1α-Hydroxylase and the action of vitamin D

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ABSTRACT
The active form of vitamin D, 1,25-dihydroxyvitamin D$_3$ (1,25(OH)$_2$D$_3$), is a pleiotropic hormone whose actions include the regulation of calcium homeostasis, control of bone cell differentiation and modification of immune responses. Synthesis of 1,25(OH)$_2$D$_3$ from the major circulating metabolite, 25-hydroxyvitamin D$_3$ (25(OH)D$_3$), is catalysed by a mitochondrial cytochrome P450 enzyme, 25-hydroxyvitamin D-1α-hydroxylase (1α-OHase). Although 1α-OHase is expressed predominantly in the kidney, extra-renal production of 1,25(OH)$_2$D$_3$ has also been demonstrated in tissues such as lymph nodes and skin. The tight regulation of 1α-OHase which occurs in both renal and peripheral tissues has made studies of the expression and regulation of this enzyme remarkably difficult. However, the recent cloning of mouse, rat and human cDNAs for 1α-OHase (CYP1α/Cyp1α) has enabled a more thorough characterization of this enzyme. In particular, analysis of the CYP1α gene has identified mutations causing the inherited disorder vitamin D-dependent rickets type 1, also known as pseudo-vitamin D deficiency rickets. Studies from our own group have focused on the distribution of 1α-OHase in both renal and extra-renal tissues. Data indicate that the enzyme is expressed throughout the nephron, suggesting discrete endocrine and paracrine/autocrine functions. Further immunohistochemical analyses have shown that the enzyme is widely distributed in extra-renal tissues, and this appears to be due to the same gene product as the kidney. Collectively, these observations have raised important new questions concerning the role of 1α-OHase in vitamin D signalling at a local level. The relationship between expression of protein for 1α-OHase and enzyme activity has yet to be fully characterized and may be dependent on membrane proteins such as megalin. Similarly, elucidation of the mechanisms involved in differential regulation of renal and extra-renal 1,25(OH)$_2$D$_3$ production will be essential to our understanding of the tissue-specific functions of 1α-OHase. These and other issues are discussed in the current review.

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INTRODUCTION
Vitamin D is a secosteroid whose actions are dependent on selective metabolic steps catalysed by cytochrome P450 enzymes. The first of these steps occurs in the liver and involves the enzyme 25-hydroxylase, which catalyses synthesis of 25-hydroxyvitamin D$_3$ (25(OH)D$_3$), the major circulating form of vitamin D. The 25(OH)D$_3$ molecule then acts as the substrate for other hydroxylase enzymes, the most important of these being 25-hydroxyvitamin D$_3$-1α-hydroxylase (1α-hydroxylase, 1α-OHase) and vitamin D$_3$-24-hydroxylase (24-OHase). Although both of these enzymes are strongly expressed in the kidney they have also been detected in a variety of extra-renal tissues. The function of 24-OHase has yet to be fully determined. On the one hand, the enzyme may function as a negative regulatory enzyme by synthesizing relatively inactive vitamin D metabolites such as 1,24,25-trihydroxyvitamin D$_3$ (1,24,25(OH)$_3$D$_3$). Alternatively, recent studies have suggested that, in specific tissues, 24-OHase plays a more active role by generating local concentrations...
of the metabolite 24,25-dihydroxyvitamin D₃ (24,25(OH)₂D₃) (St-Arnaud & Glorieux 1998). The function of 1α-OHase is more specific in that the enzyme catalyses the production of active, hormonal 1,25-dihydroxyvitamin D₃ (1,25(OH)₂D₃) (Henry 1997). Classically, 1,25(OH)₂D₃ plays a pivotal role in maintaining serum calcium homeostasis by modulating calcium/phosphate absorption, and parathyroid hormone (PTH) secretion (Reichel et al. 1989). More recently, 1,25(OH)₂D₃ has also been shown to act as a potent stimulator of cell differentiation, influencing the development of bone and immune cell lineages (Hewison & O’Riordan 1997). The actions of 1,25(OH)₂D₃ are mediated primarily through interaction with the intracellular vitamin D receptor (VDR) (Haussler et al. 1998), although several recent reports have highlighted non-genomic effects of 1,25(OH)₂D₃, particularly in cells such as growth-plate chondrocytes (Sylvia et al. 1998). Much attention has focused on the role of membrane and nuclear receptors as mediators of both classical and non-classical actions of 1,25(OH)₂D₃. However, it is important to recognize that the efficacy of these signalling pathways is largely dependent on the availability of active 1,25(OH)₂D₃ and its subsequent metabolism. In particular, characterization of the expression and regulation of 1α-OHase at both renal and extra-renal sites has provided new insights into the function of 1,25(OH)₂D₃.

