Molecular pathways mediating the anti-inflammatory effects of calcitriol: implications for prostate cancer chemoprevention and treatment

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Abstract

Calcitriol, the hormonally active form of vitamin D, exerts multiple anti-proliferative and pro-differentiating actions including cell cycle arrest and induction of apoptosis in many malignant cells, and the hormone is currently being evaluated in clinical trials as an anti-cancer agent. Recent research reveals that calcitriol also exhibits multiple anti-inflammatory effects. First, calcitriol inhibits the synthesis and biological actions of pro-inflammatory prostaglandins (PGs) by three mechanisms: i) suppression of the expression of cyclooxygenase-2, the enzyme that synthesizes PGs; ii) up-regulation of the expression of 15-hydroxyprostaglandin dehydrogenase, the enzyme that inactivates PGs; and iii) down-regulation of the expression of PG receptors that are essential for PG signaling. The combination of calcitriol and nonsteroidal anti-inflammatory drugs results in a synergistic inhibition of the growth of prostate cancer (PCa) cells and offers a potential therapeutic strategy for PCa. Second, calcitriol increases the expression of mitogen-activated protein kinase phosphatase 5 in prostate cells resulting in the subsequent inhibition of p38 stress kinase signaling and the attenuation of the production of pro-inflammatory cytokines. Third, calcitriol also exerts anti-inflammatory activity in PCa through the inhibition of nuclear factor-κB signaling that results in potent anti-inflammatory and anti-angiogenic effects. Other important direct effects of calcitriol as well as the consequences of its anti-inflammatory effects include the inhibition of tumor angiogenesis, invasion, and metastasis. We hypothesize that these anti-inflammatory actions, in addition to the other known anti-cancer effects of calcitriol, play an important role in its potential use as a therapeutic agent for PCa. Calcitriol or its analogs may have utility as chemopreventive agents and should be evaluated in clinical trials in PCa patients with early or precancerous disease.

Introduction

Prostate cancer (PCa) is the most commonly diagnosed malignancy in men after skin cancer and is a leading cause of cancer death in men in the United States (Jemal et al. 2008). Surgery and radiation are common initial treatment options for localized PCa. If disease recurs, it is often treated with androgen deprivation therapy (ADT). However, many patients eventually fail ADT and develop androgen-independent PCa (AIPC), more recently described as castrate-resistant PCa (CRPC). CRPC ultimately progresses to metastasis and may be lethal. This stage of PCa is not amenable to current therapy. A major goal of current research is the identification of new agents that would prevent and/or delay the development of CRPC or slow its progression.

Calcitriol (1,25-dihydroxyvitamin D3), 1,25(OH)2D3, the biologically most active metabolite of vitamin D, acts as a classical steroid hormone and regulates calcium homeostasis and bone metabolism through actions mediated by the vitamin D receptor (VDR) in intestine, bone, kidney, and the parathyroid glands (Feldman et al. 2007). However, calcitriol also exerts anti-proliferative and pro-differentiating effects in a number of malignant
cells and retards tumor growth in animal models of cancer raising the possibility of its use as an anti-cancer agent. Calcitriol has been shown to inhibit the development and progression of PCAs (Krishnan et al. 2003, Stewart & Weigel 2004, Beer & Myrthue 2006, Gombart et al. 2006, Deeb et al. 2007, Fleet 2008). U.V. light is essential for the synthesis of vitamin D in the skin, and epidemiological studies suggest that mortality rates due to PCAs in the US are inversely related to sunlight exposure (Hanchette & Schwartz 1992, Schwartz & Skinner 2007). Many studies suggest that vitamin D deficiency, characterized by low circulating 25-hydroxyvitamin D levels, is associated with increased PCa risk (Ahonen et al. 2000, Giovannucci et al. 2007, Stewart & Weigel 2004, Beer & Myrthue 2006, Deeb et al. 2007, Fleet 2008), although all studies do not support such a correlation (Platz et al. 2004, Ahn et al. 2008).

Inflammation and PCa

Chronic inflammation has been recognized as a risk factor for the development of many cancers (Allavena et al. 2008, Mantovani et al. 2008). Inflammation can be triggered by a variety of stimuli such as injury, infection, exposure to toxins, autoimmune disease, the development of benign or malignant tumors, or other stresses and pathologies (Fig. 1). Cancer-related inflammation is characterized by the presence in tumor tissue of inflammatory cells and the overexpression of inflammatory mediators such as cytokines, chemokines, prostaglandins (PGs), and reactive oxygen and nitrogen species (Coussens & Werb 2002, Balkwill 2004, Lucia & Torkko 2004, Mantovani et al. 2008; Fig. 1). Many of these pro-inflammatory mediators activate angiogenic switches usually under the control of vascular endothelial growth factor (VEGF) and thereby promote tumor angiogenesis, metastasis, and invasion (Angelo & Kurzrock 2007, Kundu & Surh 2008).

Nonsteroidal anti-inflammatory drugs (NSAIDs) have been shown to reduce inflammation and prevent PCa development in a rat model of prostate carcinogenesis (Narayanan et al. 2009). The use of NSAIDs such as aspirin has also been shown to lower serum prostate-specific antigen (PSA) levels in men with latent PCa (Singer et al. 2008, Fowke et al. 2009). In PCa patients, a strong association between the levels of serum C-reactive protein (CRP), a nonspecific marker of inflammation, and serum PSA has been reported (Lehrer et al. 2005). Recent studies also show that an elevated plasma CRP level is a strong predictor of poor prognosis in patients with metastatic AIPC (McArdrle et al. 2006, Beer et al. 2008). These observations suggest that inflammation might be a fundamental process in PCa. Several studies support a link between inflammation and the development of PCa (De Marzo et al. 1999, 2007, Nelson et al. 2003, 2004). De Marzo et al. (2004) postulate that exposure to infectious agents, hormonal alterations, and dietary carcinogens could cause injury to the prostate epithelium leading to inflammation and the formation of lesions referred to as proliferative inflammatory atrophy (PIA), which are the precursors of prostatic intraepithelial neoplasia (PIN). PIN lesions are characterized by abnormalities that are intermediate between normal prostatic epithelium and cancer, while progression to high grade PIN is the most likely precursor of prostate carcinoma (Montironi et al. 2004). The epithelial cells in PIA lesions have been shown to exhibit many molecular signs of stress including elevated expression of cyclooxygenase-2 (COX-2), the enzyme catalyzing the synthesis of PGs (De Marzo et al. 1999, Zha et al. 2001, Wang et al. 2007). Thus, mediators of inflammation appear to be involved in triggering the process of prostate carcinogenesis (Fig. 1).

