Arterial Calcification in Chronic Kidney Disease: Key Roles for Calcium and Phosphate

Catherine M. Shanahan, Matthew H. Crouthamel, Alexander Kapustin, Cecilia M. Giachelli

Abstract: Vascular calcification contributes to the high risk of cardiovascular mortality in chronic kidney disease (CKD) patients. Dysregulation of calcium (Ca) and phosphate (P) metabolism is common in CKD patients and drives vascular calcification. In this article, we review the physiological regulatory mechanisms for Ca and P homeostasis and the basis for their dysregulation in CKD. In addition, we highlight recent findings indicating that elevated Ca and P have direct effects on vascular smooth muscle cells (VSMCs) that promote vascular calcification, including stimulation of osteogenic/chondrogenic differentiation, vesicle release, apoptosis, loss of inhibitors, and extracellular matrix degradation. These studies suggest a major role for elevated P in promoting osteogenic/chondrogenic differentiation of VSMC, whereas elevated Ca has a predominant role in promoting VSMC apoptosis and vesicle release. Furthermore, the effects of elevated Ca and P are synergistic, providing a major stimulus for vascular calcification in CKD. Unraveling the complex regulatory pathways that mediate the effects of both Ca and P on VSMCs will ultimately provide novel targets and therapies to limit the destructive effects of vascular calcification in CKD patients. (Circ Res. 2011;109:697-711.)

Key Words: calcium ■ chronic kidney disease ■ phosphate ■ vascular calcification

Vascular calcification is a prevalent pathology in aging, atherosclerosis, hypertension, and diabetes, and it correlates with increased vessel stiffening and increased risk of myocardial infarction. Its most devastating manifestation occurs in patients with chronic kidney disease (CKD) who exhibit a hugely elevated risk of cardiovascular mortality compared with age-matched controls. CKD patients have accelerated medial and intimal calcification, and this calcifi-
Calcification rapidly progresses in patients on dialysis. The development of calcification in CKD patients is strongly linked to dysregulated mineral metabolism characterized by long-term elevation of serum phosphate (P) levels as well as transient bouts of hypercalcemia. Importantly, elevated extracellular levels of these minerals have been shown to affect the survival and phenotype of vascular smooth muscle cells (VSMCs), leading to a pattern of cellular adaptations and damage that ultimately promote calcification.

Like developmental skeletal formation, VSMC calcification is a cell-mediated process and over the past 15 years a large number of studies have revealed the key events required for its initiation and promotion (Figure 1). These include loss of inhibitor function, development of a calcifiable extracellular matrix, and induction of apoptosis and vesicle release that are accompanied by osteogenic/chondrogenic differentiation of VSMCs. The key inhibitors of VSMC calcification include the endogenous inhibitors matrix Gla protein (MGP) and pyrophosphate, as well as the inducible inhibitor, osteopontin (OPN). There are also circulating inhibitors such as fetuin-A that are taken-up by damaged VSMCs and utilized to inhibit vesicle calcification. Factors that induce VSMC death by apoptosis accelerate calcification by removing cells capable of inhibition. In addition, the resulting cellular vesicular debris can nucleate mineral to promote calcification. Concomitant with inhibitor loss and cell death, VSMCs also undergo osteogenic/chondrogenic differentiation and produce a number of mineralization-regulating proteins that act to orchestrate the calcification process. Like chondrocytes and osteoblasts, these osteogenic/chondrogenic VSMCs also release calcium (Ca)-enriched membrane-bound bodies.

**Non-standard Abbreviations and Acronyms**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ALP</td>
<td>alkaline phosphatase</td>
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<tr>
<td>BMP-2</td>
<td>bone morphogenetic protein 2</td>
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<td>Ca</td>
<td>calcium</td>
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<td>CaR</td>
<td>calcium sensing receptor</td>
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<td>CCB</td>
<td>calcium channel blocker</td>
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<td>CKD</td>
<td>chronic kidney disease</td>
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<tr>
<td>ECM</td>
<td>extracellular matrix</td>
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<tr>
<td>FGF-23</td>
<td>fibroblast growth factor 23</td>
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<tr>
<td>MGP</td>
<td>matrix Gla protein</td>
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<tr>
<td>MMP</td>
<td>matrix metalloproteinase</td>
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<tr>
<td>NaPi</td>
<td>sodium-dependent phosphate cotransporter</td>
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<td>OPN</td>
<td>osteopontin</td>
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<td>P</td>
<td>phosphate</td>
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<td>Pi</td>
<td>inorganic phosphate</td>
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<td>PTH</td>
<td>parathyroid hormone</td>
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<td>ROS</td>
<td>reactive oxygen species</td>
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<td>VSMC</td>
<td>vascular smooth muscle cells</td>
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Figure 1. Vascular calcification is mediated by vascular smooth muscle cells (VSMCs). Alterations in calcium (Ca) and phosphate (P) levels or vascular insult lead to osteogenic/chondrogenic conversion of VSMCs in the vascular wall. This is associated with dramatic loss of mineralization inhibitors, the production of calcifying matrix vesicles, and extracellular matrix (ECM) degradation. In addition, Ca and P induce VSMC apoptosis and release of apoptotic bodies, which, in turn, form the initial nidus for vascular calcification. (Illustration Credit: Cosmocyte/Ben Smith).
called matrix vesicles that can nucleate hydroxyapatite in the absence of inhibitors and form the first nidus for calcification.

Much work has shown that elevated levels of P and Ca have direct effects on VSMC function and promote calcification. These mineral ions can be taken-up or sensed by VSMCs in a number of different ways and this affects the resultant response of the VSMC to the stimulus. In this review, we discuss studies that have revealed the mechanisms whereby P and Ca alone or together act to promote VSMC dysfunction and calcification in CKD.

