Regulation of vascular smooth muscle cell calcification by extracellular pyrophosphate homeostasis: synergistic modulation by cyclic AMP and hyperphosphatemia

Domenick A. Prosdocimo, Steven C. Wyler, Andrea M. Romani, W. Charles O’Neill, and George R. Dubyak

1Department of Physiology and Biophysics, School of Medicine, Case Western Reserve University, Cleveland, Ohio; and 2Renal Division, Department of Medicine, Emory University School of Medicine, Atlanta, Georgia

Submitted 16 September 2009; accepted in final form 14 December 2009

Problems of phosphorus capture, capture, and mineralization in the calcification of extracellular PPi generation mediated by calcification was reported to affect the progress of the calcification process. These observations indicate that extracellular PPi generation is associated with the progression of calcification.

The known PPi-generating proteins include ENPP1, which catalyzes the hydrolysis of released ATP to produce PPi, and ENPP1 in a cellular system with a defined function. This gene encodes an extracellular PPi-generating enzyme, and it is a critical determinant of soft-tissue mineralization. We recently described an autocrine mechanism of extracellular PPi, generation in cultured rat aortic vascular smooth muscle cells (VSMC) that involves both ATP release coupled to the ectophosphodiesterase/pyrophosphatase ENPP1 and efflux of intracellular ATP. We now report that increased cAMP signaling and elevated extracellular inorganic phosphate (Pi) act synergistically to induce calcification of these VSMC that are correlated with progressive reduction in ability to accumulate extracellular Pi. Attenuated Pi accumulation was mediated in part by cAMP-dependent increase in ANK expression coordinated with cAMP-dependent increase in expression of TNAP, the tissue nonselective alkaline phosphatase that degrades Pi. Stimulation of cAMP signaling did not alter ATP release or ENPP1 expression, and the cAMP-induced changes in ANK and TNAP expression were not sufficient to induce calcification. Elevated extracellular Pi, alone elicited only minor calcification and no significant changes in ANK, TNAP, or ENPP1. In contrast, combined with a cAMP stimulus, elevated Pi induced decreases in the ATP release pathway(s) that supports ENPP1 activity, this resulted in markedly reduced rates of Pi, accumulation that facilitated robust calcification. Calcified VSMC were characterized by maintained expression of multiple SMC differentiation marker proteins including smooth muscle (SM) α-actin, SM22α, and calponin. Notably, addition of exogenous ATP (or Pi, per se) rescued cAMP + phosphate-treated VSMC cultures from progression to the calcified state. These observations support a model in which extracellular PPi, generation mediated by both ANK- and ATP release-dependent mechanisms serves as a critical regulator of VSMC calcification.

VASCULAR CALCIFICATION is associated with atherosclerosis, type 2 diabetes, end-stage renal disease, and aging (23, 43). It is characterized by increased vessel stiffness and loss of compliance that results in augmented arterial pulse wave velocity and pressure leading to left ventricular hypertrophy (9, 10, 46). Extracellular inorganic pyrophosphate (PPi) is a critical inhibitor of calcification (50), and its importance is highlighted by the pathological condition of generalized arterial calcification of infants (GACI) caused by inactivating mutations in the ectonucleotide pyrophosphatase/phosphodiesterase-1 (ENPP1) gene. This gene encodes an extracellular PPi-generating enzyme, ecto-ATPase (39), and loss of ENPP1 function results in reduced PPi accumulation and increased aortic calcification that can culminate in fatal aortic rupture (21, 39, 40).

Vascular calcification is characterized by the deposition of Ca2+ and inorganic phosphate (Pi) in the form of hydroxyapatite (HA) crystals within the medial or neointimal layers of blood vessels. This can involve induction of osteochondrogenic programs of gene expression in vascular smooth muscle cells (VSMC) (18). Recent studies have demonstrated the importance of extracellular Pi in acting not only as a substrate for HA formation but also an inducer of the gene expression programs that facilitate calcification (7, 8, 24). However, vascular calcification is a multifaceted process that involves not only the gain of inducers of calcification but also the loss of calcification suppressors, such as Pi. Extracellular Pi inhibits vascular calcification by directly disrupting the deposition of HA crystals. This action of Pi requires its regulated accumulation and homeostasis in extracellular compartments. We recently described (38) an autocrine program of extracellular Pi homeostasis in rat aortic VSMC that involves the coordinated functions of three known plasma membrane proteins and a molecularly undefined pathway of autocrine ATP release. The known Pi-generating proteins include ENPP1, which catalyzes the hydrolysis of released ATP to produce Pi, and progressive ankylosis disease susceptibility gene product ANK, an intrinsic plasma membrane protein that directly or indirectly mediates efflux of cytosolic Pi. These parallel ATP release/ENPP1 and ANK pathways account for the accumulation of extracellular Pi, and they are opposed by the alkaline phosphatase subtype tissue nonselective alkaline phosphatase (TNP), an ectopyrophosphatase that clears extracellular Pi.

