

REVIEW

The endocannabinoid system and cancer: therapeutic implication

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The endocannabinoid system is implicated in a variety of physiological and pathological conditions (inflammation, immunomodulation, analgesia, cancer and others). The main active ingredient of cannabis, Δ^9 -tetrahydrocannabinol (Δ^9 -THC), produces its effects through activation of CB₁ and CB₂ receptors. CB₁ receptors are expressed at high levels in the central nervous system (CNS), whereas CB₂ receptors are concentrated predominantly, although not exclusively, in cells of the immune system. Endocannabinoids are endogenous lipid-signalling molecules that are generated in the cell membrane from phospholipid precursors. The two best characterized endocannabinoids identified to date are anandamide (AEA) and 2-arachidonoylglycerol (2-AG). Here we review the relationship between the endocannabinoid system and anti-tumour actions (inhibition of cell proliferation and migration, induction of apoptosis, reduction of tumour growth) of the cannabinoids in different types of cancer. This review will focus on examining how activation of the endocannabinoid system impacts breast, prostate and bone cancers in both *in vitro* and *in vivo* systems. The therapeutic potential of cannabinoids for cancer, as identified in clinical trials, is also discussed. Identification of safe and effective treatments to manage and improve cancer therapy is critical to improve quality of life and reduce unnecessary suffering in cancer patients. In this regard, cannabis-like compounds offer therapeutic potential for the treatment of breast, prostate and bone cancer in patients. Further basic research on anti-cancer properties of cannabinoids as well as clinical trials of cannabinoid therapeutic efficacy in breast, prostate and bone cancer is therefore warranted.

LINKED ARTICLES

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Abbreviations

2-AG, 2-arachidonoylglycerol; AC, adenylyl cyclase; ACEA, arachidonyl-2'-chloroethylamide; AEA, anandamide; AKT, protein kinase B; AR, androgen receptor; ATP, adenosine triphosphate; Bax, pro-apoptotic protein; Bcl2, anti-apoptotic protein; brca1, breast cancer susceptibility gene product; cAMP, cyclic adenosine monophosphate; CBD, cannabidiol; CB, cannabinoid; CB₁, cannabinoid receptor 1; CB₂, cannabinoid receptor 2; CBN, cannabinol; Cdc2, p34 cyclin-dependent kinase 1; CDK, cyclin-dependent kinases; CNS, central nervous system; DALN, desacetyllevonantradol; Δ^9 -THC, delta 9-tetrahydrocannabinol; DRG, dorsal root ganglion; EGF, epidermal growth factor receptor; EPEA, eicosapentaenoyl ethanolamide; ERK, extracellular regulated kinase; FAAH, fatty-acid amide hydrolase; GPR55, G-protein-coupled receptor 55; H₂O₂, hydrogen peroxide; p27/KIP1, cyclin kinase inhibitor; p38MAPK, p38 mitogen-activated protein kinase; PRL, prolactin receptor; MET, methanandamide; MGL or MAGL, monoacylglycerol lipase; OTFP, 3-octylthio-1,1,1-trifluoropropan-2-one; p53, p53 protein; p21ras, p21 ras protein; PEA, palmitoylethanolamide; PI3K, phosphatidylinositol 3 kinase; PKA, protein kinase A; PKB, protein kinase B; PRL, prolactin receptor; PSA, prostate-specific antigen; Raf-1, protein Raf-1; RT-PCR, reverse transcriptase polymerase chain reaction; Trk, high-affinity nerve growth factor receptor; TRPV1, transient receptor potential cation channel V1

Introduction

Cancer resulted in approximately 7.6 million deaths worldwide in 2008 (Ferlay *et al.*, 2010). An estimated 12.7 million new cancer cases were diagnosed in 2008 alone (Ferlay *et al.*, 2010). Worldwide, an estimated 1.38 million women and 914 000 men were diagnosed with breast and prostate cancer, respectively, in 2008 (Ferlay *et al.*, 2010). If this trend continues, cancer will overtake heart disease and become the predominant cause of death (Heron *et al.*, 2009). Effective treatment and management of cancer is critical for cancer patients but the development of safe and effective treatments that improve cancer therapy remains an unmet need. Cannabinoids and modulators of the endocannabinoid system have recently been shown to produce anti-tumour actions (reduction of inflammation, cell proliferation and cell survival properties) in different models of cancer. The present review focuses on breast, prostate and bone cancer in which links to the endocannabinoid system have been studied. More work is necessary to determine whether pharmacotherapies targeting the endocannabinoid system improve the treatment of cancer in patients.

Cannabinoids are implicated in a variety of physiological and pathological conditions including inflammation, immunomodulation, analgesia, cancer and others (for reviews Pacher *et al.*, 2006; Di Marzo, 2008). The main active ingredient of cannabis, Δ^9 -tetrahydrocannabinol (Δ^9 -THC), produces its effects through activation of G-protein-coupled CB₁ (Matsuda *et al.*, 1990; Ledent *et al.*, 1999; Zimmer *et al.*, 1999) and CB₂ (Munro *et al.*, 1993; Buckley *et al.*, 2000) receptors. Endocannabinoids are endogenous lipid-signalling molecules that are generated in the cell membrane from phospholipid precursors. They bind and activate one or more cannabinoid receptor subtypes, thus producing cannabimimetic properties (for reviews Piomelli, 2005; Di Marzo, 2006). The two best studied endocannabinoids isolated to date are anandamide (AEA) and 2-arachidonoylglycerol (2-AG). Anandamide is hydrolysed by the enzyme fatty-acid amide hydrolase (FAAH) whereas 2-AG is degraded predominantly, although not exclusively, by monoacylglycerol lipase (MGL) (for reviews Pacher *et al.*, 2006; Jhaveri *et al.*, 2007; Guindon and Hohmann, 2009; Wang and Ueda, 2009). Thus, enzymes catalysing endocannabinoid hydrolysis represent potential new targets for cancer pharmacotherapies. In this review, drug and molecular target nomenclature conforming to *British Journal of Pharmacology* Guide to Receptors and Channels (Alexander *et al.*, 2009) has been employed. Here, we will refer to effects of cannabinoids blocked by CB₁ antagonists (SR141716A, AM251) as being CB₁-mediated and effects blocked by CB₂ antagonists (SR144528, AM630) as CB₂-mediated.

Cancer is marked by uncontrolled cell division and cell death emerging from cumulative damage of important regulatory genes. Multiple genes likely need to be damaged in order for a cancer to grow and develop the ability to spread (i.e. metastasize). Cancers may be hereditary and/or caused by external (tobacco, chemicals, radiation, infectious organisms and others) and/or internal (inherited mutations, hormones, mutations from metabolism and others) factors. This review will focus on uncovering connections between the endocannabinoid system and breast, prostate and bone

cancers with an emphasis on understanding how these connections could be exploited for their therapeutic anti-cancer potential.

Animal models of cancer have been developed to experimentally assess pathophysiological mechanisms implicated in the analogous clinical syndrome. These models provide insight into pathophysiological processes of the disease state and elucidate mechanisms of action that may be targeted by drug discovery efforts aimed at identifying novel therapeutics. These models thus permit preclinical evaluation and validation of therapeutic efficacy of new pharmacotherapies.

Anti-proliferative properties of cannabis compounds were first identified 35 years ago. Here, it was first shown that administration of Δ^9 -THC inhibits lung adenocarcinoma cell growth *in vivo* (i.e. after oral administration in mice) and *in vitro* (Munson *et al.*, 1975; Carchman *et al.*, 1976). It took more than two decades before the potential anti-tumour properties associated with a cannabinoid were investigated further. In the past 14 years, an emerging body of research, primarily employing *in vitro* models of different cancers, has helped elucidate the mechanisms through which cannabinoids and the endocannabinoid tumour system influences cancer cell proliferation, migration and apoptosis (i.e. programmed cell death).

The mechanisms through which cannabinoids/cannabinoids receptors impact proliferation, migration and apoptosis of cancer cells are quite complex and our understanding of these processes remain incomplete. Moreover, these mechanisms differ in different types of cancer, and both pro- and anti-apoptotic effects of cannabinoids have been reported. A schematic representation of the major signalling pathways that are implicated in the activation of different cannabinoid receptor subtypes through their agonists and their involvement in these processes is summarized in Figure 1.

Several mechanisms are likely to underline the pro-apoptotic effects of cannabinoids and explain their anti-cancer effects. Cannabinoids induce *de novo* synthesis of ceramides, a family of lipid molecules composed of sphingosine and a fatty acid, found in the cell membrane. Synthesis of ceramide occurs via activation of the enzyme ceramide synthase and leads to downstream activation of an extracellular regulated kinase (ERK) signalling cascade. This process results in cell cycle arrest and apoptosis. Activation of either CB₁ or CB₂ receptors triggers the ceramide-ERK signalling pathway to promote apoptosis (Kogan, 2005; Sarfaraz *et al.*, 2006, 2008) (Figure 1). The increase in ceramide can also activate the p38 mitogen-activated protein kinase (p38MAPK) pathway which can lead to apoptosis through multiple mechanisms (i.e. through activation of cysteine proteases (i.e. caspases) or through cytochrome C release from mitochondria). The sustained activation of ERK also promotes the induction of cyclin kinase inhibitor (p27/KIP1) which modulates regulatory molecules of the cell cycle (cyclins, cdks) resulting in cell cycle arrest and apoptosis (Kogan, 2005; Sarfaraz *et al.*, 2006, 2008) (Figure 1). Cell cycle arrest involves the up-regulation of the p53 protein which will differentially alter levels of pro- and anti-apoptotic proteins (i.e. increase the levels of the pro-apoptotic protein Bax and lower the levels of the anti-apoptotic protein Bcl2, respectively, thereby shifting the ratio towards Bax) which ulti-