**Elevated Serum P, Cardiovascular Disease, and Vascular Calcification in CKD**

Elevated serum P is now recognized as a major risk factor for cardiovascular events in CKD and the general population.\(^5\)--\(^7\) Mortality in end-stage renal disease patients is strongly correlated with serum P levels >5.5 mg/dL.\(^8\)--\(^10\) Also, relatively small elevations in serum P in the high normal range (3.5–4.5 mg/dL) have been correlated with increased risk of cardiovascular and all-cause mortality in CKD patients\(^11\) and the general population with normal renal function.\(^12\) Increased susceptibility of CKD patients to vascular calcification likely underlies this high risk of cardiovascular disease-related deaths in CKD patients.

**Dysregulation of P Homeostasis in CKD**

Phosphorus (mostly in the form of inorganic P (Pi)) is an important component of cellular and systemic homeostasis. It is needed for ATP generation, intracellular signaling, and pH buffering, and it is a prime component of bone, phospholipids, and nucleic acids. In humans, the majority of P (85%) is found in bone, whereas 14% is intracellular and 1% is in extracellular fluid.\(^13\) The western diet is rich in P sources, including meat, fish, dairy products, and additives. Most of the ingested P is absorbed by the gastrointestinal tract via passive enterocyte paracellular pathways or the sodium-dependent P cotransporter (NaPi) IIb.\(^14\) Under normal conditions, 80% to 90% of a filtered P load is reabsorbed in the renal proximal tubule, predominantly via the active NaPi-IIa.\(^15\) Although the kidney is the major regulator of serum P homeostasis under normal conditions, bone also serves as a P reservoir that can contribute to serum P regulation via bone formation and resorption.\(^16\)

Hormonal regulators of P balance have been identified, including parathyroid hormone (PTH), fibroblast growth factor 23 (FGF-23), klotho, and 1, 25-dihydroxyvitamin D. These hormones act mainly by modulating renal reabsorption or intestinal absorption of P.\(^16\) Both PTH and FGF-23 promote renal P wasting by stimulating the internalization and inactivation of the NaPi-IIa transporter, thereby decreasing renal P reabsorption. PTH also promotes bone remodeling, thereby moving P in and out of bone.\(^16\) Klotho is a required cofactor for the actions of FGF-23, but it also promotes phosphaturia independently by inactivating NaPi-IIa.\(^17\) The 1, 25-dihydroxyvitamin D promotes intestinal absorption of P by increasing NaPi-IIb transporters. Normally, these systems act to maintain serum P levels in a normal range of 2.8 to 4.5 mg/dL.\(^18\)

In early CKD, renal insufficiency leads to impaired P excretion and a decline in klotho levels, but serum P levels are maintained in the normal range by upregulation of FGF-23 and PTH.\(^19\)--\(^23\) Unfortunately, these defense mechanisms are overwhelmed as renal function continues to decline. As glomerular filtration rate declines in advanced CKD, inefficient urinary P excretion combined with disordered bone remodeling and continued ingestion of P results in hyperphosphatemia. A summary of factors controlling P homeostasis in CKD is shown in Figure 2.

**How Is P Sensed by VSMCs?**

The primary mechanism by which P enters cells is by NaPi cotransporters. There are three major families of NaPi cotransporters that are distinct based on structure, tissue expression, and biochemical characteristics.\(^22\)--\(^23\) Type I NaPi cotransporters (the SLC17 family) are found in the liver, kidney, and brain. Type II (the SLC34 family) NaPi cotransporters are mainly present in the kidney, intestine, and lung. In contrast, the type III NaPi cotransporters (the SLC20 family), known as PiT-1 and PiT-2, are ubiquitously expressed throughout the body and are the major P transport proteins found in VSMCs.\(^24\)--\(^25\) The level of mRNA expression of PiT-1 and PiT-2 in VSMCs varies between species, as

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**Figure 2. Overview of the factors involved in dysregulated calcium (Ca) and phosphate (P) homeostasis in chronic kidney disease (CKD).** In early CKD, renal insufficiency leads to a decline in klotho levels and impaired P excretion, but serum P levels are maintained in the normal range by upregulation of FGF-23 from bone and parathyroid hormone (PTH) from the parathyroid gland. Declining renal function in CKD leads to 25-dihydroxyvitamin D deficiency attributable to diminished activity of 1-alpha hydroxylase in the kidney as well as in increased serum FGF-23 levels (a direct inhibitor of 1-alpha hydroxylase activity). Low 1, 25-dihydroxyvitamin D levels lead to initial hypocalcemia, which, together with hyperphosphatemia, provide a powerful stimulus for further PTH secretion and lead to the secondary hyperparathyroidism of CKD and increased bone remodeling. Normal defense mechanisms (PTH, FGF-23, and klotho) are overwhelmed as renal function continues to decline. Vitamin D deficiency and secondary hyperparathyroidism are treated with vitamin D receptor agonists (VDRAs) that stimulate Ca and P uptake in the gut, often leading to transient hypercalcemic episodes (denoted by parentheses). Furthermore, Ca-containing P binders are commonly used to treat hyperphosphatemia, further increasing Ca burden in these individuals. Together with disordered bone remodeling, these factors contribute to dysregulated P and Ca metabolism and promote vascular calcification in CKD.
measured by real-time polymerase chain reaction. In human VSMCs, PiT-1 was shown to be the predominant P transporter, with eight-fold higher RNA expression than PiT-2, whereas no expression of type I or type II NaPi cotransporters was detected. However, similar expression levels were found for PiT-1 and PiT-2 in rat VSMCs and mouse VSMCs.