On the basis of pharmacological experiments, we reported that ATP release/ENPP1 and ANK pathways each account for −50% of the locally generated extracellular Pi, with only a modest counteracting contribution from TNP, in confluent monolayers of early-passage VSMC. This autocrine program allows these VSMC to condition their culture medium with micromolar concentrations of Pi, which is sufficient for the steady-state suppression of matrix mineralization.
Hyperphosphatemia is a major predisposing factor for development of vascular calcification that most commonly occurs in the context of chronic kidney disease (14). However, progression of vascular calcification reflects the convergence of multiple genetic, metabolic, or endocrine perturbations, such as hyperphosphatemia, that separately elicit only minor or no increases in aberrant mineralization. This is highlighted in vivo in knockout mouse models that lack expression of either ENPP1 or ANK in which each genetic deficiency alone predisposes the animal to only mild and slowly developing calcification as a function of aging (21). The rate and severity of calcification are greatly potentiated when these animals are fed a high-phosphate diet. This same high-phosphate diet alone does not induce marked mineralization in wild-type animals. Studies with ex vivo aortic ring models have also indicated that elevated extracellular Pi alone is insufficient to induce mineralization (30). These organ-cultured aortic rings calcify in response to elevated Pi only when subjected to intentional mechanical injury or when supplemented with an excess of exogenous PPi-degrading enzymes. In contrast to whole animal or ex vivo aortic ring models, in vitro cultures of VSMC can display marked calcification with elevated Pi as the only stimulus (33, 44). However, the efficacy and rate of the Pi-induced mineralization in VSMC cultures vary with species of origin, passage number, and clonal selection (24, 27, 28, 35, 48, 49, 52). Moreover, inclusion of cytokines and hormones such as parathyroid hormone, bone morphogenic proteins, VEGF, TNF-α, or vitamin D3 can markedly potentiate this Pi-dependent calcification in vitro (5, 27, 32, 36, 49). These studies clearly demonstrate how various factors synergize with elevated extracellular Pi to induce modulation of VSMC phenotype and consequent calcification. It is equally important to consider the roles these procalcification signals may play in the expression and activity of PPi homeostatic proteins in VSMC, particularly the PPi-generating pathways involving ATP re-sorption (30).

EXPERIMENTAL PROCEDURES

Materials. Sodium phosphate (Na2HPO4 and NaH2PO4) was from Fisher Scientific. Fetal bovine serum (FBS) and penicillin-streptomycin (P/S) were from Hyclone (Logan, UT). Low-glucose (1 g/l) Dulbecco’s modified Eagle’s medium (LG-DMEM), ATP standards (FL-AAS), TRizol, adenosine-5’-triphosphate (ATP), cytidine-5’-triphosphate (CTP), adenosine (Ado), sodium pyrophosphate (PPi), 3-isobutyl-1-methyloxanthine (IBMX), 8-(4-chlorophenylthio)adenosine-3’-5’-cyclic monophosphate (CPT-cAMP), H-89, KT-5720, 8-(4-chlorophenylthio)-2’-O-methyl-cAMP (8-pCPT-2’-O-Me-cAMP), 9-deoxyxoforskolin (dd-FSK), smooth muscle α-actin antibody (clone 1A4), firefly luciferase assay mix (FLAAM), adenosine-5’-phosphosulfate (APS), ATP-sulfurylase, β,γ-methylene ATP (MeATP), levamisole, cetylpyridinium chloride (CPC), para-nitrophenylphosphate (pNPP), and digitonin were from Sigma-Aldrich (St. Louis, MO). Forskolin (FSK) was from Alexis Biochemicals (San Diego, CA). Transglu/SMS22α (H-75), calponin 1 (Calp), PC-1 (L-20) (NPP1), and β-actin (C-11) antibodies were obtained from Sigma (St. Louis, MO). GAPDH antibody was from Abcam (Cambridge, MA). Alizarin Red S was from GFS Chemicals (Columbus, OH). The RNasy Mini Kit was from Qiagen (Valencia, CA). The Transcriptor first-strand cDNA synthesis kit was from Roche (Indianapolis, IN). Power SYBR Green PCR Master Mix was from Applied Biosystems (Foster City, CA). Predesigned quantitative PCR (qPCR) primer sets for rat β-actin (catalog no. P006570B), ENPP1 (PPR42431A), ANK (PPR52247A), TNAP (PPR52402A), and Runx2 (PPR53039A) were purchased from SA Biosciences (Frederick, MD), while qPCR primer pairs for rat GAPDH were designed with Primer3 software (http://frodo.wi.mit.edu) and synthesized by Operon Biotechnologies (Huntsville, AL).