Molecular mechanisms of calcitriol actions

Many molecular pathways mediate the anti-cancer effects of calcitriol in PCa cells (Deeb et al. 2007). Calcitriol inhibits the proliferation of PCa cells through cell cycle arrest in the G1/C0 phase (Krishnan et al. 2003, Yang & Burnstein 2003, Stewart & Weigel 2004) by increasing the expression of the

Figure 1 Inflammation and PCa. Inflammation can be triggered by a variety of stresses and stimuli such as infection, injury, exposure to toxins, autoimmune disease, and changes in hormonal status. Cancer-related inflammation is characterized by the presence of inflammatory cells at the tumor sites and the overexpression of inflammatory mediators such as prostaglandins, cytokines, chemokines, reactive oxygen species (ROS), and nitric oxide (NO) in tumor tissue. These pro-inflammatory mediators promote malignant transformation and cancer progression as well as angiogenesis, invasion, and metastasis. PIA, proliferative inflammatory atrophy; PIN, prostatic intraepithelial neoplasia; PCa, prostate cancer.
cyclin-dependent kinase (CDK) inhibitors p21Waf1/Cip1 and p27Kip1 (Liu et al. 1996, Blutt et al. 1997, Campbell et al. 1999, Yang & Burnstein 2003), decreasing CDK2 activity (Yang & Burnstein 2003), and causing the hypophosphorylation of the retinoblastoma protein (Jensen et al. 2001). Calcitriol-induced G0 arrest appears to be p53-dependent (Stewart & Weigel 2004). In several PCa cell lines including the androgen-independent C4-2 cells, calcitriol reduces the expression of cellular mlyoecytomatosi oncogene (c-MYC), a transcription factor known to promote G0/G1 to S-phase transition, by down-regulating c-MYC mRNA levels and decreasing the stability of the c-MYC protein (Rohan & Weigel 2009). Calcitriol also induces apoptosis in some PCa cells and suppresses the expression of anti-apoptotic genes such as BCL-2 (Blutt et al. 2000). Calcitriol stimulates differentiation and modulates growth factor actions including up-regulation of the expression of insulin-like growth factor binding protein-3 (IGFBP-3) in PCa cells, which in turn increases the expression of p21 causing cell cycle arrest (Boyle et al. 2001, Peng et al. 2004). Other mechanisms include the inhibition of invasion and metastasis (Sung & Feldman 2000, Krishnan et al. 2003, Stewart & Weigel 2004). Recent research, including observations from our laboratory, suggests that calcitriol also exerts anti-inflammatory actions that may contribute to its beneficial effects in several cancers in addition to its other known anti-proliferative actions (Krishnan et al. 2007a,b). In the following sections, we will discuss the role of the anti-inflammatory actions of calcitriol and its potential chemopreventive and therapeutic utility in PCa.

**Anti-inflammatory actions of calcitriol**

Studies that employed cDNA microarrays to examine changes in gene expression in cancer cells treated with calcitriol or its analogs identified many novel calcitriol target genes, some of which could be important molecular mediators of its potent anti-inflammatory effects (Krishnan et al. 2004, Pfehl et al. 2004, Kriebitzsch et al. 2009). Calcitriol regulates the expression of several genes involved in PG metabolism and signaling, thereby reducing the levels and biological activity of PGs (Moreno et al. 2005). PGs are pro-inflammatory molecules that promote tumorigenesis and cancer growth (Badawi 2000, Hussain et al. 2003, Zha et al. 2004). Calcitriol up-regulates the expression of mitogen-activated protein kinase phosphatase-5 (MKP5; also known as dual specificity phosphatase-10 (DUSP10)) and thereby promotes downstream anti-inflammatory effects including a reduction in the level of expression of pro-inflammatory cytokines (Nonn et al. 2006). Recent research also indicates that calcitriol interferes with the activation and signaling of nuclear factor-κ B (NFκB), a transcription factor that regulates the expression of numerous genes involved in inflammatory and immune responses and cellular proliferation (McCarty 2004). NFκB is thought to play a key role in the process leading from inflammation to carcinogenesis (Maeda & Omata 2008). In addition, calcitriol also exhibits important anti-angiogenic effects as detailed below. In the following sections, we will discuss the importance of these molecular pathways of inflammation in the development and progression of PCa and the therapeutic significance of the inhibition of these of pro-inflammatory signals by calcitriol.

**Regulation of PG metabolism and signaling**

PGs have been shown to play a role in the development and progression of many cancers, and COX-2, the enzyme that regulates PG synthesis, is an important molecular target in cancer therapy (Badawi 2000, Hussain et al. 2003, Wang et al. 2005). PGs promote carcinogenesis by multiple mechanisms such as stimulating cellular proliferation, inhibiting apoptosis, promoting angiogenesis, and activating carcinogens (Dubois et al. 1998, Hawk et al. 2002). Calcitriol has been shown to regulate the expression of several key genes involved in the PG pathway causing a decrease in PG synthesis, an increase in PG catabolism, and the inhibition of PG signaling through their receptors in normal and malignant prostate cells (Moreno et al. 2005; Fig. 2).