Pi uptake through PiT-1 and PiT-2 occurs in a time- and concentration-dependent manner. The uptake is also dependent on an inwardly facing sodium gradient and follows a 2:1 Na\(^+\)/H\(_2\)PO\(_4\)\(^-\) ratio. Kinetic studies of the PiT transporters have shown an apparent affinity for H\(_2\)PO\(_4\)\(^-\) after Michaelis-Menten kinetics with a \(K_m\) of 25 to 100 \(\mu\)mol/L and saturation below physiological P levels (<1.4 mmol/L) in rat VSMCs. Whereas the physiological roles of PiT-1 or PiT-2 have not been fully elucidated, PiT-1 appears critical for embryonic development. PiT-1 knockout embryos arrest between E11.5 and E13.5 and display severe anemia with abnormal yolk sac vasculature. PiT-1 also appears to be critical for P-induced osteogenic/chondrogenic phenotype change and matrix mineralization in cultured VSMC as described in further detail. Transgenic rats that overexpress PiT-2 have been created. The effects of this overexpression included increased serum P level, decreased bone mass, and progressive proteinuria, whereas cultured osteoblasts had increased ALP activity and P uptake. These transgenic rats died of cachexia at approximately 32 weeks of age, and proteinuria appeared to be attributable to P-dependent podocyte injury induced by overexpression of PiT-1.

No knockout of PiT-2 has yet been reported. Various cell and tissue types in the body are well-known to have compensatory methods to respond to changes in extracellular P concentration. Renal and intestinal cells can increase uptake in low P media or decrease uptake in high P media. However, it is currently unclear how VSMCs sense changes in serum P. Some evidence suggests that PiT-1 or PiT-2 might function as P sensors in addition to transporters. Similar to VSMCs, PiT-1 was identified as the major NaPi cotransporter expressed in the parathyroid. PTH secretion by the parathyroid gland is regulated by extracellular P. PiT-1 is hypothesized to function as the mediator between serum P concentrations and PTH secretion. PiT-2 also has been implicated in P sensing after Salaun et al. found that transport-deficient PiT-2 mutants still had the ability to bind P ions and undergo structural reorganization/oligomerization. Whether other P sensors or receptors exist is currently unknown.

It is also unclear whether uptake of P and a subsequent increase in intracellular P levels is required to initiate VSMC changes in response to elevated extracellular P. In particular, a role for P transport as a key modulator of P-induced vascular calcification was called into question by the studies of Villa-Bellosta et al. in rat VSMCs showing that PiT-1 and PiT-2, high-affinity P transporters, are likely to be saturated under physiological P concentrations. Furthermore, most historical studies have used phosphonoformic acid, a weak inhibitor of type III NaPi cotransporters, to determine the requirement of P transport for VSMC calcification in response to elevated P. The \(K_i\) of phosphonoformic acid for PiT-1 and PiT-2 is in the range of 2.5 to 5 mmol/L. However, we now know that inhibition of VSMC calcification by phosphonoformic acid at these concentrations also can cause physicochemical inhibition of Ca–P crystal formation, confounding interpretation of results. Finally, as mentioned for PiT-2, evidence that PiT-1 can signal independently of P uptake was provided by Beck et al., who showed that a transport-deficient mutant of PiT-1 stimulated cell proliferation in HeLa and HepG2 cells. Whether the requirement for PiT-1 in P-induced VSMC calcification is P uptake-dependent or P uptake-independent remains a critical unanswered question.

### Direct Effects of High P on Pathways Mediating VSMC Calcification

Numerous studies have shown that culturing VSMCs in elevated P conditions leads to matrix calcification. Although other cell types such as pericytes and vessel-derived stem cells may also play a role in vascular calcification, this review focuses on VSMC because most of our understanding of effects of elevated P have come from this cell type. Potential mechanisms that mediate P-induced VSMC matrix calcification include osteogenic/chondrogenic conversion, apoptosis, and matrix remodeling, as shown in Figure 3 and discussed in detail.

### VSMC Osteogenic/Chondrogenic Conversion

P-induced vascular calcification has been hypothesized to be an adaptive VSMC transition from a contractile to an osteogenic/chondrogenic phenotype characterized by calcifying vesicle formation, downregulation of mineralization inhibitory molecules, and elaboration of a calcification prone matrix. In culture, elevated P exposure results in the upregulation of osteogenic/chondrogenic gene expression (Runx2, osterix, alkaline phosphatase [ALP], OPN), and simultaneous downregulation of smooth muscle (SM) lineage gene expression (SM\(_{a}\) actin, SM22\(_{a}\)). Runx2 is a transcription factor important in osteoblastic and chondrocytic differentiation that induces the expression of major bone matrix components including type I collagen, osteocalcin, and OPN. Knockdown of Runx2 in VSMC inhibits osteogenic conversion and matrix mineralization. ALP is absolutely required for normal bone formation and is thought to regulate vascular matrix mineralization by inactivating the mineralization inhibitors, pyrophosphate and P-OPN, and simultaneously liberating free P.

Further, osteogenic/chondrogenic phenotype change induced by elevated P is characterized ultrastructurally by the appearance of matrix vesicles containing apatite and calcifying collagen fibrils on the surface of VSMCs. As in bone, these vesicles most likely act as early nucleation sites for calcification. In addition, hydroxyapatite nanocrystals shed from vesicles may further promote mineralization via direct effects on SM cell (SMC) phenotype. In support of this concept, synthetic hydroxyapatite nanocrystals and isolated high-P-induced nanocrystals induced osteogenic/chondrogenic gene expression in VSMCs.
The receptors and signaling pathways important for P-mediated VSMC osteogenic/chondrogenic phenotype change and calcification are beginning to be unraveled. Our group has demonstrated a role for PiT-1 in human VSMC osteogenic conversion and matrix mineralization. Small hairpin RNA knockdown of PiT-1 suppressed P-induced calcification and blocked induction of osteogenic markers, including Runx2, but did not mediate P loading of matrix vesicles or apoptosis.26 Matrix vesicle loading of P may instead be mediated by PiT-2, because this transporter, and not PiT-1, was localized to vesicle membranes.26 Of interest, it was subsequently shown that small hairpin RNA knockdown of Pit-1 abrogated matrix mineralization in osteoblast cultures,60,61 confirming the idea that Pit-1 is a key mediator of elevated P-induced calcification in mineralizing cell types.