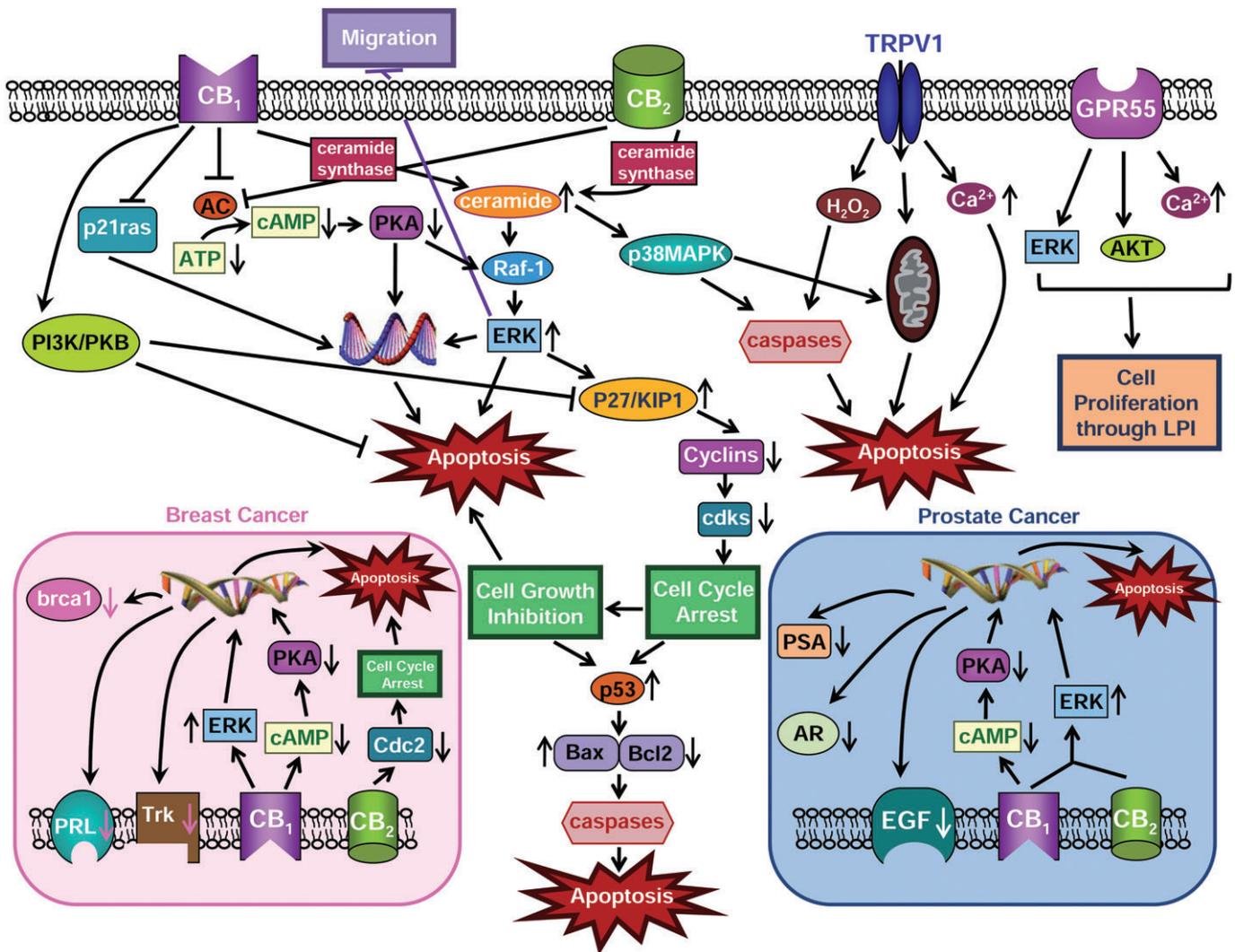


Figure 1

Schematic representation of different mechanisms/signalling pathways through which cannabinoids impact apoptosis, proliferation and migration. AC, adenylyl cyclase; AKT, protein kinase B; AR, androgen receptor; ATP, adenosine triphosphate; Bax, pro-apoptotic protein; Bcl2, antiapoptotic protein; brca1, breast cancer susceptibility gene product; cAMP, cyclic adenosine monophosphate; CB₁, cannabinoid receptor 1; CB₂, cannabinoid receptor 2; Cdc2, p34 cyclin-dependent kinase 1; CDK, cyclin-dependent kinases; EGF, epidermal growth factor; ERK, extracellular regulated kinase; GPR55, G protein-coupled receptor 55; H₂O₂, hydrogen peroxide; p27/KIP1, cyclin kinase inhibitor; PRL, prolactin receptor; p53, p53 protein; p21ras, p21 ras protein; PI3K, phosphatidylinositol 3 kinase; PKA, protein kinase A; PKB, protein kinase B; PSA, prostate-specific antigen; Raf-1, protein Raf-1; Trk, high-affinity nerve growth factor receptor; TRPV1, transient receptor potential cation channel V1.

mately leads to activation of caspases that play an essential role in triggering apoptosis (Sarfraz *et al.*, 2006). Activation of either CB₁ or CB₂ receptors also inhibits adenylyl cyclase (AC) activity and lowers both cyclic adenosine monophosphate (cAMP) levels and protein kinase A (PKA) activity, thereby causing down-regulation of gene transcription, leading to apoptosis (Guzmán, 2003; Kogan, 2005; Bifulco *et al.*, 2008; Sarfraz *et al.*, 2008). Activation of transient receptor potential cation channel V1 (TRPV1) receptors also leads to increases in intracellular levels of both hydrogen peroxide (H₂O₂) and/or calcium or the release of cytochrome C from mitochondria, causing apoptosis through both distinct and overlapping mechanisms (Figure 1) (Maccarrone *et al.*, 2000).

Cannabinoid receptor 1 ligands have pro-apoptotic properties, in part, through inhibition of the Ras protein (p21ras) which is involved in inducing DNA synthesis (Bifulco *et al.*, 2001). However, CB₁ receptor activation can also trigger activation of different tumour cascades that are linked to promotion of cancer cell survival and inhibition of apoptosis. Indeed, CB₁ ligands also stimulate the PI3K/PKB tumour pathway, an essential tumour pathway implicated in cell survival. Activation of PI3K/PKB downstream of CB₁ activation may promote apoptosis either directly or through inhibition of p27/KIP1 (Gómez del Pulgar *et al.*, 2000; Sarfraz *et al.*, 2008). Thus, both pro- and anti-apoptotic effects of cannabinoids have been reported, raising the possibility that a dysregulation of the endocannabinoid system may also

contribute to cancer/tumour development. However, activation of ERK downstream of cannabinoid receptor activation also promotes anti-cancer effects through inhibition of cancer cell migration (Blazquez *et al.*, 2003; Kogan, 2005). More work is necessary to determine the balance between these various mechanisms, and how they modulate cancer *in vivo*.

Phytocannabinoids may also interfere with the ability of lysophosphatidylinositol (LPI), a putative endogenous ligand for G-protein-coupled receptor 55 (GPR55), to promote cancer cell proliferation through activation of the putative novel cannabinoid receptor subtype (Figure 1). Pretreatment of breast and prostate cancer cells with cannabidiol, a major component of marijuana, or with SR141716A (a CB₁ antagonist that also possesses agonist/antagonist properties at GPR55), blocks the ability of LPI to induce cell proliferation through GPR55, thereby producing anti-cancer effects (Piñeiro *et al.*, 2011). Activation of GPR55 by LPI promotes cancer cell proliferation following activation of distinct intracellular tumour cascades [i.e. ERK, AKT and calcium mobilization (Piñeiro *et al.*, 2011)]; these anti-proliferative effects were also blocked using siRNA for GPR55.

Breast cancer

Breast cancer is the most common cancer among women (Ferlay *et al.*, 2010). Genetics, lack of child bearing/breastfeeding, higher hormone levels and iodine deficiency have all been identified as risk factors for developing breast cancer (Madigan *et al.*, 1995). Breast cancer, also known as malignant breast neoplasm, originates from breast tissue, usually from the milk ducts (ductal carcinomas) or the lobules (lobular carcinomas) that supply the ducts with milk (Glass *et al.*, 2007). Breast cancer cells may spread to other organs such as the bones, lungs and lymph nodes (Guise *et al.*, 2010; Pantel and Alix-Panabières, 2010). Recent research identifies a role for the endocannabinoid system in the regulation of tumour growth, induction of apoptosis (programmed cell death) and control of tumour vascularization (angiogenesis) in breast cancer (Grimaldi *et al.*, 2006; Ligresti *et al.*, 2006; Qamri *et al.*, 2009; Caffarel *et al.*, 2010). The phenomenon of angiogenesis is required for tumours to transition from a dormant to malignant state (Fontanini, 2000; Ribatti and Crivellato, 2010).

Expression of cannabinoid receptors in different breast cancer tissue/cell lines has been described. CB₁ expression by immunohistochemistry was detected in 14% of human breast cancer tumour tissue expressing a member of the epidermal growth factor (EGF) family referred to as the ErbB2 tyrosine kinase receptor. No correlation between CB₁ expression and ErbB2 expression was found (Caffarel *et al.*, 2010). CB₁ immunoreactivity was also expressed in 28% of human breast carcinoma (Qamri *et al.*, 2009). CB₁ receptors are also present in different breast cancer cell lines (MCF-7, T-47D, MDA-MB-231, TSA-E1, MDA-MB-468) and in human breast tissues using RT-PCR, immunofluorescence and/or Western blot (Melck *et al.*, 2000; Di Marzo *et al.*, 2001; McCallip *et al.*, 2005; Sarnataro *et al.*, 2005, 2006; Caffarel *et al.*, 2006; Grimaldi *et al.*, 2006; Ligresti *et al.*, 2006; Qamri *et al.*, 2009). By contrast, CB₂ immunoreactivity was detected in 72% of

human breast tumour tissue (Caffarel *et al.*, 2010). Interestingly, CB₂ receptors were found in 91% of ErbB2-positive tumour tissue, suggesting a link between CB₂ and ErbB2-expression, but not between CB₁ and ErbB2-expression (Caffarel *et al.*, 2010). In another study, CB₂ receptors immunoreactivity was observed in 35% of human breast carcinoma (Qamri *et al.*, 2009). However, CB₂ receptors are also expressed in different breast carcinoma cell lines (MCF-7, T-47D, MDA-MB-231, MDA-MB-468, EVSA-T, SkBr3) and human breast tissues using RT-PCR, immunofluorescence and/or Western blot (Melck *et al.*, 2000; Di Marzo *et al.*, 2001; McCallip *et al.*, 2005; Ligresti *et al.*, 2006; Qamri *et al.*, 2009; Caffarel *et al.*, 2006, 2010). The putative novel cannabinoid receptor subtype GPR55 was highly expressed in a MDA-MB-231 cell line using RT-PCR, but it is expressed at lower (30-fold) levels in MCF-7 breast carcinoma cell lines using RT-PCR (Ford *et al.*, 2010). Lysophosphatidylinositol (LPI), the putative endogenous ligand for GPR55, also stimulates cell migration and invasion in a MDA-MB-231 cell line and this LPI effect on migration is blocked by pretreatment with cannabidiol (CBD) (Ford *et al.*, 2010). Furthermore, it was also demonstrated that LPI stimulate proliferation and this effect was blocked by CBD (Piñeiro *et al.*, 2011). Moreover, the anandamide hydrolysing enzyme (FAAH) is found in EFM-19 and MCF-7 cancer cell lines using Northern blot analyses (Bisogno *et al.*, 1998) or RT-PCR (Takeda *et al.*, 2008). No study has evaluated whether the 2-AG hydrolysing enzyme MGL is similarly present, or whether changes in enzymes catalysing endocannabinoid synthesis or degradation accompany anti-cancer effects. Nonetheless, the literature suggests that multiple cannabinoid receptor subtypes as well as enzymes catalysing endocannabinoid hydrolysis (i.e. FAAH) show an anatomical distribution appropriate to regulate breast cancer cell proliferation, migration and/or apoptosis.

In vitro studies show that endocannabinoids and cannabinoid-like compounds inhibit proliferation and/or migration and/or induce apoptosis in different breast carcinoma (MCF-7, EFM-19, T-47D, MDA-MB-231, MDA-MB-468, MDA-MB-436, 4T1, TSA-E1, EVSA-T, SkBr3, HTB-126) cell lines. It is important to note that the MDA-MB-231 cell line represents a small proportion of all types of breast cancer; it is highly metastatic and lacks expression of other receptors (oestrogen, progesterone). The phytocannabinoid CBD inhibits cell proliferation (Ruh *et al.*, 1997; Ligresti *et al.*, 2006; McAllister *et al.*, 2007, 2010), increases apoptosis (Ligresti *et al.*, 2006) and reduces migration (McAllister *et al.*, 2007, 2010; Ford *et al.*, 2010) in different cancer cell lines (Table 1). Anti-proliferative effects of CBD are partially reversed by SR144528 (Ligresti *et al.*, 2006), although a possible role for CB₁ cannot be ruled out because its possible contribution was not evaluated. The mechanism of action of CBD in producing these effects is not fully understood and needs to be investigated further. Δ^9 -THC also possesses anti-proliferative properties (McAllister *et al.*, 2007; Caffarel *et al.*, 2006, 2008; von Bueren *et al.*, 2008), increases apoptosis (Caffarel *et al.*, 2006) and decreases cancer cell migration (McAllister *et al.*, 2007). Δ^9 -THC-induced anti-proliferative and pro-apoptotic properties are mediated by CB₂, but not CB₁ receptors (Caffarel *et al.*, 2006). The lack of effect of Δ^9 -THC on CB₁ receptors in EVSA-T cells could be explained by the lack of CB₁ receptors in this cell line. By contrast, some studies have shown that