**Cyclooxygenase-2**

COX/PG endoperoxidase synthase is the rate-limiting enzyme that catalyzes the conversion of arachidonic acid to PGs and related eicosanoids. COX exists as two isoforms, COX-1, which is constitutively expressed in many tissues and cell types, and COX-2, which is inducible by a variety of stimuli. COX-2 is regarded as an immediate-early response gene whose expression is rapidly induced by mitogens, cytokines, tumor promoters, and growth factors (Hussain et al. 2003). Evidence suggests that single nucleotide polymorphisms in the COX-2 gene may affect PCa risk (Cheng et al. 2007). Genetic and clinical studies indicate that increased COX-2 expression is one of the key steps in carcinogenesis (Markowitz 2007). Several studies suggest a causative and/or stimulatory role for COX-2 in prostate tumorigenesis and demonstrate its overexpression in prostate adenocarcinoma (Gupta et al. 2000, Yoshimura et al. 2000). However, not all
expression is found in the carcinoma cells as well as infiltrating macrophages within the tumors (Bamba et al. 1999, Chapple et al. 2000). In other cancers, COX-2 expression has been demonstrated in vascular endothelial cells, fibroblasts, and smooth muscle cells around the cancer (Goluboff et al. 1999, Mifflin et al. 2002). Immunohistochemical analyses of COX-2 expression in prostate epithelium in tissue specimens from patients with PCa and benign prostatic hyperplasia (BPH) revealed high T-lymphocyte and macrophage densities in COX-2-positive areas raising the likelihood that pro-inflammatory cytokines released by these cells up-regulate COX-2 expression in the adjacent tumor cells (Wang et al. 2004, 2005). PGs generated by COX-2 act in an autocrine and paracrine manner to stimulate cell growth. At the cellular level, both arachidonic acid, the substrate for COX, and the product prostaglandin E2 (PGE2) stimulate proliferation by regulating the expression of genes that are involved in growth regulation including c-fos (Chen & Hughes-Fulford 2000). Studies in experimental models of cancer have shown that COX-2 enhances tumor development and progression by promoting resistance to apoptosis and stimulating angiogenesis and tumor invasion, and it is therefore regarded as an oncogene (Zha et al. 2004, Kundu & Surh 2008).

15-Hydroxyprostaglandin dehydrogenase

15-Hydroxyprostaglandin dehydrogenase (15-PGDH) is the enzyme that catalyzes the conversion of PGs to their corresponding 15-keto derivatives, which exhibit greatly reduced biological activity. Therefore, 15-PGDH can be regarded as a physiological antagonist of COX-2. 15-PGDH has been described as an oncogene antagonist and plays a tumor-suppressive role in colon cancer (Yan et al. 2004, Myung et al. 2006). 15-PGDH is universally expressed in normal colon but is routinely absent or severely reduced in cancer specimens. Importantly, the stable transfection of a 15-PGDH expression vector into colon cancer cells greatly reduces the ability of the cells to form tumors and/or slows tumor growth in nude mice demonstrating that 15-PGDH functions as a tumor suppressor (Yan et al. 2004). 15-PGDH also acts as a tumor suppressor in breast cancer (Wolf et al. 2006).

PG receptors

Prostaglandin E (PGE) and prostaglandin F (PGF) are the major PGs stimulating the proliferation of PCa cells and they act by binding to G-protein-coupled membrane receptors (prostanoid receptors). There are eight members in the prostanoid receptor subfamily,
which are distinguished by their ligand-binding profile and the signal transduction pathways that they activate, accounting for some of the diverse and often opposing effects of PGs (Breyer et al. 2001). PGE acts through four different receptor sub-types (EP1–EP4), while PGF acts through the FP receptor. PCa cells express both EP and FP receptors (Chen & Hughes-Fulford 2000, Moreno et al. 2005). PG receptors are also expressed in most endothelial cells, macrophages, and stromal cells found in the tumor microenvironment. PG interaction with its receptors can send a positive feedback signal to increase COX-2 expression at the tumor sites not only in the cancer cells themselves, but also in the surrounding stromal cells and infiltrating macrophages as well as endothelial cells thereby promoting tumor progression.

**Calcitriol effects on the PG pathway in prostate cells**
As depicted in Fig. 2, calcitriol regulates the expression of several PG pathway genes in multiple PCa cell lines as well as cultured primary prostate epithelial cells established from surgically removed prostate tissue from PCa patients (Moreno et al. 2005). The levels of COX-2 mRNA and protein are significantly decreased by calcitriol treatment of these cells (Moreno et al. 2005). Calcitriol increases 15-PGDH mRNA and protein expression in various PCa cells (Moreno et al. 2005). Calcitriol has also been shown to regulate COX-2 and 15-PGDH expression in other cells such as rat macrophages and human neonatal monocytes (Pichaud et al. 1997, Aparna et al. 2008). By inhibiting COX-2 and stimulating 15-PGDH expression in PCa cells, calcitriol decreases the levels of biologically active PGs, thereby reducing the growth stimulation due to PGs. Further calcitriol also decreases the expression of EP and FP PG receptor mRNA in PCa cells (Moreno et al. 2005). The calcitriol-induced decrease in PG receptor expression results in the attenuation of PG-mediated functional responses even when exogenous PGs are added to the cell cultures. Calcitriol suppresses the induction of the immediate-early gene c-fos and the growth stimulation seen following the addition of exogenous PGs or the PG precursor arachidonic acid to PCa cell cultures (Moreno et al. 2005). The down-regulation of PG receptors by calcitriol would inhibit the positive feedback exerted by PGs on COX-2, thereby limiting the wave of COX-2 expression at the tumor sites and slowing the rate of tumor progression. Thus, calcitriol inhibits the PG pathway in PCa cells by three separate mechanisms: decreasing COX-2 expression, increasing 15-PGDH expression, and reducing PG receptor levels (Fig. 2). We postulate that these actions contribute to the suppression of the proliferative and angiogenic stimuli provided by PGs in PCa. The regulation of PG metabolism and biological actions constitutes an important anti-inflammatory pathway of calcitriol action.

Calcitriol analogs are being developed to find a therapeutic substitute that would have increased anti-cancer efficacy and decreased side effects of hypercalcemia (Masuda & Jones 2006). A recent study reports that the calcitriol analog elocalcitol also exhibits anti-inflammatory effects on human BPH cells (Penna et al. 2009). The analog causes significant decreases in COX-2 mRNA levels and PGE2 synthesis resulting in the suppression of cytokine-stimulated production of the pro-inflammatory chemokine interleukin-8 (IL-8), which is involved in BPH pathogenesis (Penna et al. 2009). Another study shows that a different calcitriol analog 1α,25-dihydroxy-16-ene-23-yne-vitamin D3 exhibits anti-inflammatory effects causing a reduction in the expression of inflammatory markers such as COX-2, inducible nitric oxide synthase, and IL-2 in experimental models of inflammation (Aparna et al. 2008). Interestingly, this study demonstrates that calcitriol and 1α, 25-dihydroxy-16-ene-23-yne-vitamin D3 also directly inhibit COX-2 enzymatic activity (Aparna et al. 2008).