The 1α-OHase gene

Studies of the mechanisms involved in regulating 1,25(OH)₂D₃ availability at both a local and a systemic level have been greatly facilitated by the recent cloning of mouse, rat and human cDNA and genomic clones for 1α-OHase (CYP1α or Cyp1α). The first of these was reported by Takeyama et al. (1997), who used a VDR knockout mouse model to isolate a candidate cDNA. The absence of functional VDR in the knockout mouse results in the loss of feedback control of renal 1,25(OH)₂D₃ production, and leads to constitutive over-expression of 1α-OHase. Using this model, a candidate 2.5 kb cDNA was isolated which corresponded to a 507-amino-acid cytochrome P450-like protein, with a predicted size of 55 kDa. The mouse 1α-OHase protein was shown to be homologous to other members of the cytochrome P450 family and, as such, has several key regions of amino acids. The mitochondrial target sequence (amino acids 13–18) showed 41.7% homology with rat 25-hydroxylase (Cyp27) and 31.6% homology with mouse 24-OHase (Cyp24). The sterol-binding domain (amino acids 367–382) was 93% homologous with rat Cyp27 and 60% with mouse Cyp24. However, the region with greatest overall homology was the haem-binding domain (70% with rat, 80% with mouse). Subsequent cloning of a human CYP1α cDNA was achieved using mRNA from a non-classical source of the enzyme. Fu et al. (1997) used cultured human keratinocytes, which have previously been shown to synthesize 1,25(OH)₂D₃ (Pillai et al. 1988). Cloning of a candidate CYP1α cDNA was achieved using PCR degenerate primers corresponding to the haem-binding domains of human CYP24 and CYP27. A full-length cDNA of 2.4 kb was shown to encode a 508-amino-acid protein with a predicted size of 56 kDa. Overall sequence identity to related human cytochrome P450 proteins ranged from 39% (CYP27) to 33% (11β-hydroxylase). Characterization of the CYP1α gene, which spans approximately 6 kb, consists of 9 exons and has approximately 500 bp of 5’ untranslated mRNA, has also highlighted the homology between CYP1α and its CYP27 counterpart (Monkawa et al. 1997). Both of these genes have the same number of exons and also have indential intronic insertions.

In parallel with the original cloning of the human gene, St-Arnaud et al. (1997) isolated the cDNA for rat Cyp1α, which has 82.5% identity to the human cDNA. This report also confirmed the location of the human CYP1α gene on chromosome 12q13-1q13.3, providing further evidence that abnormal CYP1α gene expression is the cause of hereditary pseudovitamin D-deficiency rickets (PDDR). Also known as vitamin D-dependent rickets type 1 (VDDR 1), PDDR is an autosomal recessive disorder characterized by low serum calcium, secondary hyperparathyroidism and low circulating levels of 1,25(OH)₂D₃. The disease locus for PDDR had been mapped previously to 12q13-q14, but the characterization of a specific genetic defect associated with the disorder only became possible following the cloning of the CYP1α gene. The first description of a mutation in the CYP1α gene associated with defective CYP1α activity was carried out using mRNA isolated using cultured keratinocytes from a PDDR patient (Fu et al. 1997). The absence of CYP1α activity in these cells was associated with deletion/frameshift mutations at codons 211 or 231, indicating that the patient was a compound heterozygote for two null mutations. Subsequent to this study, several other reports have been published which have documented families with mutations in the CYP1α gene (Kitanaka et al. 1998, Wang et al. 1998, Yoshida et al. 1998).

Most notable amongst these studies is a report by Mawer and colleagues, who used activated monocytes from PDDR patients to characterize abnormalities in 1,25(OH)₂D₃ production (Smith
et al. 1999). This study identified a further two unrelated families with the 7 bp insertion in exon 8. In particular, the authors noted that synthesis of 1,25(OH)₂D₃ in activated macrophages from PDDR patients was lower than that in controls, and the CYP1α mutations were detectable using cDNA from these cells. These data provide further evidence of a common genetic origin for 1α-OHase activity at both renal and extra-renal sites.