The induction of Runx2 via PiT-1 signaling is believed to be though Erk1/2 activation. Treatment of mouse VSMCs with high P, and subsequent calcification and osteogenic/chondrogenic differentiation, occurred in conjunction with increased phosphorylation of Erk1/2.62 Prevention of Runx2 upregulation by high P was achieved through inhibition of Erk phosphorylation by the mitogen-activated protein kinase inhibitor, U0126. This also stimulated expression of VSMC lineage markers.62

Bone morphogenetic protein 2 (BMP-2) and transglutaminase 2 have also been implicated as downstream mediators of P-induced VSMC calcification. In a study with human VSMCs, addition of noggin, a BMP-2 inhibitor, blocked mineralization attributable to high P media and blocked expression of the osteogenic transcription factor osterix.63 Interestingly, BMP-2 levels are increased in the serum of uremic patients, and culturing bovine VSMCs in uremic serum resulted in increases of Runx2 that was inhibited by noggin.64 Furthermore, mouse VSMCs deficient in transglutaminase 2 showed a blunted response to treatment with 2.5 mmol/L P, showing a lack of upregulation of ALP, PiT-1,
Runx2, and the osteoblastic transcription factor, Msx2. Transglutaminase 2 also has a direct role in stabilization of extracellular matrices by producing protease-resistant isopeptide bonds in substrate proteins such as collagen I, fibronectin, and OPN.

Montes de Oca et al. found that human aortic SMCs and rat aortic rings incubated with high P media (3.3 mmol/L) had increased methylation of the SM22α promoter leading to osteogenic conversion. The increased methylation resulted in reduced expression of SM22α, increased Runx2 expression, and increased ALP activity, which together resulted in an increased level of calcification. Inhibition of DNA methylation by procaine was able to prevent these transcriptional changes when VSMCs were grown in high P media, and this resulted in reduced calcification.

Reactive oxygen species (ROS) produced in response to high P loads have also been implicated as downstream mediators of osteogenic conversion of VSMCs during vascular calcification. In isolated mitochondria, P can regulate the mitochondrial membrane potential, which is important in the production of ROS. Byon et al. demonstrated that oxidative stress in the form of H₂O₂ could increase the expression and activity of the Runx2 transcription factor in mouse VSMCs, leading to conversion to an osteogenic phenotype and increased calcification. Downregulation of Runx2 by small hairpin RNA eliminated the ability of H₂O₂ to cause the phenotypic change. They also determined that the Runx2 response was dependent on phosphatidylinositol 3-kinase/protein kinase B/Runx2 signaling. More recently, Zhao et al. used bovine aortic SMCs to show that ROS production is important in the osteogenic conversion process using β-glycerophosphate exposure as their model. β-glycerophosphate is an organic P donor that leads to elevated P through the action of ALP, and in this study promoted downregulation of SMC lineage markers, an increase in osteogenic markers, and a three-fold increase in ROS production. Inhibition of mitochondrial ROS formation by the superoxide dismutase mimic MnTMPyP or the respiratory chain inhibitors rotenone or carbonyl cyanide m-chlorophenyl hydrazone, an uncoupler of oxidative phosphorylation greatly reduced the level of mitochondrial ROS and significantly decreased Ca deposition compared to treatment with β-glycerophosphate alone. Further, it was determined that mitochondrial ROS uses nuclear factor kappa-B signaling during β-glycerophosphate-mediated calcification. The receptor mediating elevated P-induced ROS was not determined.

In vivo evidence supporting a role for cell death in elevated P-induced vascular calcification include the findings of SMC drop-out in the arterial media of uremic high-P-fed mice concomitant with mineral deposition. Furthermore, calcified vessels from pediatric dialysis patients exhibited extensive SMC apoptosis.

### P Effects on Vascular Matrix Degradation

In vivo, SMCs are surrounded by a complex highly structured extracellular matrix composed of collagen, elastin, fibronectin, heparan sulfate, proteoglycans, and chondroitin sulfate proteoglycans. A consistent feature of the predominant type of arterial medial calcification induced by CKD and hyperphosphatemia in people and animal models is the accumulation of linear mineral deposits along the arterial elastic lamina (elastocalcinosis). It is known that elastin degradation increases the extracellular matrix affinity for Ca, facilitating epitactic growth of hydroxyapatite along the elastic lamellae. Elastin fragments are also able to bind to elastin laminin receptors found on the surface of VSMCs and, through transforming growth factor-β signaling, can increase proliferation and upregulate Runx2, resulting in osteogenic differentiation. This process was seen in rat aortic rings treated with high P and warfarin, which led to an early expression of matrix metalloproteinase (MMP)-9, an elastin-degrading enzyme, closely followed by transforming growth factor-β signaling, with concomitant with mineral deposition. The mineralization process can also be markedly accelerated in human VSMCs when the soluble elastin-derived peptide α-elastin is added to the high (2.5 mmol/L) P media. Interestingly, however, under normal P load, the addition of α-elastin did not result in calcification. Because the α-elastin peptide did not induce VSMC mineralization under normal P conditions, it has been suggested that P-induced VSMC osteogenic differentiation needs to be present before α-elastin can exert procalcification effects.

### Apoptosis-Dependent Matrix Mineralization

Another mechanism whereby elevated P might promote vascular matrix calcification is by stimulating VSMC apoptosis. Downregulation of growth arrest-specific gene 6 may be an important underlying mechanism. During P-induced human aortic VSMC calcification, both growth arrest-specific gene 6 and its receptor Axl expression are reduced. The growth arrest-specific gene 6–Axl survival pathway was previously implicated in osteogenic differentiation of vascular pericytes. Its antiapoptotic effect is achieved through the Bcl2-mediated phosphatidylinositol 3-kinase/protein kinase B pathway; phosphorylation inactivates Bcl2 and activates the proapoptotic protein Bcl-2–associated death promoter, resulting in caspase-3 activation and apoptosis. Again, the receptor mediating this effect of elevated P was not identified.