**Combination of calcitriol and NSAIDs as a therapeutic approach in PCa**
NSAIDs are a class of drugs that decrease PG synthesis by inhibiting COX-1 and COX-2 enzymatic activities. Several NSAIDs nonselectively inhibit both the constitutively expressed COX-1 and the inducible COX-2, while others have been shown to be more selective in preferentially inhibiting COX-2 enzymatic activity. Based on our studies in PCa cells (Moreno et al. 2005), we hypothesized that the action of calcitriol at the genomic level to reduce COX-2 expression, leading to decreased COX-2 protein levels, would allow the use of lower concentrations of NSAIDs to inhibit COX-2 enzyme activity (Fig. 2). Further, an increase in the expression of 15-PGDH and a decrease in PG receptor levels due to calcitriol actions would lower the concentrations and biological activity of PGs thereby enhancing the NSAID effect (Fig. 2). Therefore, we hypothesized that the combination of calcitriol and NSAIDs would exhibit an
Combinations of calcitriol with the COX-2-selective NSAIDs, NS398 and SC-58125, and the nonselective NSAIDs, naproxen and ibuprofen, caused a synergistic enhancement of the inhibition of PCa cell proliferation, compared to the individual agents (Moreno et al. 2005). These results led us to further hypothesize that the combination of calcitriol and NSAIDs may have clinical utility in PCa therapy (Moreno et al. 2005). As discussed below (see the section on Clinical studies), we have conducted a small clinical trial examining the effects of a combination of high-dose calcitriol and the nonselective NSAID naproxen in PCa patients with far advanced disease, and the results suggest a beneficial effect of the combination to slow the course of disease progression.

**Induction of MKP5 and inhibition of stress-activated kinase signaling**

Data from cDNA microarray studies in normal human prostate epithelial cells (Peehl et al. 2004) revealed another novel calcitriol-responsive gene, MKP5, also known as DUSP10. MKP5 is a member of the dual specificity MKP family of enzymes that dephosphorylate, and thereby inactivate, mitogen-activated protein kinases (MAPKs). MKP5 specifically dephosphorylates p38 MAPK and the stress-activated protein kinase Jun-N-terminal kinase (JNK), leading to their inactivation (Fig. 3). Calcitriol up-regulates MKP5 expression leading to downstream anti-inflammatory effects in cells derived from normal prostatic epithelium and primary, localized adenocarcinoma, supporting a role for calcitriol in the prevention and/or early treatment of PCa (Nonn et al. 2006). In primary cultures of normal prostatic epithelial cells from the peripheral zone, calcitriol increases MKP5 transcription. A putative positive vitamin D response element in the MKP5 promoter mediates the stimulation of MKP5 transcription by calcitriol. Interestingly, calcitriol up-regulation of MKP5 is seen in primary cells derived from normal prostatic epithelium and primary, localized adenocarcinoma, but not in the established PCa cell lines derived from PCa metastasis. Calcitriol inhibits the phosphorylation and activation of p38 in normal primary prostate cells in a MKP5-dependent manner as MKP5 siRNA completely abolished p38 inactivation by calcitriol (Nonn et al. 2006). A consequence of p38 stress-induced kinase activation is an increase in the production of pro-inflammatory cytokines that sustain and amplify the inflammatory response (Park et al. 2003). IL-6 is a p38-regulated pro-inflammatory cytokine implicated in PCa progression (Culig et al. 2005). Stimulation of primary prostate cells with the pro-inflammatory molecule tumor necrosis factor α (TNFα) increases IL-6 mRNA stability and concentrations of IL-6 in the conditioned media. Pre-treatment of the cells with calcitriol significantly attenuates the increase in IL-6 production following TNFα treatment, adding inhibition of IL-6 production to the spectrum of calcitriol-mediated actions (Nonn et al. 2006).

IL-6 is a major pro-inflammatory cytokine that participates in inflammation-associated carcinogenesis (Rose-John & Schooltink 2007) and has been implicated in the pathogenesis of several cancers (Schneider et al. 2000, Culig et al. 2005, Kai et al. 2005). Serum IL-6 levels are significantly elevated in PCa patients and in addition a positive correlation between IL-6 levels and the number of bone metastases is also seen (Tumminello et al. 2009). IL-6 is a growth and survival factor in human PCa cells with aggressive phenotypes and has been implicated in the progression of PCa to AIPC (Culig et al. 2005, Wegiel et al. 2008). Calcitriol reduces the production of the pro-inflammatory cytokine IL-6 by inhibiting p38 activation via MKP5 up-regulation as well as by interfering with the signaling of pleiotropic inflammatory cytokines such as TNFα (Nonn et al. 2006; Fig. 3). These observations provide evidence for significant anti-inflammatory effects of calcitriol in prostate cells. Interestingly, established PCa cell lines derived from metastasis such as LNCaP, PC-3, and DU145 exhibit low basal levels of MKP5, and calcitriol is unable to induce MKP5 expression. We therefore speculate that a loss of MKP5 expression might occur during PCa progression, as a result of a selective pressure to eliminate the tumor suppressor activity of MKP5 and/or calcitriol.