Table 1

Breast cancer *in vitro* and *ex vivo* studies

Cell line/tissue	Expressing	Apoptosis	Proliferation	Migration	Apoptosis/proliferation/ migration mediated by CB ₁	CB ₂	Reference
MCF-7	-	-	↓ by DALN, CBD	-	-	-	Ruh <i>et al.</i> , 1997
EFM-19	FAAH	-	↓ by AEA	-	SR1	-	Bisogno <i>et al.</i> , 1998
EFM-19	FAAH	-	↓ by Oleamide	-	SR1	-	Bisogno <i>et al.</i> , 1998
MCF-7	-	-	↓ by AEA	-	SR1	-	De Petrocellis <i>et al.</i> , 1998
EFM-19	-	-	↓ by 2-AG, MET, HU-210	-	-	-	De Petrocellis <i>et al.</i> , 1998
MCF-7	-	-	↓ by AEA	-	-	-	Melck <i>et al.</i> , 1999
EFM-19	-	-	↓ by AEA, arvanil	-	SR1	Not SR2	Melck <i>et al.</i> , 2000
MCF-7 T-47D	CB ₁ , CB ₂	-	↓ by 2-AG	-	-	-	Melck <i>et al.</i> , 2000
MCF-7 T-47D	CB ₁ , CB ₂	-	PEA enhance AEA ↓	-	-	Not SR2	Di Marzo <i>et al.</i> , 2001
MCF-7	CB ₁ , CB ₂	-	PEA enhance arvanil ↓	-	-	-	Di Marzo <i>et al.</i> , 2001
MCF-7	CB ₁ , CB ₂	-	PEA enhance HU-210 ↓	-	-	-	Di Marzo <i>et al.</i> , 2001
EFM-19	-	-	PEA enhance olvanil ↓	-	-	Not SR2	De Petrocellis <i>et al.</i> , 2002
MCF-7	CB ₁ low, not CB ₂	Δ ⁹ -THC no Δ	-	-	-	-	Mckallip <i>et al.</i> , 2005
4T1*	Not CB ₁ nor CB ₂	Δ ⁹ -THC no Δ	-	-	-	-	Mckallip <i>et al.</i> , 2005
MDA-MB-231	CB ₁	-	-	-	-	-	Sarnataro <i>et al.</i> , 2005
MCF-7	-	-	↑ by Δ ⁹ -THC, CBD, CBN	-	-	-	Watanabe <i>et al.</i> , 2005
EVSA-T	CB ₂	↑ by Δ ⁹ -THC	↓ by Δ ⁹ -THC	-	Not SR1 pro	SR2 pro, apo	Caffarel <i>et al.</i> , 2006
MCF-7 T-47D	-	-	↓ by Δ ⁹ -THC	-	-	-	Caffarel <i>et al.</i> , 2006
MDA-MB-231 MDA-MB-468 SkBr3	-	-	-	-	-	-	Caffarel <i>et al.</i> , 2006
Breast tumour	CB ₁ , CB ₂	-	-	-	-	-	Caffarel <i>et al.</i> , 2006
MDA-MB-231	-	MET no Δ	↓ by MET	↓ by MET	SR1 mig	-	Grimaldi <i>et al.</i> , 2006
T-47D	CB ₁	-	MET no Δ	-	-	-	Grimaldi <i>et al.</i> , 2006
TSA-E1*	CB ₁	-	↓ by MET	↓ by MET	SR1 mig	-	Grimaldi <i>et al.</i> , 2006
MCF-7	CB ₁ weak, CB ₂ weak	-	↓ by CBD, CBG, CBC, CBD acid, THC acid	-	-	-	Ligresti <i>et al.</i> , 2006
MDA-MB-231	CB ₁ weak, CB ₂ medium	↑ by CBD	↓ by CBD, CBG, CBC, CBD acid, THC acid	-	-	Partially by SR2 with CBD for pro	Ligresti <i>et al.</i> , 2006

Table 1
Continued.

Cell line/tissue	Expressing	Apoptosis	Proliferation	Migration	Apoptosis/proliferation/ migration mediated by CB ₁	Reference
MCF-7 T-47D	CB ₁	-	↓ by SR1	-	-	Sarnataro <i>et al.</i> , 2006
MDA-MB-231	CB ₁	SR1 no Δ	↓ by SR1	-	-	Sarnataro <i>et al.</i> , 2006
MDA-MB-231	-	-	↓ by Δ ⁹ -THC, CBN, WIN-2, CP55,940, CBD	↓ by Δ ⁹ -THC, CBD, WIN-2	-	McAllister <i>et al.</i> , 2007
MDA-MB-436	-	-	↓ by Δ ⁹ -THC, CBN, WIN-2, CP55,940, CBD	↓ by CBD	-	McAllister <i>et al.</i> , 2007
HTB-126	-	-	↓ by NPT, NPD	-	SR1 with NPT	Burstein and Salmonsens, 2008
EYSA-T	-	-	↓ by Δ ⁹ -THC	-	-	Caffarel <i>et al.</i> , 2008
MDA-MB-231	-	-	-	↓ by MET	SR1	Laezza <i>et al.</i> , 2008
MCF-7	FAAH Not CB ₁ nor CB ₂	-	↑ by Δ ⁹ -THC, CBD, CBN	-	Not SR1 nor AM251 with Δ ⁹ -THC	Takeda <i>et al.</i> , 2008
MCF7	-	-	↓ by Δ ⁹ -THC	-	-	von Bueren <i>et al.</i> , 2008
MCF7-AR1	-	-	↓ by Δ ⁹ -THC	-	-	Qamri <i>et al.</i> , 2009
MDA-MB-231	CB ₁ , CB ₂	↑ by JWH-133, WIN-2	↓ by JWH-133, WIN-2	↓ by JWH-133, WIN-2	siRNA and WB	Qamri <i>et al.</i> , 2009
MDA-MB-468	CB ₁ , CB ₂	-	↓ by JWH-133, WIN-2	↓ by JWH-133, WIN-2	-	Qamri <i>et al.</i> , 2009
MCF-7	-	-	↑ by Δ ⁹ -THC	-	-	Takeda <i>et al.</i> , 2009
Breast tumour	CB ₁ , CB ₂	-	-	-	-	Caffarel <i>et al.</i> , 2010
MDA-MB-231	GPR55	-	-	↓ by CBD	-	Ford <i>et al.</i> , 2010
MCF-7	-	-	↓ by MET	-	-	Laezza <i>et al.</i> , 2010
MDA-MB-231	-	-	-	-	-	McAllister <i>et al.</i> , 2010
MCF-7	-	-	↓ by CBD	↓ by CBD	-	McAllister <i>et al.</i> , 2010

Human and murine* cell line/tissue.

↑, increase; ↓, decrease; -, not tested; 2-AG, 2-arachidonoyl glycerol; apo, apoptosis; AEA, anandamide; CB₁, cannabinoid receptor 1; CB₂, cannabinoid receptor 2; CBC, cannabichromene; CBD, cannabidiol; CBD acid; cannabidiol acid; CBCG, cannabigerol; CBN, cannabinol; Δ⁹-THC, delta 9-tetrahydrocannabinol; DALN, desacetyllevonantradol; FAAH, fatty acid amide hydrolase; MET, methanandamide; mig, migration; no Δ, no change; NPD, N-palmitoyl dopamine; NPT, N-palmitoyl tyrosine; PEA, palmitoylethanolamide; pro, proliferation; siRNA, silencing RNA; SR1, SR141716A; SR2, SR144528; THC acid, tetrahydrocannabinol acid; WB, Western blot; WIN-2, WIN55,212-2.

Δ^9 -THC failed to inhibit cell proliferation (Ruh *et al.*, 1997) or induce apoptosis (McKallip *et al.*, 2005). Cannabinol (CBN), a phytocannabinoid that is both a metabolite of Δ^9 -THC and a weak agonist at CB₁ and CB₂ receptors, also inhibits cell proliferation (McAllister *et al.*, 2007). Another study provided findings contradictory to these observations; CBD, Δ^9 -THC and CBN all stimulated proliferation at low (1 μ M) or high (up to 20 μ M) concentrations in MCF-7 cells, but there were limitations in the studies which affect data interpretation. For example, these groups failed to demonstrate the expression of CB₁ or CB₂ receptors (Watanabe *et al.*, 2005; Takeda *et al.*, 2008), a finding which conflicts with other studies that show CB₁ and CB₂ receptor expression in the same cell line (Movsesyan *et al.*, 2004; McKallip *et al.*, 2005). Nonetheless, the possibility remains that the combination of phytocannabinoids in cannabis may offer greater therapeutic potential compared with Δ^9 -THC or CBD alone.

Endocannabinoids exhibit anti-proliferative properties *in vitro*. Indeed, AEA inhibits cell proliferation (Bisogno *et al.*, 1998; De Petrocellis *et al.*, 1998; Melck *et al.*, 1999, 2000) which is mediated by CB₁ (Bisogno *et al.*, 1998; De Petrocellis *et al.*, 1998; Melck *et al.*, 2000), but not by CB₂ (Melck *et al.*, 2000) receptors (Table 1). However, CB₂-mediated effects of AEA cannot be discounted because only one study evaluated their possible contribution (Melck *et al.*, 2000). Moreover, 2-AG, oleamide and arvanil all inhibit cell proliferation. The anti-proliferative effects of oleamide and arvanil are inhibited by CB₁ (Bisogno *et al.*, 1998; Melck *et al.*, 2000), but not CB₂ (Melck *et al.*, 2000) receptor antagonists. Interestingly, palmitoylethanolamide (PEA), a fatty-acid amide that does not bind to cannabinoid receptors, enhances the anti-proliferative effects of AEA, arvanil, olvanil and HU-210 (Di Marzo *et al.*, 2001; De Petrocellis *et al.*, 2002), which is suggestive of synergism or an entourage effect (Ben-Shabat *et al.*, 1998; De Petrocellis *et al.*, 2002). Moreover, the enhancement of AEA and olvanil anti-proliferative effects does not involve CB₂ receptors (Di Marzo *et al.*, 2001; De Petrocellis *et al.*, 2002). Methanandamide inhibits both cell proliferation (De Petrocellis *et al.*, 1998; Grimaldi *et al.*, 2006; Laezza *et al.*, 2010) and cell migration (Grimaldi *et al.*, 2006; Laezza *et al.*, 2008). The methanandamide-induced inhibition of cell migration involves CB₁ receptors (Grimaldi *et al.*, 2006). By contrast, the mixed CB₁/CB₂ agonist WIN55,212-2 and CB₂ agonist JWH-133 inhibits both cell proliferation (McAllister *et al.*, 2007; Qamri *et al.*, 2009) and migration (McAllister *et al.*, 2007; Qamri *et al.*, 2009) through a mechanism that requires CB₂ receptor activation, although a possible role for CB₁ was not assessed (Qamri *et al.*, 2009) (Table 1). Surprisingly, both cannabinoid agonists such as CP55 940 (McAllister *et al.*, 2007) and HU-210 (De Petrocellis *et al.*, 1998) and cannabinoid CB₁ antagonists such as SR141716A (Sarnataro *et al.*, 2006) have all been shown to inhibit cell proliferation. Amide derivatives such as N-palmitoyl tyrosine and N-palmitoyl dopamine also possess anti-proliferative properties; in the case of N-palmitoyl tyrosine, effects are mediated by CB₁ receptors (Burstein and Salmonsén, 2008). Cannabigerol, cannabichromene, cannabidiol acid and THC acid (Ligresti *et al.*, 2006) as well as desacetyllevonantradol (Ruh *et al.*, 1997) also inhibit cell proliferation in different breast cancer cell lines (Table 1).

In breast cancer cells, cannabinoid receptor agonists inhibit breast cancer cell proliferation by a down-regulation of high-affinity nerve growth factor (Trk) and prolactin (PRL) receptors as well as down-regulation of breast cancer susceptibility gene product (brca1) through the cAMP-PKA/MAPK/Raf-ERK signalling pathways (De Petrocellis *et al.*, 1998; Melck *et al.*, 1999, 2000; Bifulco *et al.*, 2008) (Figure 1, left inset). Furthermore, it has been demonstrated that Δ^9 -THC decreased the levels of Cdc2 (major cyclin dependent kinase controlling the entrance of cells in mitosis), thereby causing cell cycle arrest and subsequent apoptosis (Caffarel *et al.*, 2006) (Figure 1, left inset). Other signalling pathways could be involved or discovered in future studies.