**Renal distribution of 1α-OHase**

The availability of sequence information for CYP1α has also facilitated the development of new molecular tools for further analysis of the expression and regulation of 1,25(OH)₂D₃ synthesis by both renal and non-renal cells. Specifically, we have developed polyclonal antisera to both human and mouse 1α-OHase which have allowed us to document, for the first time, the precise distribution of this enzyme in the kidney and other tissues. Data using normal human kidneys confirmed the expression of mRNA and protein for 1α-OHase in proximal tubules (Zehnder et al. 1999). However, protein and mRNA were also expressed in distal tubules and in collecting ducts. The specificity of 1α-OHase expression in the kidney was emphasized by stringent controls for both the in situ hybridization and the immunohistochemistry analyses. The other key sites of 1α-OHase expression along the nephron were the medullary collecting ducts and papillary epithelium. RT-PCR, Western blots and enzyme-activity studies using primary cell culture confirmed the presence of 1α-OHase in human cortical and medullary renal tissue, with mRNA and protein corresponding to the size of previously reported species for the enzyme.

Although previous studies of the renal function of vitamin D have focused primarily on the production and function of 1,25(OH)₂D₃ in proximal tubules, there is increasing evidence of a role for this hormone in more distal parts of the nephron. In view of studies with vitamin D deficient animals, it seems likely that production of 1,25(OH)₂D₃ in the proximal tubules acts in an endocrine fashion to support circulating levels of 1,25(OH)₂D₃, whereas more distal areas of the nephron fulfil an autocrine or paracrine function. Previous studies have shown that 1,25(OH)₂D₃, as well as calcitonin and PTH, stimulate calcium absorption in the distal nephron (Bouhtiauy et al. 1993, Friedman & Gesek 1993, You et al. 1997, Hoenderop et al. 1999). It is also important to recognize that in some cases the impact of 1,25(OH)₂D₃ on renal function may occur through indirect mechanisms. In particular, the observation that the calcium-sensing receptor is primarily regulated by 1,25(OH)₂D₃, and not PTH or calcium, suggests that this may be the key target for local 1α-OHase activity in the distal nephron (Brown et al. 1996).

**Extra-renal expression of 1α-OHase**

The original description of extra-renal 1α-OHase expression was based on studies of the granulomatous disease sarcoidosis, which frequently presents with associated hypercalcaemia (Papapoulos et al. 1979, Barbour et al. 1981). Enzyme-activity analyses using lymph-node homogenates and pulmonary alveolar macrophages from patients with sarcoidosis showed high levels of 1α-OHase activity (Adams et al. 1983, Adams & Gacad 1985, Reichel et al. 1987). Furthermore, addition of exogenous 1,25(OH)₂D₃ did not appear to inhibit macrophage 1α-OHase as is classically observed with its renal counterpart. This would explain the apparently unregulated synthesis of 1,25(OH)₂D₃ which is characteristic of the more severe forms of this disease, but also suggested that the expression and regulation of 1α-OHase in extra-renal tissues was different from that observed with the kidney enzyme. Prior to the cloning of the 1α-OHase gene it seemed likely that extra-renal production of 1,25(OH)₂D₃ was due to a separate enzyme. However, as illustrated above, it now appears that renal and extra-renal 1α-OHase activity is due to a single gene product. On the basis of these observations, we have used immunohistochemistry and Western analyses with renal 1α-OHase antisera to characterize the extra-renal distribution of the enzyme in human tissues (Zehnder et al. 2000). As would be predicted from previous in vitro studies, 1α-OHase was detectable in tissues such as normal skin (stratum basalis) and sarcoïd lymph nodes. In the latter, staining for 1α-OHase was coincident with expression of the cell-surface antigen CD68, which is a macrophage marker. 1α-OHase was also highly expressed in skin from sarcoïd patients. In this case, the enzyme was observed predominantly in inflammatory infiltrates, with expression in the stratum basalis remaining normal. In contrast, analysis of psoriatic skin indicated that 1α-OHase was expressed in keratinocytes throughout the dysregulated stratum spynosum. This observation is somewhat paradoxical in view of the fact that current therapy for psoriasis includes the use of 1,25(OH)₂D₃ analogues as antiproliferative agents (Bikle 1995). Immunohistochemistry also confirmed previous enzyme-activity studies which indicated that 1α-OHase is expressed in decidual cells (Weisman et al. 1979, Glorieux et al. 1995). However, the enzyme was also detectable in
trophoblasts and syncytiotrophoblasts, suggesting potentially diverse functions for 1α-OHase in placentation and feto–placental calcium homeostasis (Kovacs & Kronenberg 1997). Novel sites for 1α-OHase expression included the parathyroids, pancreas, adrenal medulla, colon and cerebellum, with negative tissues including the heart, liver and adrenal cortex. In all cases, Western blot analyses suggested that expression of 1α-OHase was due to the reported protein species.