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vivo, elastin degradation alone in the absence of a P load was insufficient to induce vascular calcification in uremic mice. 

In vivo evidence supporting a role for matrix remodeling in elevated P-induced vascular calcification include studies in uremic high-P-fed mice that observed elastin remodeling and elevated elastase levels including MMP-2, MMP-9, and cathepsin S in calcified arterial medias. Furthermore, cathepsin S was required for arterial calcification in apolipoprotein E−/− mice with chronic renal insufficiency. Finally, a strong correlation between MMP-2 upregulation and elastic fiber disorganization, stiffness, calcification, and vasomotor dysfunction was observed in the arterial vasculature in dialysis patients, and upregulation of arterial MMP-2 and MMP-9 were correlated with arterial stiffening in diabetic CKD patients.

Elevated Ca, Cardiovascular Disease, and Vascular Calcification in CKD

Although much of the epidemiological and experimental evidence to date has focused on the role of elevated serum P as the main trigger of calcification in CKD, evidence also implicates a pivotal role for elevated serum Ca and an elevated Ca×P product in driving calcification. Historically, elevated serum Ca has been associated with increased risk of myocardial infarction, coronary calcification, and plaque thickness in the non-CKD population. More recently, a number of studies have shown an association with elevated serum Ca and calcification in the CKD population. A strong correlation between calcification and an elevated Ca×P product has also been demonstrated and in many of these studies the association between cardiovascular dysfunction or mortality was found with Ca levels in the high normal range. It should be noted that serum Ca is tightly regulated and this may be one reason why Ca has been overlooked as a risk factor driving calcification when compared to P. However, sporadic hypercalcemia is a relatively common occurrence in dialysis patients in response to a number of factors, including dialysate composition, vitamin D therapy, and potentially Ca containing P binders and these sporadic events are often not taken into account or may be missed in routine blood analysis. Overall, these studies suggest that even sporadic elevations of Ca in a high P environment is highly detrimental, and this idea is supported by clinical trials showing that use of non-Ca–based P binders attenuated vascular calcification and, more controversially, mortality and dialysis patients.

Dysregulation of Ca Homeostasis in CKD

Ca (in the diffusible ionized form) is critical for a number of physiological processes, including neuronal signaling, muscle contraction, and blood clotting, in addition to being a major component of bone. In humans, 99% of Ca is found in bone, with the remainder in blood and cells. Serum Ca is normally bound to protein such that the free ionized Ca comprises approximately half of the total Ca. The American diet provides approximately 600 to 1000 mg Ca per day, primarily from dairy sources. Ca is absorbed in the small intestine by both diffusion-driven paracellular processes and active transport mechanisms. Active transport occurs principally in the duodenum via the coordinated action of transient receptor potential vallinoid receptor type 6 channels, calbindin-D, and the Na-Ca exchanger, NCX1, and PMCA1b. In addition, approximately 500 mmol Ca per day normally moves in and out of bone through bone formation and resorptive processes.

The principal mechanisms controlling serum Ca levels are active vitamin D metabolites, PTH, klotho, and calcitonin. The 1, 25-dihydroxyvitamin D increases serum Ca by increasing intestinal Ca absorption, decreasing Ca excretion, and increasing Ca resorption from bone. PTH serves to increase serum Ca levels by promoting 1-α hydroxylase activity in the kidney, thereby increasing the production of active 1,25-dihydroxyvitamin D. Furthermore, PTH decreases renal excretion of Ca and can have variable effects on bone, with Ca resorption increased at high doses and bone formation increased at low doses. Finally, klotho also maintains serum Ca levels by stimulating transient receptor potential vallinoid receptor type 5-mediated Ca resorption activity in renal cells. In contrast, calcitonin lowers serum Ca by decreasing osteoclast-mediated bone resorption. These mechanisms serve to keep Ca levels tightly controlled in a normal range of 9 to 10.5 mg/dL.

Declining renal function in CKD leads to 1, 25-dihydroxyvitamin D deficiency because of diminished activity of 1-α hydroxylase in the kidney as well as increased serum FGF-23 levels (a direct inhibitor of 1-α hydroxylase activity). Low 1, 25-dihydroxyvitamin D levels lead to hypocalcemia that, together with hyperphosphatemia, provide a powerful stimulus for PTH secretion and cause the secondary hyperparathyroidism commonly observed in CKD. Vitamin D deficiency and the secondary hyperparathyroidism of CKD are traditionally treated with activated vitamin D receptor agonists and have been associated with hypercalcemic episodes. Furthermore, Ca-containing P binders are commonly used to treat hyperphosphatemia, further increasing Ca burden in these susceptible individuals. Together with disordered bone remodeling, these factors contribute to dysregulation of Ca homeostasis in CKD. A summary of factors controlling Ca homeostasis and their dysregulation in CKD is shown in Figure 2.

It should be noted, however, that elevated serum Ca is not the only mechanism that can lead to the exposure of VSMCs to high extracellular Ca. Ca is released in the vessel wall at sites of apoptotic or necrotic cell death, and this can lead to huge local elevations in extracellular Ca of up to 30 mmol/L. Nanocrystalline Ca crystals can be taken-up by VSMCs, and this can lead to intracellular Ca overload, as can chronic dysregulated signaling events, and all of these have the capacity to impact on local VSMC Ca homeostasis.

How Is Ca Sensed by VSMCs?

