflammation to cancer. *Front Biosci* 2008; 13: 5094–5107.
169. Wang D *et al.* Loss of cannabinoid receptor 1 accelerates intestinal tumor growth. *Cancer Res* 2008; 68: 6468–6476.
170. Izzo AA *et al.* Increased endocannabinoid levels reduce the development of precancerous lesions in the mouse colon. *J Mol Med* 2008; 86: 89–98.
171. Pertwee RG. Emerging strategies for exploiting cannabinoid receptor agonists as medicines. *Br J Pharmacol* 2009; 156: 397–411.
172. Liu WM *et al.* Enhancing the *in vitro* cytotoxic activity of Delta-9-tetrahydrocannabinol in leukemic cells through combinatorial approach. *Leuk Lymphoma* 2008; 49: 1800–1809.
173. Desai AG *et al.* Medicinal plants and cancer chemoprevention. *Curr Drug Metab* 2008; 9: 581–591.
174. Parolaro D, Massi P. Cannabinoids as potential new therapy for the treatment of gliomas. *Expert Rev Neurother* 2008; 8: 37–49.
175. Sidney S *et al.* Marijuana use and cancer incidence (California, United States). *Cancer Causes Control* 1997; 8: 722–728.
176. Aldington S *et al.* Cannabis use and risk of lung cancer: a case-control study. *Eur Respir J* 2008; 31: 280–286.
177. Sewell RA *et al.* Doubts about the role of cannabis in causing lung cancer. *Eur Respir J* 2008; 32: 815–816.
178. Daling *et al.* Association of marijuana use and the incidence of testicular germ cell tumors. *Cancer* 2009; 115: 1215–1223.