The regulation of vitamin D metabolism
The apparent widespread distribution of protein and mRNA for 1α-OHase in both renal and extra-renal tissues has raised important questions concerning the local enzyme activity at these sites. The relationship between expression of 1α-OHase and actual synthesis of 1,25(OH)₂D₃ in a particular tissue probably involves two specific mechanisms, the first of these being substrate access, and the second being auto-regulation of 1α-OHase activity by 1,25(OH)₂D₃ itself. The former questions the assumption that, in common with other steroid hormones, 1,25(OH)₂D₃ enters cells by a passive mechanism by virtue of its lipophilic nature. The latter raises the possibility that local 1α-OHase activity in extra-renal tissues is under even tighter control than that observed with the endocrine enzyme and, thus, local production of 1,25(OH)₂D₃ in vivo may be difficult to detect.
Circulating vitamin D metabolites can bind to a variety of serum proteins, but by far the most important of these is the vitamin D-binding protein (DBP), which is synthesized in the liver. Previous studies in vitro have suggested that DBP-bound vitamin D metabolites have limited access to target cells and, as such, the free forms of vitamin D metabolites, with greater apparent accessibility to target cells, are more biologically active (Bikle & Gee 1989). However, analysis of the DBP null mice indicated that these animals were less susceptible than the wild type to vitamin D-induced hypercalcemia (Safadi et al. 1999). The DBP null mice also developed vitamin D deficiency much earlier than their normal litter-mates. Taken together, these findings suggest that, in addition to its function as a transport protein, DBP may play an active role in directing vitamin D responses. In particular, because of its relatively high capacity for binding 25(OH)D3, DBP is likely to be a key determinant of the availability of substrate to 1α-OHase. Recent studies have shown that DBP and DBP-bound vitamin D metabolites are filtered through the glomerulus and reabsorbed by the luminal endocytic receptor megalin (gp330) in the proximal tubules (Nykjaer et al. 1999). Megalin belongs to the low-density-lipoprotein receptor gene family (Saito et al. 1994) and is expressed in a variety of tissues (Lundgren et al. 1997). The precise physiological role of this receptor has yet to be fully clarified, but, importantly, megalin-null mice have high urinary excretion of 25(OH)D3 and DBP with associated bone disease (Nykjaer et al. 1999). Megalin has also been shown to be located in the brush border membrane of the proximal tubules, whereas cells of the distal nephron appear to be megalin-negative (Lundgren et al. 1997). Thus, megalin-mediated endocytosis of DBP-bound 25(OH)D3 may act as an additional mechanism controlling tissue-specific synthesis of 1,25(OH)2D3 by modulating the availability of substrate to the 1α-OHase protein. This may provide a partial explanation for the discrepancy between widespread 1α-OHase protein expression along the nephron and more discrete patterns of actual enzyme activity in vivo.

Previous studies have shown that, during vitamin D sufficiency, 1,25(OH)2D3 production by the kidneys is very tightly regulated, but there is a striking up-regulation of 1α-OHase activity in proximal tubule cells in vitamin D-deficient states (Brunette 1977, Kawashima et al. 1981). This response appears to be a function of several direct and indirect mechanisms, including changes in accessory proteins such as ferrodoxin, or alterations in VDR or 24-OHase expression. Studies in vivo suggest that the key activator of 1α-OHase is a PTH and that this effect is mediated, at least in part, by target-cell induction of cAMP (Henry & Luntao 1989) (see Figure 1). More recent reports have highlighted potential cAMP response elements in downstream areas (~1·4 kb) which are PTH-responsive in promoter–reporter assays (Brenza et al. 1998, Kong et al. 1999). In both of these studies, the authors were unable to show any self-regulation of basal CYP1α promoter activity, and no vitamin D response elements (VDREs) were identified in the 1·4 kb fragment. However, in each case 1,25(OH)2D3 was able to suppress PTH-induced transactivation. This suggests either that the CYP1α gene promoter has an atypical VDRE, or that 1,25(OH)2D3 achieves its effects by an indirect mechanism. These reports contrast with analysis of the murine promoter, which demonstrated both positive (PTH) and negative (1,25(OH)2D3) responsiveness in a region downstream of ~0·9 kb (Murayama et al. 1998). In this study, calcitonin was shown to be a potent stimulator of 1α-OHase expression, supporting previous reports in which calcitonin was shown to stimulate 1α-OHase mRNA and activity under normocalcaemic conditions (Shinki et al. 1999). This suggests that calcitonin, acting via distal areas of the nephron, may play an important role in the ‘fine-tuning’ of serum 1,25(OH)2D3 levels during vitamin D sufficiency.