In vivo studies demonstrate that cannabinoids reduce tumour growth and metastasis as well as cell proliferation and angiogenesis in mice injected with different breast cancer cell lines. For example, Δ^9 -THC decreases tumour size as well as the number of tumour and lung metastases and inhibits both cell proliferation and angiogenesis in an engineered animal model of ErbB2 (tyrosine kinase receptor)-driven metastatic breast cancer (Caffarel *et al.*, 2010) (see Table 2 for more details). This inhibition of cell proliferation involves CB₂, but not CB₁ receptors (Caffarel *et al.*, 2010). Further evidence for a role for CB₂ receptors in these anti-cancer properties is based upon the ability of the CB₂ agonist JWH-133 to decrease size and number of tumours, reduce the number and size of lung metastases, inhibit cell proliferation and decrease angiogenesis in mice injected with different breast cancer cell lines (Qamri *et al.*, 2009; Caffarel *et al.*, 2010). These effects were mediated by CB₂, but not CB₁ receptors (Qamri *et al.*, 2009; Caffarel *et al.*, 2010). In CB-17 immunodeficient mice injected with MDA-MB-231 cells, the mixed CB₁/CB₂ agonist WIN55,212-2 also reduces tumour size, decreases the number and size of lung metastases, inhibits proliferation and reduces angiogenesis; these effects were mediated by CB₁ and CB₂ receptors (Qamri *et al.*, 2009) (Table 2). Furthermore, the phytocannabinoid cannabidiol (CBD) also reduces tumour growth (size) and decreases the number of lung metastases in mice injected with MDA-MB-231 (Ligresti *et al.*, 2006) or 4T1 (McAllister *et al.*, 2010) breast cancer cell lines (see Table 2). Moreover, the anandamide analogue methanandamide also reduces the number and size of lung tumour nodules in mice injected with TSA-1 mammary carcinoma cell line through a CB₁ receptor mechanism (Grimaldi *et al.*, 2006) (Table 2). Strikingly, the CB₁ antagonist SR141716A, administered alone, has also been reported to decrease tumour size in mice injected with MDA-MB-231 cancer cells (Sarnataro *et al.*, 2006); more work is necessary to determine whether effects of SR141716A observed here can be attributed to direct activation of CB₁ receptors or to other receptor mechanisms (e.g. GPR55). However, conflicting data are reported in the literature in this regard because systemic administration of Δ^9 -THC has been reported to increase the local tumour size and the number/size of metastasis in mice injected with 4T1 tumour cells into the rear foot-pads (McKallip *et al.*, 2005). These unusual findings are potentially explained by the fact that Δ^9 -THC suppresses the anti-tumour immune response which involves CB₂, but not the CB₁ receptors (McKallip *et al.*, 2005). Moreover, SCID-NOD mice, which are devoid of anti-tumour immune responses, do not exhibit increases in tumour size or metastasis following Δ^9 -THC administration

Table 2

Breast cancer *in vivo* studies

Mouse strain	Tumour induction (cell line)	Drugs	Dose and route	Tumour		Metastasis		Proliferation (pro)/apoptosis (apo)/angiogenesis (ang)		Mediated by		Reference
				Size	Number	Size	Number	Number	Number	CB ₁	CB ₂	
BALB/c	4T1 paw	Δ ⁹ -THC	12.5–50 mg·kg ⁻¹ i.p.	↑ by Δ ⁹ -THC	-	↑ by Δ ⁹ -THC	-	↑ by Δ ⁹ -THC	-	-	-	McKallip <i>et al.</i> , 2005
BALB/c	4T1 paw	Δ ⁹ -THC	25–50 mg·kg ⁻¹ i.p.	↑ by Δ ⁹ -THC	-	-	-	↑ by Δ ⁹ -THC	-	-	-	McKallip <i>et al.</i> , 2005
SCID-NOD	4T1 paw	Δ ⁹ -THC	25 mg·kg ⁻¹ i.p.	Δ ⁹ -THC no Δ	-	-	-	Δ ⁹ -THC no Δ	-	-	-	McKallip <i>et al.</i> , 2005
C57BL/6N	TSA-E1 paw	MET	0.5 mg·kg ⁻¹ i.p.	-	-	↓ by MET	-	↓ by MET	-	SR1	-	Grimaldi <i>et al.</i> , 2006
Athymic	MDA-MB-231 dorsal side	CBD	5–6.5 mg·kg ⁻¹ s.c.	↓ by CBD	-	-	-	-	-	-	-	Ligresti <i>et al.</i> , 2006
Balb/c	MDA-MB-231 paw	CBD	5–6.5 mg·kg ⁻¹ s.c.	-	-	-	-	↓ by CBD	-	-	-	Ligresti <i>et al.</i> , 2006
CD1	MDA-MB-231 flank	SR1	0.7 mg·kg ⁻¹ s.c.	↓ by SR1	-	-	-	-	-	-	-	Sarnataro <i>et al.</i> , 2006
CB-17 immuno	MDA-MB-231 flank	JWH-133	5 mg·kg ⁻¹ p.t.	↓ by JWH-133	-	-	-	JWH-133 ↓ pro, ↓ ang	pro, ↓ ang	-	SR2	Qamri <i>et al.</i> , 2009
CB-17 immuno	MDA-MB-231 flank	WIN-2	5 mg·kg ⁻¹ p.t.	↓ by WIN-2	-	-	-	WIN-2 ↓ pro, ↓ ang	pro, ↓ ang	AM251	SR2	Qamri <i>et al.</i> , 2009
CB-17 immuno	MDA-MB231-luc-D3H2LN lateral vein	JWH-133	5 mg·kg ⁻¹ i.p.	-	-	↓ by JWH-133	-	↓ by JWH-133	-	-	SR2	Qamri <i>et al.</i> , 2009
CB-17 immuno	MDA-MB231-luc-D3H2LN lateral vein	JWH-133, WIN-2	5 mg·kg ⁻¹ i.p.	-	-	↓ by WIN-2	-	↓ by WIN-2	-	AM251	SR2	Qamri <i>et al.</i> , 2009
PyMT	NA	JWH-133	5 mg·kg ⁻¹ i.p.	↓ by JWH-133	-	-	-	JWH-133 ↓ pro, ↓ ang	pro, ↓ ang	-	-	Qamri <i>et al.</i> , 2009
MMTV-neu	NA	Δ ⁹ -THC	0.5 mg p.t.	↓ by Δ ⁹ -THC	↓ by Δ ⁹ -THC	-	-	↓ by Δ ⁹ -THC	Δ ⁹ -THC ↓ pro, ↑ apo, ↓ ang	Not SR1 pro	SR2 pro	Caffarel <i>et al.</i> , 2010
MMTV-neu	NA	JWH-133	0.05 mg p.t.	↓ by JWH-133	↓ by JWH-133	-	-	↓ by JWH-133	JWH-133 ↓ pro, ↑ apo, ↓ ang	Not SR1 pro	SR2 pro	Caffarel <i>et al.</i> , 2010
Balb/c	4T1 fourth major nipple	CBD	1–5 mg·kg ⁻¹ s.c.	↓ by CBD	-	↓ by CBD	-	↓ by CBD	-	-	-	McAllister <i>et al.</i> , 2010

↑, increase; ↓, decrease; -, not tested; ang, angiogenesis; apo, apoptosis; CB₁, cannabinoid receptor 1; CB₂, cannabinoid receptor 2; CBD, cannabidiol; Δ⁹-THC, delta-9-tetrahydrocannabinol; immuno, immunodeficient; i.p., intraperitoneal; MET, methanandamide; MMTV-neu mice, genetically engineered mice of ErbB2 (tyrosine kinase receptor)-driven metastatic breast cancer; NA, not applicable; no Δ, no change; pro, proliferation; p.t., peritumoral; PyMT mice, transgenic mice developing mammary gland tumours; s.c., subcutaneous; SCID-NOD, devoid of anti-tumour immune response; SR1, SR141716A; SR2, SR144528; WIN-2, WIN55,212-2.

(McKallip *et al.*, 2005). None of these models of breast cancer is actually injecting tumour cells into the milk ducts or lobules of the breast which diminishes the translation relevance to human breast cancer and reinforces the need to develop new animal models that better reproduce the disease state.

Prostate cancer

Prostate cancer is the second most frequently diagnosed malignancy in men (Bray *et al.*, 2010; Ferlay *et al.*, 2010). Genetics, diet, medical exposure and viral infection are all factors implicated in occurrence or incidence of the disease (Djulgovic *et al.*, 2010). Prostate cancer develops in the prostate, a gland in the male reproductive system. Most prostate cancers grow slowly although cases of aggressive prostate cancers are also observed. These cancer cells may metastasize from the prostate to other parts of the body, particularly to the bones and lymph nodes (Parkin *et al.*, 2001; Schroder *et al.*, 2009; Djulgovic *et al.*, 2010).

Several studies have also evaluated the expression of cannabinoid receptors in different prostate cancer tissue/cell lines. Indeed, it was shown that high CB₁ receptor immunoreactivity score in prostate cancer tissue is associated with prostate cancer severity and outcome (Chung *et al.*, 2009). It was also demonstrated that CB₁ expression is up-regulated in prostate cancer tissue (Czifra *et al.*, 2009). Moreover, multiple prostate cancer cell lines (i.e. PC-3, DU-145, LNCaP, CWR22Rv1, CA-HPV-10) and human prostate cancer tissues express CB₁ receptors using RT-PCR, immunofluorescence, and Western blot (Ruiz *et al.*, 1999; Melck *et al.*, 2000; Sánchez *et al.*, 2003a; Nithipatikom *et al.*, 2004; Sarfaraz *et al.*, 2005; Chung *et al.*, 2009; Czifra *et al.*, 2009; Brown *et al.*, 2010). CB₂ receptors are also expressed in different prostate cancer cell lines (PC-3, DU-145, LNCaP, CWR22Rv1, CA-HPV-10) using RT-PCR, immunofluorescence and Western blot (Melck *et al.*, 2000; Sánchez *et al.*, 2003a; Nithipatikom *et al.*, 2004; Sarfaraz *et al.*, 2005; Brown *et al.*, 2010). Moreover, expression of FAAH is demonstrated in prostate cancer cell lines (PC-3, DU-145, LNCaP) and human prostate cancer tissue using Western blot, immunohistochemistry and RT-PCR (Ruiz-Llorente *et al.*, 2004; Endsley *et al.*, 2008; Takeda *et al.*, 2008; Brown *et al.*, 2010; Thors *et al.*, 2010; Wang *et al.*, 2008) (Table 3). Furthermore, the putative cannabinoid receptor GPR55 is also expressed in PC-3 and DU-145 prostate carcinoma cell lines using Western blot and RT-PCR (Piñeiro *et al.*, 2011). Thus, multiple cannabinoid receptor subtypes and endocannabinoid hydrolysing enzymes are localized to prostate tissue and synthetic cannabinoids, endocannabinoids and related compounds inhibit prostate cancer cell proliferation and produce apoptosis through CB₁ and/or CB₂ receptor mechanisms.

In vitro studies have extensively evaluated the ability of different endocannabinoids or cannabis-like compounds to inhibit prostate cancer cell proliferation and/or induce apoptosis in different prostate carcinoma (PC-3, DU-145, LNCaP, CWR22Rv1, CA-HPV-10) cell lines (Table 3). Δ^9 -THC possesses anti-proliferative (Velasco *et al.*, 2001) and pro-apoptotic properties in prostate cancer cell lines (Ruiz *et al.*, 1999). The pro-apoptotic effects of Δ^9 -THC are not mediated by CB₁

receptors, although a possible role for CB₂ receptors was not assessed (Ruiz *et al.*, 1999). Methanandamide has also been shown to inhibit prostate cancer cell proliferation (Melck *et al.*, 2000; Nithipatikom *et al.*, 2004; Olea-Herrero *et al.*, 2009a,b) and induce apoptosis (Olea-Herrero *et al.*, 2009a); these effects are mediated by CB₂, but not CB₁ receptors. Both Δ^9 -THC and methanandamide induce cell proliferation at nanomolar concentrations (Velasco *et al.*, 2001; Sánchez *et al.*, 2003a,b), suggesting that the observed effects are likely to be physiologically relevant. The mixed cannabinoid agonist WIN55,212-2 also inhibits cell proliferation (Nithipatikom *et al.*, 2004; Sarfaraz *et al.*, 2005) and induces apoptosis (Sarfaraz *et al.*, 2005, 2006); these effects are mediated by both CB₁ and CB₂ receptors (Sarfaraz *et al.*, 2005). Furthermore, the CB₂-preferring agonist JWH-015 has anti-proliferative (Sánchez *et al.*, 2003b; Olea-Herrero *et al.*, 2009a) and pro-apoptotic properties (Olea-Herrero *et al.*, 2009a) and these effects are mediated by CB₂, but not CB₁ receptors (Olea-Herrero *et al.*, 2009a). HU-210 also inhibits cell proliferation (Melck *et al.*, 2000), although pharmacological specificity was not evaluated. Finally, synthetic endocannabinoids also exhibit anti-proliferative properties. In fact, AEA inhibits cell proliferation through CB₂, but not CB₁ receptors (Melck *et al.*, 2000; Mimeault *et al.*, 2003), whereas induction of apoptosis involves both CB₁ and CB₂ receptors (Mimeault *et al.*, 2003). Inhibition of endocannabinoid hydrolysis by methyl arachidonyl fluorophosphonate (Nithipatikom *et al.*, 2004), which targets FAAH and MGL, and by CAY10401 (Endsley *et al.*, 2008), which aims FAAH, suggests that elevation of endocannabinoids also inhibits cell proliferation. Inhibition of 2-AG hydrolysis by OTFP (3-octylthio-1,1,1-trifluoropropan-2-one), a compound containing a trifluoromethylketone moiety, also inhibited cell proliferation (Nithipatikom *et al.*, 2005; Endsley *et al.*, 2007) through a CB₁-dependent mechanism (Nithipatikom *et al.*, 2005). More work is necessary to demonstrate the specificity of OTFP for MGL in the model system. Phytocannabinoids including CBD, cannabigerol and cannabichromene, cannabidiol acid and THC acid (Ligresti *et al.*, 2006) as well as putative endocannabinoids such as arvanil (Melck *et al.*, 2000) and noladin ether (Nithipatikom *et al.*, 2004) all inhibit cell proliferation in different prostate cancer cell lines (Table 3). Anti-proliferative effects of arvanil are mediated by CB₁, but not CB₂ receptors (Melck *et al.*, 2000). Interestingly, palmitoylethanolamide (PEA) enhances the anti-proliferative effects of AEA, arvanil and HU-210 in a prostate cancer cell line (Di Marzo *et al.*, 2001), suggestive of an entourage effect. Omega-3 fatty-acid ethanolamides such as eicosapenta enoyl ethanolamide (EPEA) also exhibit anti-proliferative properties which involve both CB₁ and CB₂ receptors (Brown *et al.*, 2010).