Ca signaling in VSMCs is complex and involves Ca channels, exchangers, and pumps that regulate extracellular Ca entry.
into the cell and maintain Ca concentrations in the cytosol and in the intracellular Ca stores (mainly sarcoplasmic reticulum). Ca uptake and release are also linked to mechanisms of Ca extrusion from the cell and all are tightly bound by fine spatial and temporal coordination and cross-talk.\textsuperscript{112} Ca regulation is also dependent on the VSMC phenotypic state.\textsuperscript{113,114} Differentiated contractile VSMCs express high levels of the voltage-activated L-type Ca channels that mediate extracellular Ca uptake and the sarcoplasmic reticulum intracellular Ca release channel the ryanodine receptor. When VSMCs undergo phenotypic modulation, which coincides with the initiation of osteogenic/chondrogenic differentiation, VSMCs downregulate L-type channel expression and increase expression of the low-voltage–activated T-type channels. The ryanodine receptor is also downregulated and this is compensated for by increased expression of other sarcoplasmic reticulum ion pumps.\textsuperscript{113} Thus changes in both intracellular and extracellular Ca pools are likely to impact dramatically on VSMC function with the impact of the change dependent on the phenotype of the VSMC. In addition to plasma membrane uptake mechanisms, Ca can also be “sensed” by VSMCs via the Ca sensing receptor (CaR).\textsuperscript{115} Although some progress has been made on examining the role of Ca signaling in VSMC calcification, this area is highly complex and still requires much exploration. Therefore, we have limited our discussion in this review to the relatively few aspects of Ca homeostasis that have been implicated or investigated as having a role in VSMC calcification.

**Channel-Mediated Ca Uptake**

Plasma membrane voltage-dependent L-type Ca channels have long been recognized as important for Ca homeostasis in VSMCs. These channels as well as T-type Ca channels can be targeted by drugs known as Ca channel blockers (CCBs) widely used in the treatment of hypertension.\textsuperscript{116,117} In a prospective clinical trial, CCBs were shown to slow the progression of calcification in hypertensive patients with and without renal failure,\textsuperscript{118–121} whereas association studies have shown they can reduce mortality in renal patients.\textsuperscript{122} Pioneering studies by Fleckenstein\textsuperscript{119} showed that in response to vitamin D overload in rats vascular calcification could be prevented by treatment with the CCBs verapamil or nifedipine. Although it was assumed that the mechanism of action was via prevention of Ca uptake in the hypercalcemic environment induced in the rats in response to vitamin D, other direct VSMC effects have not been excluded. For example, CCBs are effective in blocking calcification induced by either gluteraldehyde or warfarin treatments, and these are not associated with hypercalcemia.\textsuperscript{123,124} CCBs can also partially block atherogenesis in animal models and this may be attributable to their known effects on VSMC differentiation, proliferation, and matrix synthesis.\textsuperscript{125,126} Despite the importance of Ca uptake in VSMCs, few studies have investigated CCBs in the context of calcification in vitro. In a recent study, Chen et al\textsuperscript{127} using bovine VSMCs showed that verapamil and not nifedipine could block VSMC calcification, potentially via downregulation of ALP activity. Interestingly, verapamil also blocked mineralization of VSMC-derived matrix vesicles that did not express L-type Ca channels, suggesting that its mode of action was not via L-type Ca channel blockade. The authors speculated that these effects on matrix vesicles may have been via effects on membrane phospholipid composition;\textsuperscript{127} therefore, it remains unclear whether blockade of Ca uptake by VSMCs can directly affect calcification.

**The CaR**

Elevated extracellular Ca also has a direct signaling role in VSMC calcification without any need for uptake.\textsuperscript{128} The CaR is a G-protein-coupled receptor capable of sensing changes in extracellular Ca concentrations in the mmol/L range. The CaR was first identified in the parathyroid, where it regulates Ca homeostasis by suppressing PTH secretion and renal Ca reabsorption. However, it is also widely expressed on tissues that are not involved in the regulation of Ca homeostasis, including VSMC and endothelial cells. In contractile VSMCs within the vessel wall the CaR has been shown to play a physiological role in regulating vascular myogenic tone.\textsuperscript{129} In cultured VSMCs it regulates proliferation\textsuperscript{129,130} and survival with stimulation of the CaR leading to ERK1/2 activation, suggesting the CaR may be important in both contractile and synthetic VSMC phenotypic contexts.\textsuperscript{131}

In calcified arteries from CKD patients, expression of the CaR is downregulated\textsuperscript{131} and studies in vitro have shown that when VSMCs are induced to calcify in response to elevated extracellular Ca, expression of the CaR is also downregulated.\textsuperscript{132} Moreover, ablation of CaR function increased VSMC calcification in response to both Ca and P, whereas calcimimetics, drugs that increase the sensitivity of the CaR to Ca, can ameliorate calcification in the same model.\textsuperscript{132} Although these studies suggest that the CaR is deregulated in CKD, they were unable to identify a mechanism to account for reduced calcification in the presence of a functional CaR. However, a role for the CaR in regulating expression of the key calcification inhibitor MGP previously has been shown.\textsuperscript{133} Increased extracellular Ca can increase MGP transcription, and this transcriptional activation can be mimicked by treatment with CaR agonists. Thus, Ca sensing may be critical for the feedback response of VSMCs to increased extracellular Ca leading to the production of inhibitory proteins. This notion is supported by in vivo studies showing treatment of animals with or without renal failure with calcimimetics increases aortic MGP production.\textsuperscript{134} If calcimimetics have direct effects on VSMC calcification, then these drugs, which are in clinical use for hyperparathyroidism, also may be useful in blocking progression of calcification.