![Figure 3 MKP5-mediated inhibition of stress-activated kinase signaling by calcitriol. In prostate cells, calcitriol induces the expression of MKP5, which inhibits the phosphorylation and activation of the p38 stress kinase, resulting in the attenuation of the production of pro-inflammatory cytokines such as IL-6. Adapted from Nonn et al. (2006).](Image)
Inhibition of NFκB activation and signaling

NFκB comprises a family of inducible transcription factors ubiquitously present in all cells that are important regulators of innate immune responses and inflammation (Karin & Lin 2002). In the basal state, most NFκB dimers are bound to specific inhibitory proteins called IκB. Many pro-inflammatory signals activate NFκB mainly through IκB kinase-dependent phosphorylation and degradation of the inhibitory IκB proteins (Maeda & Omata 2008). Free NFκB then translocates to the nucleus and activates the transcription of pro-inflammatory cytokines, chemokines, and anti-apoptotic factors (Ghosh & Karin 2002). In contrast to normal cells, many cancer cells have elevated levels of active NFκB (Sovak et al. 1997, Palayoor et al. 1999), and constitutive activation of NFκB has been observed in AIPC (Gasparian et al. 2002, Ismail et al. 2004, Suh & Rabson 2004). The NFκB protein RelB is uniquely expressed at high levels in PCa with high Gleason scores (Lessard et al. 2005). NFκB plays a major role in the control of immune responses and inflammation and promotes malignant behavior by increasing the transcription of the anti-apoptotic gene BCL-2 (Catz & Johnson 2001), cell cycle progression factors such as c-MYC and cyclin D1, proteolytic enzymes such as matrix metalloproteinase 9 (MMP-9) and urokinase-type plasminogen activator, and angiogenic factors such as VEGF and IL-8 (Huang et al. 2001, Suh & Rabson 2004). IL-8, an angiogenic factor and a downstream target of NFκB, is also a potent chemotactic factor for neutrophils and is associated with the initiation of the inflammatory response (Ferrera et al. 1998).

Calcitriol is known to directly modulate basal and cytokine-induced NFκB activity in many cells including human lymphocytes (Yu et al. 1995), fibroblasts (Harant et al. 1998), and peripheral blood monocytes (Stio et al. 2007). A reduction in the levels of the NFκB-inhibitory protein IκBz has been reported in fibroblasts derived from knockout mice lacking the VDR (Sun et al. 2006). Calcitriol and its analogs block NFκB activation by increasing the expression of IκB in macrophages and peripheral blood mononuclear cells (Cohen-Lahav et al. 2006, 2007, Stio et al. 2007). VDR appears to play an inhibitory role in the regulation of basal NFκB signaling in colon cancer cells, and the VDR antagonist ZK191732 increases NFκB activity by decreasing IκBz (Schwab et al. 2007). Calcitriol and its analogs also inhibit NFκB activation in different types of immune cells (Dong et al. 2003, Giarratana et al. 2004, Penna et al. 2007). There is considerable evidence for the inhibition of NFκB signaling by calcitriol in PCa cells. Calcitriol decreases the levels of the angiogenic and pro-inflammatory cytokine IL-8 in immortalized normal human prostate epithelial cell lines (HPr-1 and RWPE-1) and established PCa cell lines (LNCaP, PC-3, and DU145; Bao et al. 2006a). The suppression of IL-8 by calcitriol appears to be due to the inhibition of NFκB signaling. Calcitriol reduces the nuclear translocation of the NFκB subunit p65 thereby inhibiting the NFκB complex from binding to its DNA response element and consequently suppressing the NFκB stimulation of transcription of downstream targets such as IL-8 (Bao et al. 2006a). Thus, calcitriol could delay the progression of PCa by suppressing the expression of angiogenic and pro-inflammatory genes such as VEGF and IL-8 (Fig. 4). The calcitriol analog elocalcitol inhibits the production of IL-8 by human BPH cells by arresting NFκB p65 nuclear translocation (Penna et al. 2009). NFκB also provides an adaptive response to PCa cells against cytotoxicity induced by redox-active therapeutic agents and is implicated in radiation resistance of cancers (Kimura et al. 1999, Criswell et al. 2003). Calcitriol significantly enhances the sensitivity of PCa cells to irradiation by selectively suppressing radiation-mediated RelB activation (Xu et al. 2007). Thus, calcitriol may serve as an effective agent for sensitizing PCa cells to radiation therapy via suppression of the NFκB pathway.

In addition to the direct inhibition, calcitriol also indirectly inhibits NFκB signaling by up-regulating the expression of other proteins that interfere with NFκB activation such as IGFBP-3 and clusterin (CLU) as discussed below. Calcitriol up-regulates the expression of IGFBP-3 (Boyle et al. 2001, Peng et al. 2004), which has been shown to interfere with NFκB signaling in PCa cells by suppressing p65 NFκB protein levels and the phosphorylation of IκBz (Jogie-Brahim et al. 2009; Fig. 4). Apart from its ability to inhibit NFκB, IGFBP-3 has multiple anti-PCa actions including inhibition of proliferation, stimulation of apoptosis, and a variety of anti-inflammatory effects (Boyle et al. 2001, Ali et al. 2003, Peng et al. 2004, 2008, Jogie-Brahim et al. 2009; Fig. 4). NFκB activity is also modulated by apolipoprotein J or CLU. CLU is a protein expressed in virtually all tissues and is regulated in inflammation, apoptosis, and cancer. Its nuclear form (nCLU) is implicated in apoptosis (Gleave & Chi 2005, Shannon et al. 2006). In human neuroblastoma cells and mouse embryonic fibroblasts, CLU has been shown to strongly inhibit NFκB activity through the stabilization of IκB proteins (Santilli et al. 2003). Calcitriol and its analogs up-regulate CLU expression with an accompanying apoptotic response
in several cells including human BPH cells (Crescioli et al. 2004) and human breast cancer cells (Simboli-Campbell et al. 1997).

**Inhibition of angiogenesis**

Angiogenesis is the process of formation of new blood vessels from existing vasculature and is a crucial step in continued tumor growth, progression, and metastasis (Folkman 1995). VEGF is the most potent stimulator of angiogenesis. PGs, as discussed below, are also important pro-angiogenic factors. The initiation of angiogenesis is controlled by local hypoxia, which induces the synthesis of pro-angiogenic factors that activate signaling pathways leading to the structural reorganization of endothelial cells favoring new capillary formation (Sakamoto et al. 2008). Stimulation of angiogenesis in response to hypoxia is mediated by hypoxia-inducible factor 1 (HIF-1), which directly increases the expression of several pro-angiogenic factors including VEGF (Giacca et al. 2003, Rankin & Giaccia 2008). Early studies indicate that calcitriol is a potent inhibitor of tumor cell-induced angiogenesis in experimental models (Majewski et al. 1996). Calcitriol inhibits VEGF-induced endothelial cell tube formation *in vitro* and decreases tumor vascularization *in vivo* in mice bearing xenografts of breast cancer cells overexpressing VEGF (Mantell et al. 2000). Calcitriol and its analogs also directly inhibit the proliferation of endothelial cells (Bernardi et al. 2002, Furigay & Swamy 2004, Ben-Shoshan et al. 2007, Chung et al. 2009) leading to the inhibition of angiogenesis.