In prostate cancer cells, cannabinoids, following receptor binding, inhibit cell proliferation and induce cell cycle arrest and apoptosis through cAMP-PKA/Raf-ERK signalling pathways. Indeed, treatment with anandamide produced an inhibition of epidermal growth factor (EGF)-induced proliferation via cell cycle arrest in prostate cancer cells and a down-regulation of EGF receptors levels (Mimeault *et al.*, 2003; Bifulco *et al.*, 2008) (Figure 1, right inset). Another study showed that treatment with WIN55,212-2 decreased androgen receptor (AR) expression and prostate specific antigen (PSA) levels in prostate cancer cells and also induced

Table 3

Prostate cancer *in vitro* and *ex vivo* studies

Human cell line/tissue	Expressing	Apoptosis	Proliferation	Apoptosis/proliferation mediated by		Reference
				CB ₁	CB ₂	
PC-3	CB ₁	↑ by Δ ⁹ -THC	–	Not AM251	–	Ruiz <i>et al.</i> , 1999
DU-145	CB ₁ , low CB ₂	–	↓ by AEA, 2-AG, MET, HU-210, arvanil	SR1 for AEA, arvanil	Not SR2 for AEA, arvanil	Melck <i>et al.</i> , 2000
DU-145	–	–	↓ by AEA, arvanil, HU-210 enhanced by PEA	–	–	Di Marzo <i>et al.</i> , 2001
PC-3	–	–	↓ by Δ ⁹ -THC	Not SR1	–	Velasco <i>et al.</i> , 2001
PC-3	–	–	↑ by Δ ⁹ -THC	SR1	–	Velasco <i>et al.</i> , 2001
PC-3	–	↑ by AEA	↓ by AEA	SR1 for apo	SR2 for apo; not SR2 for pro	Mimeault <i>et al.</i> , 2003
LNCaP	–	↑ by AEA	↓ by AEA	SR1 for pro	Not SR2 for pro	Mimeault <i>et al.</i> , 2003
DU-145	–	–	–	–	–	–
PC-3	CB ₁ , CB ₂	–	↑ by Δ ⁹ -THC, MET	–	–	Sánchez <i>et al.</i> , 2003a
LNCaP	–	–	↑ by Δ ⁹ -THC, MET	SR1 for MET	SR2 for MET	Sánchez <i>et al.</i> , 2003b
LNCaP	–	–	↓ by JWH-015	–	–	Sánchez <i>et al.</i> , 2003b
PC-3	CB ₁ , CB ₂	–	↓ by Noladin ether, WIN-2, MET	–	–	Nithipatikom <i>et al.</i> , 2004
DU-145	–	–	–	–	–	–
PC-3	CB ₁ , CB ₂	–	↓ by endocannabinoid hydrolysis blockade (MAFP)	SR1	–	Nithipatikom <i>et al.</i> , 2004
DU-145	–	–	–	–	–	–
LNCaP	CB ₁ , CB ₂	–	–	–	–	Nithipatikom <i>et al.</i> , 2004
PC-3	FAAH	–	–	–	–	Ruiz-Llorente <i>et al.</i> , 2004
PC-3	–	–	↓ by 2-AG hydrolysis blockade (OTFP)	SR1	–	Nithipatikom <i>et al.</i> , 2005
DU-145	–	–	↓ by 2-AG hydrolysis blockade (OTFP)	–	–	Nithipatikom <i>et al.</i> , 2005
LNCaP	CB ₁ , CB ₂	↑ by WIN-2	↓ by WIN-2	SR1	SR2	Sarfraz <i>et al.</i> , 2005
DU-145	CB ₁ , CB ₂	–	–	–	–	Sarfraz <i>et al.</i> , 2005
PC-3	–	–	–	–	–	–
CWR22Rv1	–	–	–	–	–	–
CA-HPV-10	–	–	–	–	–	–
DU-145	–	CBD no Δ	↓ by CBD, CBG, CBC, CBD acid, THC acid	–	–	Ligresti <i>et al.</i> , 2006
LNCaP	–	↑ by WIN-2	–	–	–	Sarfraz <i>et al.</i> , 2006
PC-3	–	–	↓ by 2-AG hydrolysis blockade (OTFP)	–	–	Endsley <i>et al.</i> , 2007
Prostate tumour	FAAH high	–	–	–	–	Endsley <i>et al.</i> , 2008
LNCaP	FAAH high	–	↓ by FAAH blockade (CAY10401)	–	–	Endsley <i>et al.</i> , 2008
DU-145	FAAH medium	–	–	–	–	Endsley <i>et al.</i> , 2008
PC-3	FAAH low	–	–	–	–	Endsley <i>et al.</i> , 2008
LNCaP	FAAH	–	–	–	–	Wang <i>et al.</i> , 2008
PC-3	–	–	–	–	–	–
DU-145	–	–	–	–	–	–
Prostate tumour	CB ₁ high in severe cancer	–	–	–	–	Chung <i>et al.</i> , 2009
Prostate tumour	CB ₁ high	–	–	–	–	Czifra <i>et al.</i> , 2009
PC-3	–	↑ by MET, JWH-015	↓ by MET, JWH-015	Not SR1	SR2 apo	Olea-Herrero <i>et al.</i> , 2009a
LNCaP	–	↑ by MET, JWH-015	↓ by MET, JWH-015	–	–	Olea-Herrero <i>et al.</i> , 2009a
DU-145	–	–	–	–	–	–
PC-3	–	↑ by MET	↓ by MET	Not SR1	SR2 partially	Olea-Herrero <i>et al.</i> , 2009b
LNCaP	CB ₁ , CB ₂ , FAAH	–	↓ by EPEA	–	–	Brown <i>et al.</i> , 2010
PC-3	CB ₁ , CB ₂	–	↓ by EPEA	AM281	AM630	Brown <i>et al.</i> , 2010

↑, increase; ↓, decrease; –, not tested; 2-AG, 2-arachidonoyl glycerol; AEA, anandamide; apo, apoptosis; CAY10401, fatty-acid amide hydrolase inhibitor; CB₁, cannabinoid receptor 1; CB₂, cannabinoid receptor 2; CBC, cannabichromene; CBD, cannabidiol; CBD acid, cannabidiol acid; CBG, cannabigerol; Δ⁹-THC, delta-9 tetrahydrocannabinol; EPEA, eicosapentaenoyl ethanolamide; FAAH, fatty-acid amide hydrolase; MAFP, methyl arachidonyl fluorophosphonate; MET, methanandamide; no Δ, no change; OTFP (3-octylthio-1,1,1-trifluoropropan-2-one; PEA, palmitoylethanolamide; pro, proliferation; SR1, SR141716A; SR2, SR144528; THC acid, tetrahydrocannabinol; WIN-2, WIN55,212-2.

Table 4

Bone cancer *in vitro* and *ex vivo* studies

Murine cell line\tissue	Tumour induction (cell line)	Expressing	Apoptosis	Bone loss	Reference
NCTC-2472	NA	CB ₁ , CB ₂	WIN-2	–	Hald <i>et al.</i> , 2008
Femur	NCTC-2472	–	–	No Δ by WIN-2	Hald <i>et al.</i> , 2008
DRG	NCTC-2472	↑ by CB ₂ ipsi; no Δ CB ₁	–	–	Hald <i>et al.</i> , 2008
Spinal cord	NCTC-2472	No Δ CB ₁ , CB ₂	–	–	Hald <i>et al.</i> , 2008
DRG	NCTC-2472	↑ by CB ₁ ipsi	–	–	Khasabova <i>et al.</i> , 2008
DRG and plantar skin	NCTC-2472	↑ by FAAH activity	–	–	Khasabova <i>et al.</i> , 2008
Spinal cord	NCTC-2472	No Δ CB ₁	–	–	Furuse <i>et al.</i> , 2009
Spinal cord and DRG	NCTC-2472	No Δ CB ₂	–	–	Curto-Reyes <i>et al.</i> , 2010
Spinal cord and DRG	B16-F10	No Δ CB ₂	–	–	Curto-Reyes <i>et al.</i> , 2010
Femur	NCTC-2472	–	–	↓ by AM1241	Lozano-Ondoua <i>et al.</i> , 2010

↑, increase; ↓, decrease; –, not tested; CB₁, cannabinoid receptor 1; CB₂, cannabinoid receptor 2; DRG, dorsal root ganglion; FAAH, fatty-acid amide hydrolase; ipsi, ipsilateral side; no Δ, no change; NA, not applicable; WIN-2, WIN55,212-2.

apoptosis (Sarfaraz *et al.*, 2005, 2006) (Figure 1, right inset). However, other signalling pathways may also be involved or implicated in the modulation of apoptosis, cell cycle arrest and/or proliferation by cannabinoids.

One *in vivo* model of prostate cancer has evaluated the ability of a cannabinoid to inhibit tumour growth. In this model, subcutaneous injection of PC-3 cells (prostate carcinoma cells) in the right flank of athymic nude male mice induced the development of tumours (Olea-Herrero *et al.*, 2009a). Interestingly, direct peritumoral administration of the CB₂ preferring agonist JWH-015 reduced tumour growth in the mice and this reduction of growth was inhibited by the CB₂ receptor antagonist SR144528 (Olea-Herrero *et al.*, 2009a). Injection of canine prostate carcinoma (ACE-1) cells into the mouse femur produces bone pain and bone remodelling, sprouting of calcitonin gene-related peptide (CGRP) and of sensory nerve fibres (Jimenez-Andrade *et al.*, 2010a), changes which impact processes implicated in bone metastasis observed following prostate cancer. The development of new animal models which better reproduce prostate cancer observed clinically may improve prostate cancer treatment; injection of prostate tumour cells into the flank limits translational relevance of the model and does not truly reproduce cancer originating in the prostate gland.

Bone cancer

Primary bone cancer identified as sarcomas arises in the cartilage. Chondrosarcoma and osteosarcoma are the most frequent primary bone cancers (Bové *et al.*, 2010). Secondary bone cancer is more frequent as it is associated with the wide spread of other cancers through bone metastases from lung or other solid tumours (Mercadante, 1997; Portenoy *et al.*, 1999).

In mice injected with NCTC-2472 sarcoma cell lines, CB₁ (Khasabova *et al.*, 2008) or CB₂ (Hald *et al.*, 2008) receptors are up-regulated in DRG ipsilateral to cancer bearing limb.

However, no change in the expression of CB₁ (Hald *et al.*, 2008; Furuse *et al.*, 2009) or CB₂ (Hald *et al.*, 2008; Curto-Reyes *et al.*, 2010) receptors was observed in the spinal cord, suggesting that the observed up-regulation was restricted to the periphery. Another study failed to observe up-regulation of CB₂ in DRG (Curto-Reyes *et al.*, 2010). Furthermore, FAAH activity is also increased in DRG and plantar skin of mice injected with NCTC-2472 sarcoma cells (Khasabova *et al.*, 2008).

In vitro studies demonstrate that multiple cannabinoid or cannabis-derived compounds induce apoptosis and/or reduce bone resorption in different bone sarcoma (i.e. NCTC-2472, B16-F10) cell lines (Table 4). WIN55,212-2 induces apoptosis in the NCTC-2472 sarcoma cell line (Hald *et al.*, 2008). Furthermore, the CB₂ agonist AM1241 produced a reduction in bone loss in the femur of mice injected with NCTC-2472 sarcoma cell line (Lozano-Ondoua *et al.*, 2010). Thus, regulatory changes in the endocannabinoid system (in DRG and plantar skin) are observed in models of bone cancer pain and activation of cannabinoid CB₁ or CB₂ receptors produces anti-nociception and apoptosis. Activation of CB₂ receptors additionally reduces bone loss in tumour-treated mice, suggesting that many aspects of cannabinoid pharmacology may promote anti-cancer effects.