**Regulation of Intracellular Ca in VSMCs**

Because of their contractile properties, VSMCs have large intracellular stores of Ca that must be regulated and buffered to prevent intracellular Ca overload. Intracellular Ca homeostasis can be disrupted by many stimuli, including excess Ca uptake or release from these intracellular stores including the sarcoplasmic reticulum/ER, lysosomes, and mitochondria. The sarcoplasmic reticulum is the main organelle that mediates spark alterations in intracellular Ca levels required for
SM contraction, whereas the mitochondria and lysosomes are involved in longer-term events that also may be crucial for VSMC calcification. Two recent studies have demonstrated that the release of intracellular Ca from lysosomes may act to promote calcification. In the first study, human VSMCs were exposed to Ca–P nanocrystals of varying size. Phagocytotic uptake of the smallest crystals by VSMCs was shown to induce an intracellular Ca burst that resulted in necrotic/apoptotic cell death. This process could be inhibited by treatment with the lysosomal proton pump inhibitor bafilomycin A1, suggesting lysosomal processing of the mineral caused toxic intracellular Ca release.\textsuperscript{110} Importantly, the vascular wall in CKD patients has a very high Ca load and this Ca is deposited in the extracellular matrix surrounding VSMCs as nanocrystals.\textsuperscript{78,135} Thus, at the early stages of mineral nidus formation in the vessel wall, uptake of previously deposited mineral by VSMCs would be predicted to promote cell death. This notion is supported by evidence from an ex vivo model using human vessels treated with Ca/P, where it was shown that VSMCs undergo a wave of rapid apoptosis concomitantly with the formation of the first crystalline nidus of calcification observable by electron microscopy.\textsuperscript{136}

In a second study, Ca/P nanocrystals were found to promote VSMC osteogenic differentiation. This phenotypic change was restricted to upregulation of BMP-2 expression within 24 hours and was not associated with elevated Runx2.\textsuperscript{99} The mechanism that induced osteogenic gene expression remains unknown but may also involve Ca release from intracellular stores. More speculatively, Ca overload has been associated with aging of the vasculature and BMP-2 was recently shown to be increased in senescent VSMCs.\textsuperscript{137} It is plausible that uptake of nanocrystals promotes Ca-induced or P-induced VSMC senescence, which drives further osteogenic differentiation via the BMP-2 pathway.\textsuperscript{138}

ER stress can be induced by deregulated Ca homeostasis, and emerging evidence indicates there may be a role for ER stress in vascular calcification. First, ER stress recently has been implicated as essential for bone development and mineralization because it regulates osteoblast differentiation via Runx2 and collagen I secretion.\textsuperscript{139–141} The ER stress markers Grp78, Grp94, and CHOP were found in homogenates from rat aortas, where medial vascular calcification was induced by vitamin D treatment, which is known to induce intracellular Ca overload in VSMCs. These ER stress markers were associated with increased VSMC apoptosis and signaling via JNK, as well as activation of caspases 3 and 12.\textsuperscript{142} So far, expression of these markers has not been explored in vessels from CKD patients.

Mitochondrial Ca overload is also a prominent feature of many calcified tissues and, interestingly, this was observed in normal arteries after long-term exposure to Ca and P ex vivo.\textsuperscript{136,143,144} This contrasted to the predominant calcification of the extracellular matrix with no sign of mitochondrial damage and Ca overload, which was observed in CKD arteries exposed to the same conditions. One explanation for this is possibly the different mechanisms of adaptation to elevated Ca by contractile and phenotypically modified VSMCs. Massive release of Ca-loaded vesicles by phenotypically modified VSMCs may mitigate intracellular Ca overload and prevent mitochondrial damage. However, further studies are required to fully explore the effects of extracellular Ca on intracellular Ca handling in VSMCs to further our understanding of homeostatic and pathological changes.

**Direct Effects of High Ca That Mediate VSMC Calcification**

Ca Induces VSMC Calcification In Vitro and Ca and P Are Synergistic

In addition to the changes in Ca handling that have been discussed, in vitro evidence also strongly supports a role for Ca in promoting VSMC calcification. Two key studies first demonstrated that Ca alone, when added to human VSMCs, promotes mineralization. Moreover, when Ca and P were added together to the culture medium they were synergistic in inducing mineralization.\textsuperscript{145,146} Further studies using vessel rings ex vivo demonstrated that for a given Ca×P product, elevated Ca was more potent at inducing VSMC calcification than elevated P.\textsuperscript{54,55,136} Importantly, these simple studies corroborated what had been found in human epidemiological studies and highlighted the role elevated levels of Ca have on the calcification process. We have already discussed how deregulated Ca uptake, release, and signaling can impinge on VSMC calcification. In the next section we focus on the precise mechanisms whereby Ca itself can promote mineralization. These mechanisms differ from those of P and primarily implicate Ca as a major nucleator of crystalline hydroxyapatite (Figure 4).

Ca and VSMC Osteogenic Differentiation

Unlike P, which seems to have dramatic effects on promoting the osteogenic differentiation of VSMCs, elevated Ca alone does not seem to mediate this phenotypic transition. Synergism between Ca and P in driving Runx2 expression has been observed in dialysis vessels treated with Ca/P ex vivo; however, the mechanism may not be direct but involve increased PiT-1 expression or ROS production.\textsuperscript{136} Of note, in studies in which calcification was induced in response to Ca alone or Ca/P, calcification proceeds in the absence of elevated ALP activity, suggesting Ca may promote calcification by different mechanisms than P and this is consistent with their synergy.\textsuperscript{136}

Ca and VSMC Apoptosis, Vesicle Release, and Calcification

One of the major mechanisms whereby elevated extracellular Ca drives VSMC calcification is via its capacity to form mineral nucleation sites and participate in the earliest events in the calcification cascade. Treatment of VSMCs in vitro with elevated Ca was found to promote apoptosis with marked synergism of apoptosis induced by combined Ca and P treatment. Apoptotic bodies have been shown to form a nidus for calcification and the propensity of these to calcify was markedly increased after Ca and P treatment.\textsuperscript{146,147} Ca also acted to promote VSMC matrix vesicle release, and calcification with Ca and P is also synergistic in promoting this process.\textsuperscript{146} Using electron microscopy and energy dis-
persive x-ray analysis, Ca was shown to induce matrix vesicles to become what is known as “mineralization competent,” characterized by the presence of preformed crystalline hydroxyapatite mineral. P alone, even at very high concentrations, was unable to do this. The mechanisms whereby elevated Ca promotes vesicle calcification are still unclear; however, Ca can increase expression of the P transporter, Pit-1.145 This is present on the plasma membrane of VSMCs and also matrix vesicles, and increased expression is likely to drive increased mineral accumulation.