At the molecular level, calcitriol exerts its anti-angiogenic effects by regulating the expression of key factors that control angiogenesis. Calcitriol reduces the expression of VEGF in several malignant cells including PCa cells through transcriptional repression of HIF-1 (Ben-Shoshan et al. 2007). Furthermore, as discussed above, calcitriol inhibits PCa cell-induced angiogenesis by suppressing the expression of the pro-angiogenic factor IL-8 in an NFκB-dependent manner (Bao et al. 2006a). Chung et al. (2009) established transgenic adenocarcinoma of the mouse prostate (TRAMP) -2 tumors in wild-type mice and VDR knockout mice and found enlarged vessels and increased vessel volume in TRAMP tumors in the VDR knockout mice, suggesting an inhibitory role for VDR and calcitriol in tumor angiogenesis. The study further showed increased expression of
pro-angiogenic factors such as HIF-1α, VEGF, angiopoietin-1, and platelet-derived growth factor in the tumors in the VDR knockout mice (Chung et al. 2009).

Interestingly, another important mechanism by which COX-2 promotes tumor progression is through the stimulation of angiogenesis, and COX-2 inhibitors have been used to block angiogenesis and tumor proliferation (Sahin et al. 2009). The pro-angiogenic effect of COX-2-generated PGE$_2$ might be due to its action to increase HIF-1α protein synthesis in cancer cells (Fukuda et al. 2003). In PCa cells, PGE$_2$ mediates hypoxic effects on VEGF by promoting the translocation of HIF-1α protein to the nucleus (Liu et al. 2002). The selective COX-2 inhibitor NS398 has been shown to suppresses the growth of PC-3 xenografts in vivo by a combination of the direct induction of tumor cell apoptosis and the down-regulation of tumor VEGF, leading to the inhibition of angiogenesis as demonstrated by decreased microvessel density of the tumors (Liu et al. 2000). An immunohistochemical analysis of human PCa specimens by Wang et al. (2005) reveals that increased COX-2 immunostaining is associated with an increased infiltration of T-lymphocytes and macrophages and increased CD31-marked microvessel density, indicating a positive correlation between COX-2 expression and inflammation and angiogenesis. The authors postulate that pro-inflammatory cytokines released by tumor-adjacent inflammatory cells such as T-lymphocytes and macrophages may induce COX-2 in the epithelial cells in prostate atrophic lesions promoting tumor progression (Wang et al. 2004). Suppression of COX-2 expression by calcitriol therefore provides an important indirect mechanism by which calcitriol inhibits angiogenesis, in addition to its direct suppressive effects on pro-angiogenic factors such as HIF-1 and VEGF. It has been suggested that VEGF induction of p38 and JNK pathways is necessary for COX-2 expression in endothelial cells (Wu et al. 2006). As discussed above, calcitriol inactivates the p38 pathway by inducing MKP5 expression. Thus, MKP5 induction and VEGF suppression by calcitriol could further contribute to its anti-angiogenic effects through p38 inactivation.

MMPs promote angiogenesis by mediating the degradation of the basement membrane of the vascular epithelium and the extracellular matrix, thereby creating a passageway in these barriers for the formation of new capillaries (Sakamoto et al. 2008). In human PCa cells, calcitriol decreases the expression and activity of MMP-9 while increasing the activity of its counterpart tissue inhibitor of metalloproteinase-1 (TIMP-1), thereby decreasing the invasive potential of these cells (Bao et al. 2006b).

**Inhibition of invasion and metastasis**

Calcitriol reduces the invasive and metastatic potential of many malignant cells including PCa cells. The mechanisms underlying this effect include the inhibition of angiogenesis (discussed above) and regulation of the expression of key molecules involved in invasion and metastasis (Osborne & Hutchinson 2002). Calcitriol decreases the tumor size and lung metastasis of the highly metastatic Mat-lyLu and R 3327-AT-2 Dunning PCa cells in vivo (Getzenberg et al. 1997). Calcitriol inhibits the invasiveness and migration potential of metastatic PCa cells such as DU145 and PC-3, due in part to decreasing the expression of α6 and β4 integrins (Sung & Feldman 2000). In PCa cells, calcitriol and its analogs also increase the expression of E-cadherin, a tumor suppressor gene whose expression is inversely correlated to metastatic potential (Campbell et al. 1997). Calcitriol-mediated suppression of MMP-9 activity and increase in TIMP-1 also decrease the invasive potential of PCa cells (Bao et al. 2006b).

**The role of anti-inflammatory effects of calcitriol in PCa prevention and treatment**

PCa generally progresses very slowly, likely over decades, before symptoms become clinically detectable and a diagnosis is made (Fang et al. 2001, Whittemore et al. 2005, Loeb et al. 2006, Steyerberg et al. 2007). Recently, inflammation in the prostate has been proposed to be an etiological factor in the development of PCa (Nelson et al. 2004, De Marzo et al. 2007). The observed latency in PCa provides a long window of opportunity for intervention by chemopreventive agents. Treatment with COX-2-selective NSAIDs such as celecoxib has been shown to suppress prostate carcinogenesis in the TRAMP model (Gupta et al. 2004). Our studies on the inhibitory effects of calcitriol on COX-2 expression and the PG pathway and MKP5 induction with the resultant stress kinase inactivation and inhibition of pro-inflammatory cytokine production as well as other multiple published observations of calcitriol actions to inhibit NFκB signaling and tumor angiogenesis suggest that calcitriol exhibits significant anti-inflammatory and anti-angiogenic effects in vitro and in vivo (Fig. 4). Therefore, calcitriol has the potential to be useful as a chemopreventive agent in PCa (Chen & Holick 2003, Banach-Petrosky et al. 2006, Krishnan et al. 2007a,b). Foster et al. have demonstrated that administration of high-dose calcitriol (20 μg/kg), intermittently
3 days/week for up to 14–30 weeks, suppresses prostate tumor development in TRAMP mice (Alagbala et al. 2005, 2006). The efficacy of calcitriol as a chemopreventive agent has been examined in Nkx3.1; Pten mutant mice, which recapitulate stages of prostate carcinogenesis from PIN lesions to adenocarcinoma (Banach-Petrosky et al. 2006). The data reveal that calcitriol significantly reduces the progression of PIN from low-grade to high-grade lesions. Calcitriol is more effective when administered before, rather than subsequent to, the initial occurrence of PIN. These animal studies as well as in vitro observations suggest that clinical trials in PCa patients with PIN or early disease evaluating calcitriol and its analogs as agents that prevent and/or delay PCa progression are warranted.