In vivo bone cancer models differ from breast and prostate cancer models in that they more readily lend themselves to direct assessments of therapeutic effects of cannabinoids such as anti-nociception (Jimenez-Andrade *et al.*, 2010b). These studies have evaluated the efficacies of cannabinoids in suppressing tumour-evoked hyperalgesia and/or reductions of tumour growth and metastasis. Injection of different cancer (fibrosarcoma NCTC-2472 or melanoma B16-F10) cells into the calcaneus, tibial or femur bones of mice produces bone tumours (Table 5). Systemic injection of CP55 940 produced anti-nociceptive properties in the tail flick test and suppressed mechanical hyperalgesia (to von Frey stimulation) in this model (Hamamoto *et al.*, 2007). These anti-nociceptive effects were mediated by CB₁, but not CB₂ receptors

Table 5

Bone cancer *in vivo* studies

Mouse strain	Tumour induction (cell line)	Drugs	Dose and route	Anti-nociception	Mechanical anti-allodynia	Catalepsy	Mediated by CB ₁	Mediated by CB ₂	Reference
C3H/HeNcr	NCTC-2472 calcaneus	CP55,940	0.1–3 mg·kg ⁻¹ i.p.	CP55,940 TF	CP55,940 VF	CP55,940 BT	SR1 TF, VF, BT	Not SR2 TF, VF, BT	Hamamoto <i>et al.</i> , 2007
C3H/HeN	NCTC-2472 femur	WIN-2	0.5–5 mg·kg ⁻¹ s.c.	WIN-2 WB, OF	WIN-2 VF	-	-	-	Hald <i>et al.</i> , 2008
C3H/HeN	NCTC-2472 calcaneus	AEA	1 µg i.p.	-	AEA VF	-	AM281 VF	Not AM630 VF	Khasabova <i>et al.</i> , 2008
C3H/HeN	NCTC-2472 calcaneus	URB597	9 µg i.p.	-	URB597 VF	-	AM281 VF	Not AM630 VF	Khasabova <i>et al.</i> , 2008
C3H/He	NCTC-2472 calcaneus	WIN-2	1.5–10 µg i.pl.	-	WIN-2 VF	No WIN-2	AM251 VF	AM630 VF	Potenzieri <i>et al.</i> , 2008
C57BL/6j	NCTC-2472 femur	ACEA	1 nmol i.t.	ACEA SF, LU, WB	-	No ACEA	AM251 SF, LU, WB	Not AM630 SF, LU, WB	Furuse <i>et al.</i> , 2009
C57BL/6j	NCTC-2472 femur	URB597	0.3–3 nmol i.t.	No SF, LU, WB	-	-	-	-	Furuse <i>et al.</i> , 2009
C57BL/6j	NCTC-2472 femur	URB602	0.17–1.7 nmol i.t.	No SF, LU, WB	-	-	-	-	Furuse <i>et al.</i> , 2009
C3H/He	NCTC 2472 tibia	AM1241	1–10 mg·kg ⁻¹ i.p.	AM1241 HP	AM1241 VF	-	Not AM251 HP, VF	SR2 HP, VF	Curto-Reyes <i>et al.</i> , 2010
C3H/He	NCTC 2472 tibia	AM1241	0.1–1 µg i.t.	AM1241 HP	AM1241 VF	-	-	SR2 HP, VF	Curto-Reyes <i>et al.</i> , 2010
C57BL/6	B16-F10 tibia	AM1241	1–10 mg·kg ⁻¹ i.p.	AM1241 HP	AM1241 VF	-	Not AM251 HP, VF	SR2 HP, VF	Curto-Reyes <i>et al.</i> , 2010
C3H/Hej	NCTC-2472 femur	AM1241	6 mg·kg ⁻¹ i.p.	AM1241 SF, LU	AM1241 VF	-	-	SR2 SF, LU, VF	Lozano-Ondoua <i>et al.</i> , 2010

↑, increase; ↓, decrease; -, not tested; AEA, anandamide; ACEA, arachidonyl-2'-chloroethylamide; BT, bar test; CB₁, cannabinoid receptor 1; CB₂, cannabinoid receptor 2; HP, hot plate; i.p., intraperitoneal; i.pl., intraplantar; i.t., intrathecal; LU, limb use; no Δ, no change; OF, open field; s.c., subcutaneous; SF, spontaneous flinches; SR1, SR141716A; SR2, SR144528; TF, tail flick; VF, von Frey; WIN-2, WIN55,212-2; WB, weight bearing.

(Hamamoto *et al.*, 2007) (Table 5). Effects of subcutaneously administered WIN55,212-2 on weight bearing and mechanical hyperalgesia were consistent with cannabinoid receptor-mediated anti-nociception (Hald *et al.*, 2008). WIN55,212-2 also attenuates tumour-evoked mechanical hyperalgesia following local (intraplantar) administration through activation of CB₁ and CB₂ receptors (Potenziari *et al.*, 2008). Endocannabinoids and modulators of the endocannabinoid system also attenuate tumour-evoked pain. Indeed, intraplantar administration of AEA reduces mechanical hyperalgesia and URB597, a potent inhibitor of FAAH, increases AEA levels and decreases hyperalgesia in a model of calcaneus bone cancer pain (Khasabova *et al.*, 2008). These effects of AEA and URB597 are mediated by CB₁, but not CB₂ receptors (Khasabova *et al.*, 2008). However, intrathecal administration of either FAAH (URB597) or MGL (URB602) inhibitors failed to produce anti-nociception when tested for spontaneous flinches, limb use and weight bearing (Furuse *et al.*, 2009). Moreover, the CB₁ agonist arachidonoyl-2-chloroethylamide (ACEA) produces anti-nociceptive properties following intrathecal administration in this model; ACEA suppressed spontaneous flinches and increased limb use and weight bearing through CB₁, but not CB₂ receptor mechanisms (Furuse *et al.*, 2009) (Table 5). Furthermore, systemic and intrathecal administration of the CB₂ agonist AM1241 produces anti-nociception measured with multiple dependent measures (i.e. flinches, limb use, hot plate, von Frey) (Curto-Reyes *et al.*, 2010; Lozano-Ondoua *et al.*, 2010). These anti-nociceptive effects, assessed with multiple different testing methods, are all mediated by CB₂, but not CB₁ receptors (Curto-Reyes *et al.*, 2010; Lozano-Ondoua *et al.*, 2010). Animal models of bone cancer closely reproduce human bone cancer because tumour cells are injected directly into the bone, where the cancer originates in humans. New techniques for injection of mammary rat metastasis tumour cells in the femur have also recently been developed in rats (Doré-Savard *et al.*, 2010).

Cannabinoids in clinical cancer studies

Cannabinoids have been evaluated in cancer patients for their anti-emetic, anti-nociceptive and orexigenic properties. Numerous studies have been published documenting the anti-emetic properties of cannabis-like compounds (Davis, 2008; Navari, 2009; Parker *et al.*, 2011 for reviews). Fewer clinical trials have evaluated pain relief following cannabinoid administration in cancer patients. Indeed, the role of cannabinoids in relieving pain associated with cancer has been evaluated in only five clinical studies. Four of these studies were performed more than 32 years ago (Noyes *et al.*, 1975a,b; Jochimsen *et al.*, 1978; Staquet *et al.*, 1978; Johnson *et al.*, 2010). In the initial study, oral THC, at doses of 15 and 20 mg, produced analgesic effects in patients experiencing cancer pain (Noyes *et al.*, 1975a). The same study showed that oral administration of single lower dose of Δ^9 -THC (10 mg) to patients with cancer pain was well-tolerated and produced a mild analgesic effect, whereas higher doses of Δ^9 -THC (20 mg) also produced adverse side effects (Noyes *et al.*, 1975b). Another study, using a nitrogen analogue of Δ^9 -THC, showed that pain relief was superior to placebo in patients with

cancer (Staquet *et al.*, 1978). Another group, also using a nitrogen analogue of Δ^9 -THC, showed that the cannabinoid (2 or 4 mg) was not effective as an analgesic, compared with placebo and even appeared to augment pain perception in patients with chronic pain due to malignancies (Jochimsen *et al.*, 1978). A more recent study demonstrated that the administration of Sativex (Δ^9 -THC: CBD in a 1:1 ratio) reduced pain scores when compared with placebo, whereas effects of Δ^9 -THC administration alone on pain did not reach significance (Johnson *et al.*, 2010).

The present studies suggest that additional clinical trials evaluating the therapeutic efficacy of cannabinoids in cancer pain are warranted, particularly in light of other aspects of cannabinoid receptor pharmacology that hold considerable therapeutic potential (i.e. anti-emetic and anti-tumour properties).

Conclusion and limitations

The available literature suggests that the endocannabinoid system may be targeted to suppress the evolution and progression of breast, prostate and bone cancer as well as the accompanying pain syndromes. Although this review focuses on these three types of cancer, activation of the endocannabinoid signalling system produces anti-cancer effects in other types of cancer including skin, brain (gliomas) and lung (Velasco *et al.*, 2007; Bíró *et al.*, 2009; Pacher and Mechoulam, 2011 for reviews). Interestingly, cannabis trials in population-based studies failed to show any evidence for increased risk of respiratory symptoms/chronic obstructive pulmonary disease (Tan *et al.*, 2009; Hancox *et al.*, 2010) or lung cancer (Tashkin, 2005) associated with smoking cannabis. Moreover, synthetic cannabinoids and the endocannabinoid system play a role in inhibiting cancer cell proliferation and angiogenesis, reducing tumour growth and metastases and inducing apoptosis in all three types of cancers reviewed here. These observations raise the possibility that a dysregulation of the endocannabinoid system may promote cancer, by fostering physiological conditions that allow cancer cells to proliferate, migrate and grow. These observations also raise the exciting possibility that enhancing cannabinoid tone through cannabinoid-based pharmacotherapies may attenuate these harmful processes to produce anti-cancer effects in humans. However, the basic research findings are far from being completely understood and further research is warranted to better understand the complexity of dynamic changes in the endocannabinoid system in cancer. One of the reasons for this complexity is likely attributable to the highly interactive nature of lipid signalling pathways which recruit different signalling pathways and mechanisms of action. Indeed, endocannabinoids are known to interact with the cyclooxygenase enzyme, inhibit the transcription of genes implicated in metastasis processes, induce cell cycle arrest, activate the formation of reactive oxygen species and ensure the integrity of raft/caveolae needed for anti-proliferative properties. However, other mechanisms are also likely to be involved and interact with the endocannabinoid system in ways that are yet to be discovered.

Many *in vitro* and *in vivo* studies have shown that cannabinoids are efficacious in reducing cancer progression (i.e.

inhibition of tumour growth and metastases as well as induction of apoptosis and other anti-cancer properties) in breast, prostate and bone cancer. However, further research is needed because the complexity of the effects of cannabinoids and their interaction with other mechanisms and signalling pathways remain to be elucidated. The need for further study is particularly crucial in the case of prostate cancer; only one study, performed in mice, has evaluated *in vivo* effects of a cannabinoid (JWH-015) on tumour growth. The paucity of *in vivo* preclinical and clinical data is striking given the large number of compounds that have been tested *in vitro* in different types of prostate cancer cell lines.

Despite the need for further *in vitro* and *in vivo* studies, the literature is nearly unanimous in suggesting that cannabinoids and endocannabinoids reduce the progression of cancer in both *in vivo* preclinical and *in vitro* model systems. The need for additional clinical trials of cannabinoid therapeutic efficacy in cancer appears beyond doubt; only few studies have evaluated the effects of cannabinoid in alleviating cancer pain, in contrast to the extensive literature supporting efficacy of cannabinoids as anti-emetics. Furthermore, future research needs to explore the therapeutic potential of multimodal analgesic strategies that combine cannabinoids with other commonly used medications (opioids) or employ multiple phytocannabinoids in combination. The use of different pharmacotherapies in combination may increase the likelihood of synergistic interactions between compounds with multiple distinct mechanisms of action; such combinations may produce a more beneficial therapeutic ratio in cancer patients compared with conventional analgesics, resulting in improved pain relief and anti-cancer effects with fewer adverse side effects. Moreover, because cannabinoids attenuate neuropathy produced by cancer chemotherapy through CB₁ and CB₂-dependent mechanisms (Rahn and Hohmann, 2009 for review), the possibility remains that cannabinoids in combination with chemotherapy may enhance both anti-tumour actions of chemotherapy and attenuate unwanted iatrogenic side effects (e.g. emesis, neuropathy). Further basic research on cannabinoid anti-cancer properties as well as clinical trials evaluating cannabinoid efficacy in cancer are required before cannabinoid use can be established and accepted as effective adjuncts to cancer therapy.