Amongst the most prominent inhibitors of 1α-OHase are calcium, phosphate and 1,25(OH)2D3 itself, the latter also stimulating an increase in 24-OHase activity (Murayama et al. 1999). It seems likely that many of these effects are mediated indirectly through modulation of PTH production and secretion. However, as a consequence of the tight regulation of 1,25(OH)2D3 production, analysis of the precise mechanisms involved in controlling 1α-OHase has proved difficult. In recent studies using a transformed human proximal tubule cell line, HKC-8, we confirmed the cAMP-mediated up-regulation of 1α-OHase expression as well as inhibition of expression by 1,25(OH)2D3 (Bland et al. 1999). However, we also noted that the most potent and rapid modulation of 1α-OHase expression and activity occurred following changes in extra-cellular calcium. Relatively high levels of calcium (2 mM versus 1 mM) reduced the synthesis of 1,25(OH)2D3, whereas relatively low levels (0·5 mM versus 1 mM) increased the enzyme activity. These responses occurred within 4 h but were transient, with activities returning to normal at 24 h. These observations, coupled with the widespread expression of calcium-sensing receptors along the nephron, suggest that changes in
local calcium sensing may act as a major determinant of tissue-specific 1,25(OH)₂D₃ production (Figure 1).

Another approach to the in vitro analysis of 1α-OHase has been to use preparations of keratinocytes or activate macrophages as a source of 1α-OHase activity. The main difficulty associated with these model systems is that current evidence suggests that there are substantial differences between the regulation of 1α-OHase in the kidney and that in extra-renal sites. For example, the synthesis of 1,25(OH)₂D₃ by activated macrophages is not inhibited by 1,25(OH)₂D₃, and this appears to be the basis for the unregulated 1α-OHase activity associated with granulomatous diseases such as sarcoidosis, and which frequently leads to hypercalcaemia in these patients (Papapoulos et al. 1979, Barbour et al. 1981, Adams et al. 1983, Adams & Gacad 1985, Reichel et al. 1987). This is difficult to explain, particularly in view of recent studies which suggest that renal and extra-renal 1α-OHase are due to the same gene product. Macrophage-like cells are known to express VDR, and several groups (including ourselves) have demonstrated functional responses to 1,25(OH)₂D₃ in these cells (Hewison & O’Riordan 1997). Therefore, the most likely explanation is that induction of extra-renal 1α-OHase involves regulatory pathways that differ from renal, cAMP-mediated mechanisms and are less sensitive to autoregulation by 1,25(OH)₂D₃. Induction of extra-renal 1α-OHase frequently involves antigenic activators such as lipopolysaccharide or inflammatory mediators such as interferon-γ. Because these agents signal via nuclear factor κB we can postulate that this pathway activates 1α-OHase in a manner unlike that of calcitriotropic factors and, as a consequence, shows differential sensitivity to feedback control by 1,25(OH)₂D₃. Further analysis of the signal-transduction pathways involved in regulating 1α-OHase will be crucial to our understanding of the way in which 1,25(OH)₂D₃ functions in extra-renal tissues (see Figure 1).

Summary

In recent years, our understanding of the molecular endocrinology of vitamin D metabolism has increased dramatically. Mutations in the CYP1α gene have been shown to be associated with rare inherited disorders of 1,25(OH)₂D₃ production; current data suggest that a single gene product is responsible for renal and extra-renal 1α-OHase expression. Analysis of the renal and extra-renal expression of 1α-OHase has provided the first definitive picture of the tissue distribution of 1α-OHase protein. Data indicate that the enzyme is expressed throughout the kidney, suggesting novel roles for local synthesis of 1,25(OH)₂D₃ (particularly in the distal nephron). Extra-renal studies have confirmed the presence of 1α-OHase in tissues such as the skin and lymph nodes but also highlight novel sites such as the pancreas and the colon. Future analysis of the mechanisms involved in the production of 1,25(OH)₂D₃ will provide a clearer picture of the importance of 1α-OHase as a modulator of both renal and extra-renal tissue function.

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