**Clinical studies of calcitriol in PCa**

Several investigators have conducted clinical trials evaluating the use of calcitriol in PCa patients. In an early clinical study in PCa patients who had undergone previous radiation or surgical treatment, a statistically significant decrease in the rate of rise of serum PSA levels was seen following the administration of modest daily doses of calcitriol (Gross et al. 1998), suggesting a beneficial effect of calcitriol in slowing the progression of the disease. Calcitriol is an FDA approved drug (for other indications). The side effects associated with calcitriol use are the development of hypercalcemia and renal stones and possibly increased soft tissue and vascular calcification. Some investigations have followed the approach of administering very high doses of calcitriol intermittently, such as three times a week (Trump et al. 2006) or once weekly (Beer et al. 2003), when it apparently can still elicit anti-proliferative effects but cause only transient hypercalcemia and limited toxicity (Beer et al. 2003, Trump et al. 2006). The use of nutrient vitamin D (cholecalciferol), the biochemical precursor of calcitriol, has also been evaluated in a pilot clinical study, revealing a beneficial effect of prolongation of PSA doubling time (Woo et al. 2005).

Many academic investigators and pharmaceutical companies have undertaken intense research to develop structural analogs of calcitriol, which exhibit increased anti-proliferative activity and reduced tendency to cause hypercalcemia (Ma et al. 2006, Masuda & Jones 2006). A phase II study in PCa patients with advanced hormone-refractory PCa evaluated the calcitriol analog 1α-OH-D2 that had exhibited a reduced calcemic effect but an equal or greater anti-proliferative effect in comparison to calcitriol in preclinical studies (Liu et al. 2003). PSA response was not considered a surrogate marker in this study. Although no objective responses were seen, 30% of the patients experienced stable disease for >6 months, suggesting possible cytostatic activity (Liu et al. 2003). In a phase I/II study of the calcitriol analag 19-nor-1α-25(OH)2D2 (paricalcitol) in patients with AIPC, no PSA or objective responses were seen (Schwartz et al. 2005). However, the data suggested that paricalcitol might be beneficial in the reduction of skeletal morbidity (Schwartz et al. 2005). Administration of the VDR agonist elocalcitol (BXL-628) has been shown to arrest prostate growth in patients with BPH (Maggi et al. 2006).

Calcitriol and its analogs have also been tested in PCa patients and in other cancers in combination with various therapeutic agents. Preclinical (Torrance et al. 2000) and clinical studies (Meyskens et al. 2008) on colon and other cancers have successfully used the strategy of combining low doses of two active drugs to achieve a more effective chemoprevention and therapeutic outcome compared to the individual agents (Sporn & Hong 2008). The combination approach would also minimize the toxicities of the individual drugs by allowing them to be used at lower doses while achieving a significant therapeutic effect. Calcitriol is also being used in combination therapy with other agents that may enhance its anti-proliferative activity while reducing its hypercalcemic tendency (Trump et al. 2006, Beer et al. 2007). Trump et al. (2006) carried out a phase II trial in patients with AIPC using high-dose oral calcitriol (12 µg/day 3 times/week) with dexamethasone (4 mg/day 4 times/week), and the results showed a 50% reduction in PSA in 28% of the patients and no hypercalcemia. Another phase II trial tested the combination of calcitriol, dexamethasone, and carboplatin in patients with hormone-refractory PCa and found a PSA response in 13 out of 34 patients (Flaig et al. 2006).

Studies suggest that the addition of calcitriol to chemotherapy drugs might be beneficial in the management of advanced, hormone-refractory PCa (Berry & Eisenberger 2005, Kantoff 2005). The ASCENT I clinical trial in advanced CRPC patients who had failed other therapies studied the administration of a very high dose (45 µg) of calcitriol (DN101, Novacea, South San Francisco, CA, USA), administered once weekly along with the chemotherapy drug docetaxel (Taxotere, sanofi-aventis, Bridgewater, NJ, USA) at the usual regimen in use at the time of that trial (once weekly) compared to docetaxel alone. The results of the trial appeared to indicate that the combination caused a very significant improvement in overall survival and time to progression, suggesting that calcitriol could enhance...
the efficacy of active drugs in cancer treatment (Beer et al. 2007, 2008). The ASCENT I trial did not meet its primary endpoint, i.e. a lowering of serum PSA. However, based on the promising survival results (16.4 months in the docetaxel arm versus 24.5 months in the docetaxel plus calcitriol arm), a larger phase III trial (ASCENT II) with survival as an endpoint was initiated. A new, improved docetaxel regimen (every 3 week dosing) was used in the control arm of the ASCENT II trial, which was compared to DN101 plus the older docetaxel dose regimen (once a week), resulting in an asymmetric study design. Unfortunately, the improved survival due to the combination demonstrated in the ASCENT I trial could not be confirmed in the ASCENT II trial (Press Release, June 04, 2008, http://novacea.com/). In fact, the trial was prematurely stopped by the data safety monitoring committee after 900 patients were enrolled, when an excess number of deaths were noted in the study arm (DN101 plus old docetaxel regimen) versus the control arm (new docetaxel regimen). This negative result eventually led to the company Novacea ending its DN-101 PCa program.