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References

- Alexander SPH, Mathie A, Peters JA (2009). Guide to Receptors and Channels (GRAC), 4th Edition. *Br J Pharmacol* 158 (Suppl.1): S1–S254.
- Ben-Shabat S, Frider E, Sheskin T, Tamiri T, Rhee MH, Vogel Z *et al.* (1998). An entourage effect: inactive endogenous fatty acid glycerol esters enhance 2-arachidonoyl-glycerol cannabinoid activity. *Eur J Pharmacol* 353: 23–31.
- Bifulco M, Laezza C, Portella G, Vitale M, Orlando P, De Petrocellis L *et al.* (2001). Control by the endogenous cannabinoid system of ras oncogene-dependent tumor growth. *FASEB J* 15: 2745–2747.
- Bifulco M, Malfitano AM, Pisanti S, Laezza C (2008). Endocannabinoids in endocrine and related tumours. *Endocr Relat Cancer* 15: 391–408.
- Bíró T, Tóth BI, Haskó G, Paus R, Pacher P (2009). The endocannabinoid system of the skin in health and disease: novel perspectives and therapeutic opportunities. *Trends Pharmacol Sci* 30: 411–420.
- Bisogno T, Katayama K, Melck D, Ueda N, De Petrocellis L, Yamamoto S *et al.* (1998). 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* 254: 634–642.
- Blazquez C, Casanova ML, Planas A, Gomez Del Pulgar T, Villanueva C, Fernandez-Acenero MJ *et al.* (2003). Inhibition of tumor angiogenesis by cannabinoids. *FASEB J* 17: 529–531.
- Bovée JV, Hogendoorn PC, Wunder JS, Alman BA (2010). Cartilage tumours and bone development: molecular pathology and possible therapeutic targets. *Nat Rev Cancer* 10: 481–488.
- Bray F, Lortet-Tieulent J, Ferlay J, Forman D, Auvinen A (2010). Prostate cancer incidence and mortality trends in 37 European countries: an overview. *Eur J Cancer* 46: 3040–3052.
- Brown I, Cascio MG, Wahle KW, Smoum R, Mechoulam R, Ross RA *et al.* (2010). Cannabinoid receptor-dependent and -independent anti-proliferative effects of omega-3 ethanolamides in androgen receptor-positive and -negative prostate cancer cell lines. *Carcinogenesis* 31: 1584–1591.
- Buckley NE, McCoy KL, Mezey E, Bonner T, Zimmer A, Felder CC *et al.* (2000). Immunomodulation by cannabinoids is absent in mice deficient for the cannabinoid CB₂ receptor. *Eur J Pharmacol* 396: 141–149.
- von Bueren AO, Schlumpf M, Lichtensteiger W (2008). Delta(9)-tetrahydrocannabinol inhibits 17beta-estradiol-induced proliferation and fails to activate androgen and estrogen receptors in MCF7 human breast cancer cells. *Anticancer Res* 28: 85–89.
- Burstein S, Salmons R (2008). Acylamido analogs of endocannabinoids selectively inhibit cancer cell proliferation. *Bioorg Med Chem* 16: 9644–9651.
- Caffarel MM, Sarrió D, Palacios J, Guzmán M, Sánchez C (2006). Delta9-tetrahydrocannabinol inhibits cell cycle progression in human breast cancer cells through Cdc2 regulation. *Cancer Res* 66: 6615–6621.
- Caffarel MM, Moreno-Bueno G, Cerutti C, Palacios J, Guzman M, Mechta-Grigoriou F *et al.* (2008). JunD is involved in the antiproliferative effect of Delta9-tetrahydrocannabinol on human breast cancer cells. *Oncogene* 27: 5033–5044.
- Caffarel MM, Andradás C, Mira E, Pérez-Gómez E, Cerutti C, Moreno-Bueno G *et al.* (2010). Cannabinoids reduce ErbB2-driven breast cancer progression through Akt inhibition. *Mol Cancer* 9: 196–206.
- Carchman RA, Harris LS, Munson AE (1976). The inhibition of DNA synthesis by cannabinoids. *Cancer Res* 36: 95–100.

- Chung SC, Hammarsten P, Josefsson A, Stattin P, Granfors T, Egevad L *et al.* (2009). A high cannabinoid CB(1) receptor immunoreactivity is associated with disease severity and outcome in prostate cancer. *Eur J Cancer* 45: 174–182.
- Curto-Reyes V, Llamas S, Hidalgo A, Menéndez L, Baamonde A (2010). Spinal and peripheral analgesic effects of the CB2 cannabinoid receptor agonist AM1241 in two models of bone cancer-induced pain. *Br J Pharmacol* 160: 561–573.
- Czifra G, Varga A, Nyeste K, Marincák R, Tóth BI, Kovács I *et al.* (2009). Increased expressions of cannabinoid receptor-1 and transient receptor potential vanilloid-1 in human prostate carcinoma. *J Cancer Res Clin Oncol* 135: 507–514.
- Davis MP (2008). Oral nabilone capsules in the treatment of chemotherapy-induced nausea and vomiting and pain. *Expert Opin Investig Drugs* 17: 85–95.
- De Petrocellis L, Melck D, Palmisano A, Bisogno T, Laezza C, Bifulco M *et al.* (1998). The endogenous cannabinoid anandamide inhibits human breast cancer cell proliferation. *Proc Natl Acad Sci USA* 95: 8375–8380.
- De Petrocellis L, Bisogno T, Ligresti A, Bifulco M, Melck D, Di Marzo V (2002). Effect on cancer cell proliferation of palmitoylethanolamide, a fatty acid amide interacting with both the cannabinoid and vanilloid signalling systems. *Fundam Clin Pharmacol* 16: 297–302.
- Di Marzo V (2006). Endocannabinoids: synthesis and degradation. *Rev Physiol Biochem Pharmacol* 160: 1–24.
- Di Marzo V (2008). Targeting the endocannabinoid system: to enhance or reduce? *Nat Rev Drug Discov* 7: 438–455.
- Di Marzo V, Melck D, Orlando P, Bisogno T, Zagoory O, Bifulco M *et al.* (2001). Palmitoylethanolamide inhibits the expression of fatty acid amide hydrolase and enhances the anti-proliferative effect of anandamide in human breast cancer cells. *Biochem J* 358: 249–255.
- Djulgovic M, Beyth RJ, Neuberger MM, Stoffs TL, Vieweg J, Djulgovic B *et al.* (2010). Screening for prostate cancer: systematic review and meta-analysis of randomised controlled trials. *BMJ* 341: 4543–4551.
- Doré-Savard L, Otis V, Belleville K, Lemire M, Archambault M, Tremblay L *et al.* (2010). Behavioral, medical imaging and histopathological features of a new rat model of bone cancer pain. *Plos One* 5: 13774–13788.
- Endsley MP, Aggarwal N, Isbell MA, Wheelock CE, Hammock BD, Falck JR *et al.* (2007). Diverse roles of 2-arachidonoylglycerol in invasion of prostate carcinoma cells: Location, hydrolysis and 12-lipoxygenase metabolism. *Int J Cancer* 121: 984–991.
- Endsley MP, Thill R, Choudhry I, Williams CL, Kajdacsy-Balla A, Campbell WB *et al.* (2008). Expression and function of fatty acid amide hydrolase in prostate cancer. *Int J Cancer* 123: 1318–1326.
- Ferlay J, Shin HR, Bray F, Forman D, Mathers C, Parkin DM (2010). Estimates of worldwide burden of cancer in 2008: GLOBOCAN 2008. *Int J Cancer* 127: 2893–2917.
- Fontanini G (2000). Angiogenesis and cancer. *Surg Technol Int* 9: 25–32.
- Ford LA, Roelofs AJ, Anavi-Goffer S, Mowat L, Simpson DG, Irving AJ *et al.* (2010). A role for L-alpha-lysophosphatidylinositol and GPR55 in the modulation of migration, orientation and polarization of human breast cancer cells. *Br J Pharmacol* 160: 762–771.
- Furuse S, Kawamata T, Yamamoto J, Niiyama Y, Omote K, Watanabe M *et al.* (2009). Reduction of bone cancer pain by activation of spinal cannabinoid receptor 1 and its expression in the superficial dorsal horn of the spinal cord in a murine model of bone cancer pain. *Anesthesiology* 111: 173–186.
- Glass AG, Lacey JV Jr, Carreon JD, Hoover RN (2007). Breast cancer incidence, 1980–2006: combined roles of menopausal hormone therapy, screening mammography, and estrogen receptor status. *J Natl Cancer Inst* 99: 1152–1161.
- Gómez del Pulgar T, Velasco G, Guzmán M (2000). The CB1 cannabinoid receptor is coupled to the activation of protein kinase B/Akt. *Biochem J* 347: 369–373.
- Grimaldi C, Pisanti S, Laezza C, Malfitano AM, Santoro A, Vitale M *et al.* (2006). Anandamide inhibits adhesion and migration of breast cancer cells. *Exp Cell Res* 312: 363–373.
- Guindon J, Hohmann AG (2009). The endocannabinoid system and pain. *CNS Neurol Disord Drug Targets* 8: 403–421.
- Guise TA, Brufsky A, Coleman RE (2010). Understanding and optimizing bone health in breast cancer. *Curr Med Res Opin* 26: 3–20.
- Guzmán M (2003). Cannabinoids: potential anticancer agents. *Nat Rev Cancer* 3: 745–755.
- Hald A, Ding M, Egerod K, Hansen RR, Konradsen D, Jørgensen SG *et al.* (2008). Differential effects of repeated low dose treatment with the cannabinoid agonist WIN 55,212-2 in experimental models of bone cancer pain and neuropathic pain. *Pharmacol Biochem Behav* 91: 38–46.
- Hamamoto DT, Giridharagopalan S, Simone DA (2007). Acute and chronic administration of the cannabinoid receptor agonist CP 55,940 attenuates tumor-evoked hyperalgesia. *Eur J Pharmacol* 558: 73–87.
- Hancox RJ, Poulton R, Ely M, Welch D, Taylor DR, McLachlan CR *et al.* (2010). Effects of cannabis on lung function: a population-based cohort study. *Eur Respir J* 35: 42–47.
- Heron M, Hoyert DL, Murphy SL, Xu J, Kochanek KD, Tejada-Vera B (2009). Deaths: final data for 2006. *National Vital Statistics Reports* 57: 1–135.
- Jhaveri MD, Richardson D, Chapman V (2007). Endocannabinoid metabolism and uptake: novel targets for neuropathic and inflammatory pain. *Br J Pharmacol* 152: 624–632.
- Jimenez-Andrade JM, Bloom AP, Stake JI, Mantyh WG, Taylor RN, Freeman KT *et al.* (2010a). Pathological sprouting of adult nociceptors in chronic prostate cancer-induced bone pain. *J Neurosci* 30: 14649–14656.
- Jimenez-Andrade JM, Mantyh WG, Bloom AP, Ferng AS, Geffre CP, Mantyh PW (2010b). Bone cancer pain. *Ann N Y Acad Sci* 1198: 173–181.
- Jochimsen PR, Lawton RL, VerSteeg K, Noyes R (1978). Effect of benzopyranoperidine, a delta-9-THC congener, on pain. *Clin Pharmacol Ther* 24: 223–227.
- Johnson JR, Burnell-Nugent M, Lossignol D, Ganae-Motan ED, Potts R, Fallon MT (2010). Multicenter, double-blind, randomized, placebo-controlled, parallel-group study of the efficacy, safety, and tolerability of THC:CBD extract and THC extract in patients with intractable cancer-related pain. *J Pain Symptom Manage* 39: 167–179.
- Khasabova IA, Khasabov SG, Harding-Rose C, Coicou LG, Seybold BA, Lindberg AE *et al.* (2008). A decrease in anandamide signaling contributes to the maintenance of cutaneous mechanical hyperalgesia in a model of bone cancer pain. *J Neurosci* 28: 11141–11152.