However, the major mechanism is more likely related to the ability of Ca to change the intrinsic properties of matrix vesicles.148 In bone, an increase in intracellular Ca promotes matrix vesicle calcification via activating changes in annexin content, phospholipid composition, and MMP activation.149,150 Annexins together with phospholipids can bind Ca and form nucleation complexes for crystalline hydroxyapatite.151 VSMC-derived matrix vesicles are also enriched in annexins,152,153 and a recent study has shown that a similar increase in intracellular Ca in VSMCs, induced by uptake of excess Ca from the extracellular milieu, drives VSMC matrix vesicle calcification via annexin A6 and phosphatidyl serine complex formation.148 Importantly, under normal conditions these Ca-dependent changes in matrix vesicle properties are ameliorated by loading of the vesicles with calcification inhibitors. These include the endogenous inhibitor MGP and the circulating inhibitor fetuin-A, which is taken-up from the serum and loaded into matrix vesicles. The loading of fetuin-A into matrix vesicles is increased in the presence of Ca, and this protein is a major buffer of excess Ca in the cell and in the matrix.146,153,154 Fetuin-A levels are reduced in patients on dialysis and this is likely to promote Ca-dependent calcification mediated by matrix vesicles.155 Similarly, CKD patients have reduced levels of the noncarboxylated form of MGP that is not functional as a calcification inhibitor.156 Importantly, Ca has been shown to upregulate

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**Figure 4. Role of calcium (Ca) in vascular smooth muscle cell (VSMC) calcification.** Ca elevation induces vesicle production and can lead to cell apoptosis and necrosis. High local levels of Ca trigger mineral nucleation in the matrix vesicles and apoptotic bodies. Accumulation of mineralized matrix vesicles and apoptotic bodies, and their uptake accelerate cell death and facilitate further crystal growth. Degradation of extracellular matrix (ECM) and nucleation of Ca apatite induces ECM protein mineralization.
MGP production in a number of studies, potentially as an adaptive response aimed at inhibiting calcification.\textsuperscript{133,157–159} However, constant stimulation may lead to ER stress and act to deregulate carboxylation pathways localized in the ER, leading to the production of unprocessed MGP. In addition to this mechanism of MGP inactivation, a recent study has demonstrated that exposure of VSMCs to elevated Ca eventually depletes MGP from matrix vesicles, further enhancing their calcification capacity. This study also showed that matrix vesicles are loaded with MMP-2 and Ca acts to increase activation of this metalloproteinase, which would further accelerate elastin degradation and calcification.\textsuperscript{148} Studies in vivo and ex vivo have led further support to these in vitro findings. Using vessels obtained from children with CKD or on dialysis, it was shown that Ca load in the vessel wall correlated with time averaged Ca×P.\textsuperscript{78} Moreover, in dialysis, vessels calcification correlated with increased apoptosis and increased vesicle release shown by increased annexin A6 deposition in the vessel wall.\textsuperscript{78} Extending these studies by using vessels from these same children in organ culture experiments, it was shown that control vessels were entirely resistant to the induction of calcification by Ca or P. In contrast, vessels obtained from children on dialysis extensively calcified in response to Ca/P. Again, the predominant mechanism appeared to be increased apoptosis and increased vesicle deposition, leading to extracellular matrix calcification.\textsuperscript{136} In addition, increased depotions of both fetuin-A and uncarboxylated MGP were observed in vessels from dialysis patients, and this deposition was dramatically increased in response to Ca/P treatment ex vivo. EM analysis of the vessels showed large numbers of calcified and noncalcified matrix vesicles deposited in the extracellular matrix, consistent with the induction of vesicular calcification once inhibitors had been exhausted. Further studies are now required to determine the cell biological mechanisms driving vesicle calcification and inhibitor dysfunction in VSMCs in response to Ca.

Conclusions

It is clear that dysregulated Ca and P homeostasis plays a major role in driving VSMC calcification in CKD. In addition to increasing the Ca×P, elevated Ca and P can act directly on VSMC to drive distinct, as well as overlapping, pathways that predispose to calcification (Figure 5). The body of data presented in this review suggests that the maintenance of Ca and P levels in the normal range is the most important aim in CKD patients to minimize the vascular damage induced by dysregulated mineral metabolism. However, there are many other factors associated with the CKD milieu that may also act to drive VSMC calcification. Some of these include advanced glycation end products,\textsuperscript{160} ROS,\textsuperscript{70,161} and potentially vitamin D and PTH,\textsuperscript{162} although the calcific properties of these factors may be dose-dependent and context-dependent. In addition to these factors, there are emerging areas such as the FGF-23/klotho signaling axis that may prove to be significant players in driving calcification. Although these factors are key to regulating Ca and P homeostasis, long-term exposure of VSMCs to elevated levels of FGF-23 or reduced klotho levels may potentially effect calcification. Recent data suggests that klotho may be a direct inhibitor of VSMC calcification acting via effects on P transport.\textsuperscript{163} However, klotho also regulates cellular aging, and vascular calcification is an age-associated pathology with the vasculature of CKD patients often regarded as “prematurely aged.” It will be interesting to determine whether there is an association between dysregulated mineral metabolism and cellular aging given recent data suggesting that aged or senescent VSMCs exhibit a pro-osteogenic phenotype.\textsuperscript{164,165}

In summary, although we have made huge advances in understanding some of the mechanisms that drive VSMC calcification, we still have many more questions than answers, and hopefully these will be addressed in future studies.

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