Another recent study has tested the combination of high-dose calcitriol (DN-101) with mitoxantrone and prednisone in patients with metastatic AIPC without previous chemotherapy, and has concluded that calcitriol did not significantly add to the activity of mitoxantrone and prednisone as assessed by the decline in serum PSA levels (Chan et al. 2008). In a randomized, double-blinded phase II study in a similar patient population, the addition of daily doses of doxercalciferol (1α-hydroxyvitamin D3) to weekly docetaxel did not enhance the PSA response rate or survival (Attia et al. 2008). Interestingly, another study testing the effect of the combination of weekly high-dose calcitriol and docetaxel in PCa patients whose disease progressed after first-line chemotherapy using docetaxel alone showed that high-dose calcitriol restored the sensitivity to chemotherapy with docetaxel (Petrioli et al. 2007).

Preclinical observations in prostate cell cultures (Moreno et al. 2005) suggested that a combination of calcitriol with a NSAID would be a beneficial approach in PCa therapy. The combination strategy would allow the use of lower concentrations of NSAIDs thereby minimizing their undesirable side effects. It has become clear recently that the long-term use of COX-2-selective inhibitors such as rofecoxib (Vioxx) causes an increase in cardiovascular complications in patients (Ray et al. 2002, Antman et al. 2005, Graham et al. 2005, Solomon et al. 2006). Very recently, even the use of nonselective NSAIDs has been shown to increase cardiovascular risk in patients with heart disease (Gislason et al. 2009). However, in comparison to COX-2-selective inhibitors, nonselective NSAIDs such as naproxen may be associated with fewer cardiovascular adverse effects (Bombardier et al. 2000, Gislason et al. 2009). Preclinical data showed that the combinations of calcitriol with nonselective or selective NSAIDs were equally effective in inducing synergistic growth inhibition (Moreno et al. 2005). Based on these data, we have recently carried out a single-arm, open-label phase II study evaluating the combination of the nonselective NSAID naproxen and calcitriol in patients with early recurrent PCa (Srinivas & Feldman 2009). Patients in this study had no evidence of metastases. All of the patients received 45 μg of calcitriol (DN-101) orally once a week and 375 mg naproxen twice a day for 1 year. The trial was prematurely stopped after 21 patients had been enrolled when the FDA put a temporary hold on DN-101 based on the preliminary data from the ASCENT II trial described above. The therapy was well tolerated by most patients in the trial. Serum PSA levels were monitored every 2 months. Bone scans were done every 3 months along with ultrasound of the kidney to assess the possibility of asymptomatic renal stones. One patient developed a small asymptomatic renal stone and was removed from the study. He required no intervention for his renal stone. Only four patients showed evidence of progression and they were removed from the study and offered other therapy. Changes in PSA doubling time (PSA-DT) post intervention were compared to baseline PSA-DT values. A prolongation of the PSA-DT was achieved in 75% of the patients suggesting a potential beneficial effect of the combination therapy (Krishnan et al. 2009, Srinivas & Feldman 2009).

The use of calcitriol or various vitamin D analogs in trials in men with PCs has thus far been disappointing. Based on preclinical data from cell culture and animal models showing substantial benefits, the modest efficacy thus far achieved in patients is underwhelming. The most promising study, ASCENT I, using very high doses of calcitriol intermittently (to avoid complicating side-effects) in combination with docetaxel had very encouraging findings since the data showed improved survival and not just changes in the surrogate marker PSA (Beer et al. 2007). However, the expanded follow-up trial, ASCENT II, not only failed to show any benefit but put a shadow over the use of calcitriol for PCs therapy when it was stopped prematurely because of increased deaths in the calcitriol arm. However, the trial was poorly designed with asymmetric placebo and treatment arms. Since the
The epidemiological studies indicating increased risk of cancer in vitamin D deficiency (Giovannucci 2005, Garland et al. 2006) and the high frequency of vitamin D deficiency in the population (Tangpricha et al. 2002) indicate that at a minimum, vitamin D status should be assessed and deficiency should be vigorously treated with vitamin D supplements in men at high risk for PCa or those that have already been diagnosed with cancer. The available data suggest that the likelihood of vitamin D or calcitriol having a beneficial effect in the prevention of PCa development or in treatment of early disease is better than its effects on advanced disease. Therefore, the detection and correction of vitamin D deficiency in the population at large is worthwhile for this and many other reasons. In the future, improved vitamin D analogs with increased efficacy and decreased tendency to cause hypercalcemia may be the best therapeutic option (Ma et al. 2006, Masuda & Jones 2006). However, in the interim until those drugs are developed and become available, treatment with high doses of dietary vitamin D seems to be a safe and worthwhile approach. The prostate expresses 25-hydroxyvitamin D₃-1α-hydroxylase, the enzyme that can convert circulating 25-hydroxyvitamin D to calcitriol (Schwartz et al. 1998, Hsu et al. 2001, Chen et al. 2003). Thus, dietary vitamin D supplements can lead to local calcitriol production within the prostate where it acts as a paracrine hormone to inhibit prostate growth and perhaps to delay or prevent the progression to cancer (Schwartz et al. 1998, Chen et al. 2003). This seems a worthwhile strategy for a safe and effective approach until new, more potent drugs become available.

Conclusions

Recent research has identified several new calcitriol target genes revealing multiple molecular pathways of calcitriol action in prostate cells (Figs 1–4). The data suggest that calcitriol has several anti-inflammatory actions in addition to its other well-known therapeutic and cancer-preventive effects in PCa. We conclude that calcitriol or its analogs may have the best utility as chemopreventive agents in PCa and/or when used in early disease. Studies in animal models suggest that calcitriol is more effective when administered before, rather than subsequent to, the initial occurrence of PIN. We believe that calcitriol and its analogs should therefore be further evaluated in clinical trials in PCa patients with early or precancerous disease. The avoidance of vitamin D deficiency should be a goal for reducing the incidence of PCa.
Additional trials in men with minimal or early disease, treating with high doses of dietary vitamin D, new potent analogs or, combination therapy may finally demonstrate the promise of benefit of vitamin D in the prevention and treatment of PCa.

Declaration of interest

We declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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