- Kogan NM (2005). Cannabinoids and Cancer. *Mini Rev Med Chem* 5: 941–952.
- Laezza C, Pisanti S, Malfitano AM, Bifulco M (2008). The anandamide analog, Met-F-AEA, controls human breast cancer cell migration via the RHOA/RHO kinase signaling pathway. *Endocr Relat Cancer* 15: 965–974.
- Laezza C, Malfitano AM, Proto MC, Esposito I, Gazzero P, Formisano P *et al.* (2010). Inhibition of 3-hydroxy-3-methylglutaryl-coenzyme A reductase activity and of Ras farnesylation mediate antitumor effects of anandamide in human breast cancer cells. *Endocr Relat Cancer* 17: 495–503.
- Ledent C, Valverde O, Cossu G, Petitet F, Aubert JF, Beslot F *et al.* (1999). Unresponsiveness to cannabinoids and reduced addictive effects of opiate in CB1 receptor knockout mice. *Science* 283: 401–404.
- Ligresti A, Moriello AS, Starowicz K, Matias I, Pisanti S, De Petrocellis L *et al.* (2006). Antitumor activity of plant cannabinoids with emphasis on the effect of cannabidiol on human breast carcinoma. *J Pharmacol Exp Ther* 318: 1375–1387.
- Lozano-Ondoua AN, Wright C, Vardanyan A, King T, Largent-Milnes TM, Nelson M *et al.* (2010). A cannabinoid 2 receptor agonist attenuates bone cancer-induced pain and bone loss. *Life Sci* 86: 646–653.
- McAllister SD, Christian RT, Horowitz MP, Garcia A, Desprez PY (2007). Cannabidiol as a novel inhibitor of Id-1 gene expression in aggressive breast cancer cells. *Mol Cancer Ther* 6: 2921–2927.
- McAllister SD, Murase R, Christian RT, Lau D, Zielinski AJ, Allison J *et al.* (2010). Pathways mediating the effects of cannabidiol on the reduction of breast cancer cell proliferation, invasion, and metastasis. *Breast Cancer Res Treat* DOI: 10.1007/S10549-010-1177-4. PMID: 20859676.
- McKallip RJ, Nagarkatti M, Nagarkatti PS (2005). Delta-9-tetrahydrocannabinol enhances breast cancer growth and metastasis by suppression of the antitumor immune response. *J Immunol* 174: 3281–3289.
- Maccarrone M, Lorenzon T, Bari M, Melino G, Finazzi-Agro A (2000). Anandamide induces apoptosis in human cells via vanilloid receptors. Evidence for a protective role of cannabinoid receptors. *J Biol Chem* 275: 31938–31945.
- Madigan MP, Ziegler RG, Benichou J, Byrne C, Hoover RN (1995). Proportion of breast cancer cases in the United States explained by well-established risk factors. *J Natl Cancer Inst* 87: 1681–1685.
- Matsuda LA, Lolait SJ, Brownstein MJ, Young AC, Bonner TI (1990). Structure of a cannabinoid receptor and functional expression of the cloned cDNA. *Nature* 346: 561–564.
- Melch D, Rueda D, Galve-Roperh I, De Petrocellis L, Guzmán M, Di Marzo V (1999). 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* 463: 235–240.
- Melch D, De Petrocellis L, Orlando P, Bisogno T, Laezza C, Bifulco M *et al.* (2000). Suppression of nerve growth factor Trk receptors and prolactin receptors by endocannabinoids leads to inhibition of human breast and prostate cancer cell proliferation. *Endocrinology* 141: 118–126.
- Mercadante S (1997). Malignant bone pain: pathophysiology and treatment. *Pain* 69: 1–18.
- Mimeault M, Pommery N, Watzet N, Bailly C, Hénichart JP (2003). 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* 56: 1–12.
- Movsesyan VA, Stoica BA, Yakovlev AG, Knoblach SM, Lea PM 4th, Cernak I *et al.* (2004). Anandamide-induced cell death in primary neuronal cultures: role of calpain and caspase pathways. *Cell Death Differ* 11: 1121–1132.
- Munro S, Thomas KL, Abu-Shaar M (1993). Molecular characterization of a peripheral receptor for cannabinoids. *Nature* 365: 61–65.
- Munson AE, Harris LS, Friedman MA, Dewey WL, Carchman RA (1975). Antineoplastic activity of cannabinoids. *J Natl Cancer Inst* 55: 597–602.
- Navari RM (2009). Antiemetic control: toward a new standard of care for ematogenic chemotherapy. *Expert Opin Pharmacother* 10: 629–644.
- Nithipatikom K, Endsley MP, Isbell MA, Falck JR, Iwamoto Y, Hillard CJ *et al.* (2004). 2-arachidonoylglycerol: a novel inhibitor of androgen-independent prostate cancer cell invasion. *Cancer Res* 64: 8826–8830.
- Nithipatikom K, Endsley MP, Isbell MA, Wheelock CE, Hammock BD, Campbell WB (2005). A new class of inhibitors of 2-arachidonoylglycerol hydrolysis and invasion of prostate cancer cells. *Biochem Biophys Res Commun* 332: 1028–1033.
- Noyes R, Brunk SF, Baram DA, Canter A (1975a). Analgesic effect of delta-9-tetrahydrocannabinol. *J Clin Pharmacol* 15: 139–143.
- Noyes R, Brunk SF, Avery DA, Canter AC (1975b). The analgesic properties of delta-9-tetrahydrocannabinol and codeine. *Clin Pharmacol Ther* 18: 84–89.
- Olea-Herrero N, Vara D, Malagarie-Cazenave S, Díaz-Laviada I (2009a). Inhibition of human tumour prostate PC-3 cell growth by cannabinoids R(+)-Methanandamide and JWH-015: involvement of CB2. *Br J Cancer* 101: 940–950.
- Olea-Herrero N, Vara D, Malagarie-Cazenave S, Díaz-Laviada I (2009b). The cannabinoid R+ methanandamide induces IL-6 secretion by prostate cancer PC3 cells. *J Immunotoxicol* 6: 249–256.
- Pacher P, Mechoulam R (2011). Is lipid signaling through cannabinoid 2 receptors part of a protective system? *Prog Lipid Res* 50: 193–211.
- Pacher P, Batkai S, Kunos G (2006). The endocannabinoid system as an emerging target of pharmacotherapy. *Pharmacol Rev* 58: 389–462.
- Pantel K, Alix-Panabières C (2010). Circulating tumour cells in cancer patients: challenges and perspectives. *Trends Mol Med* 16: 398–406.
- Parker LA, Rock E, Limebeer C (2011). Regulation of nausea and vomiting by cannabinoids. *Br J Pharmacol* 163: 1411–1422.
- Parkin D, Bray F, Devesa S (2001). Cancer burden in the year 2000. The global picture. *Eur J Cancer* 37: S4–S66.
- Piñero R, Maffucci T, Falasca M (2011). The putative cannabinoid receptor GPR55 defines a novel autocrine loop in cancer cell proliferation. *Oncogene* 30: 142–152.
- Piomelli D (2005). The endocannabinoid system: a drug discovery perspective. *Curr Opin Investig Drugs* 6: 672–679.
- Portenoy RK, Payne D, Jacobsen P (1999). Breakthrough pain: characteristics and impact in patients with cancer pain. *Pain* 81: 129–134.
- Potenzieri C, Harding-Rose C, Simone DA (2008). The cannabinoid receptor agonist, WIN 55, 212-2, attenuates tumor-evoked hyperalgesia through peripheral mechanisms. *Brain Res* 1215: 69–75.

- Qamri Z, Preet A, Nasser MW, Bass CE, Leone G, Barsky SH *et al.* (2009). Synthetic cannabinoid receptor agonists inhibit tumor growth and metastasis of breast cancer. *Mol Cancer Ther* 8: 3117–3129.
- Rahn EJ, Hohmann AG (2009). Cannabinoids as pharmacotherapies for neuropathic pain: from the bench to the bedside. *Neurotherapeutics* 6: 713–737.
- Ribatti D, Crivellato E (2010). Mast cells, angiogenesis and tumour growth. *Biochim Biophys Acta* DOI: 10.1016/j.bbadi.2010.11.010. PMID: 21130163.
- Ruh MF, Taylor JA, Howlett AC, Welshons WV (1997). Failure of cannabinoid compounds to stimulate estrogen receptors. *Biochem Pharmacol* 53: 35–41.
- Ruiz L, Miguel A, Díaz-Laviada I (1999). Delta9-tetrahydrocannabinol induces apoptosis in human prostate PC-3 cells via a receptor-independent mechanism. *FEBS Lett* 458: 400–404.
- Ruiz-Llorente L, Ortega-Gutiérrez S, Viso A, Sánchez MG, Sánchez AM, Fernández C *et al.* (2004). Characterization of an anandamide degradation system in prostate epithelial PC-3 cells: synthesis of new transporter inhibitors as tools for this study. *Br J Pharmacol* 141: 457–467.
- Sánchez MG, Ruiz-Llorente L, Sánchez AM, Díaz-Laviada I (2003a). Activation of phosphoinositide 3-kinase/PKB pathway by CB(1) and CB(2) cannabinoid receptors expressed in prostate PC-3 cells. Involvement in Raf-1 stimulation and NGF induction. *Cell Signal* 15: 851–859.
- Sánchez MG, Sánchez AM, Ruiz-Llorente L, Díaz-Laviada I (2003b). Enhancement of androgen receptor expression induced by (R)-methanandamide in prostate LNCaP cells. *FEBS Lett* 555: 561–566.
- Sarfaraz S, Afaq F, Adhami VM, Mukhtar H (2005). Cannabinoid receptor as a novel target for the treatment of prostate cancer. *Cancer Res* 65: 1635–1641.
- Sarfaraz S, Afaq F, Adhami VM, Malik A, Mukhtar H (2006). 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* 281: 39480–39491.
- Sarfaraz S, Adhami VM, Syed DN, Afaq F, Mukhtar H (2008). Cannabinoids for cancer treatment: progress and promise. *Cancer Res* 68: 339–342.
- Sarnataro D, Grimaldi C, Pisanti S, Gazzero P, Laezza C, Zurzolo C *et al.* (2005). 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* 579: 6343–6349.
- Sarnataro D, Pisanti S, Santoro A, Gazzero P, Malfitano AM, Laezza C *et al.* (2006). The cannabinoid CB1 receptor antagonist rimonabant (SR141716) inhibits human breast cancer cell proliferation through a lipid raft-mediated mechanism. *Mol Pharmacol* 70: 1298–1306.
- Schroder FH, Hugosson J, Roobol MJ, Tammela TL, Ciatto S, Nelen V *et al.* (2009). Screening and prostate-cancer mortality in a randomized European study. *N Engl J Med* 360: 1320–1328.
- Staquet M, Gantt C, Machin D (1978). Effect of a nitrogen analog of tetrahydrocannabinol on cancer pain. *Clin Pharmacol Ther* 23: 397–401.
- Takeda S, Yamaori S, Motoya E, Matsunaga T, Kimura T, Yamamoto I *et al.* (2008). Delta(9)-Tetrahydrocannabinol enhances MCF-7 cell proliferation via cannabinoid receptor-independent signaling. *Toxicology* 245: 141–146.
- Takeda S, Yamamoto I, Watanabe K (2009). Modulation of Delta9-tetrahydrocannabinol-induced MCF-7 breast cancer cell growth by cyclooxygenase and aromatase. *Toxicology* 259: 25–32.
- Tan WC, Lo C, Jong A, Xing L, Fitzgerald MJ, Vollmer WM *et al.* (2009). Marijuana and chronic obstructive lung disease: a population-based study. *CMAJ* 180: 814–820.
- Tashkin DP (2005). Smoked marijuana as a cause of lung injury. *Monaldi Arch Chest Dis* 63: 93–100.
- Thors L, Bergh A, Persson E, Hammarsten P, Stattin P, Egevad L *et al.* (2010). Fatty acid amide hydrolase in prostate cancer: association with disease severity and outcome, CB1 receptor expression and regulation by IL-4. *Plos One* 5: 12275–12286.
- Velasco L, Ruiz L, Sánchez MG, Díaz-Laviada I (2001). Delta(9)-Tetrahydrocannabinol increases nerve growth factor production by prostate PC-3 cells. Involvement of CB1 cannabinoid receptor and Raf-1. *Eur J Biochem* 268: 531–535.
- Velasco G, Carracedo A, Blázquez C, Lorente M, Aguado T, Haro A *et al.* (2007). Cannabinoids and gliomas. *Mol Neurobiol* 36: 60–67.
- Wang J, Ueda N (2009). Biology of the endocannabinoid synthesis system. *Prostaglandins Other Lipid Mediat* 89: 112–119.
- Wang J, Zhao LY, Uyama T, Tsuboi K, Wu XX, Kakehi Y *et al.* (2008). Expression and secretion of N-acyl ethanolamine-hydrolysing acid amidase in human prostate cancer cells. *J Biochem* 144: 685–690.
- Watanabe K, Motoya E, Matsuzawa N, Funahashi T, Kimura T, Matsunaga T *et al.* (2005). Marijuana extracts possess the effects like the endocrine disrupting chemicals. *Toxicology* 206: 471–478.
- Zimmer A, Zimmer AM, Hohmann AG, Herkenham M, Bonner TI (1999). Increased mortality, hypoactivity, and hypoalgesia in cannabinoid CB1 receptor knockout mice. *Proc Natl Acad Sci USA* 96: 5780–5785.