VSMC isolation and cell culture. Primary rat aortic VSMC were isolated with an explant culture aortic ring model as previously described (4, 38). Male Sprague-Dawley rats (250 g) were euthanized by intraperitoneal injection of a saturated pentobarbital sodium solution (40 mg/kg body wt) as approved by the Case Western Reserve University Institutional Animal Care and Use Committee. The thoracic aorta was isolated under sterile airflow, and the adventitial and endothelial layers were gently removed to expose the media layer. The stripped media segment was sectioned into 2- to 3-mm rings that were placed onto a prescratched surface of a six-well plate incubated with 2 ml of LG-DMEM + 10% FBS, 1% P/S containing 0.9 mM Pi and 1.8 mM Ca²⁺. The rings were maintained at 37°C in a 10% CO2 humid atmosphere for 1 wk, after which primary VSMC were passaged weekly by trypsinization. All experiments utilized confluent monolayers of passage 2–4 VSMC at ≥7 days after plating on six-well culture plates at a cell density of 0.1–0.4 × 10⁶ cells/well. The cells were maintained in 2 ml of LG-DMEM + 10% FBS, 1% P/S with addition of fresh medium every 3–4 days.

Induction of calcification. In vitro VSMC calcification was induced by elevation of extracellular phosphate and/or FSK-mediated activation of cAMP signaling as previously described (15). VSMC were seeded at 0.1 × 10⁶ cells/well and allowed to attach and grow for 2 days. The FBS-containing DMEM growth medium was then variously supplemented with 1) 2.1 or 4.1 mM Na₂HPO4/NaH₂PO₄ pH 7.4 to yield a final 3 or 5 mM phosphate concentration, respectively; 2) 1 μM FSK; or 3) a combination of 3 or 5 mM final phosphate plus 1 μM FSK. Parallel control wells were maintained in the standard FBS-containing DMEM growth medium. Media with the various supplements (elevated phosphate and/or forskolin) were replaced at 3-day intervals for up to 12 days. Parallel wells of similarly treated VSMC at the indicated days after induction with the various calcification stimuli were used for analysis of calcification, extracellular PPi, and ATP homeostasis or altered gene expression, as described below.
Alizarin Red S-based measurement of calcification. Calcification was quantified by Alizarin Red S staining and organic extraction (11, 20, 47). VSMC monolayers were washed three times with 150 mM NaCl and fixed with 70% ethanol for 30 min at room temperature. The fixed cells were then washed three times with 25% ethanol followed by H2O. After addition of Alizarin Red S (0.5%) pH 5.0 (1 ml/well), the cells were incubated for 10 min at room temperature before aspiration of the Alizarin Red solution. The wells were then washed four times with 1× PBS (pH 7.4) to remove unbound Alizarin Red, and the deposited Alizarin-Ca2+ complexes were extracted by the addition of 1–2 ml of 10% CPC. This extract was diluted 1:10 before measurement of the absorbance at 570 nm (A570) with a Beckman DU640B spectrophotometer. The A570 values were normalized to total cellular protein, which was determined by the Bradford assay.

qPCR analysis of mRNAs encoding pyrophosphate homeostatic proteins. Total RNA from control or treated VSMC was isolated with TRIzol as previously described (38). RNA was purified and concentrated with the RNeasy Mini Kit (Qiagen). The purified RNA was primed with oligo(dT) primer, and first-strand cDNA was synthesized with the Transcripter first-strand cDNA synthesis kit (Roche); qPCR analysis of ENPP1, TNAP, ANK, Runx2, and GAPDH transcripts was performed with the StepOne-Plus Real-Time PCR system (Applied Biosystems). qPCR reactions were performed in 25-μl reaction volumes containing 1× Power SYBR Green PCR Master Mix, 400 nM primer mix, and 1:100 dilution of RT reaction product. Running conditions were 95°C for 10 min, followed by 40 cycles of 95°C for 15 s and 60°C for 60 s. Melting curves were performed at the end of each experiment, with all products demonstrating one predominant peak. Relative expression was calculated by the ΔΔCt method (where Cc is threshold cycle) with the use of StepOne software v.2.1 and values normalized to GAPDH.

Quantitation of ATP and PPi, levels in extracellular medium samples. VSMC monolayers cultured under control or procollagenization conditions were processed for analysis of extracellular ATP and PPi, accumulation as previously described (38). After removal of the growth or calcification medium, the intact cell monolayers were washed twice with PBS (pH 7.4) and then bathed in 1.2 ml of fresh basal salt solution (BSS) containing (in mM) 130 NaCl, 5 KCl, 1.5 CaCl2, 1 MgCl2, 25 Na-HEPES (adjusted to pH 7.5 at room temperature), and 5 mM glucose, with 0.1% BSA, to initiate test incubations at 37°C in the absence or presence of the indicated pharmacological agents. Extracellular aliquots of 100 μl were removed at various times (routinely 5, 60, and 120 min) after addition of BSS and analyzed for ATP and PPi content. ATP and PPi contents in the conditioned medium samples were quantified with a luciferase-based coupled enzyme assay (38). Heat-inactivated extracellular medium samples (75 μl) were mixed with 0.5 μl of 20 mM APS and 4 μl of concentrated FLAAM, and the resulting bioluminescence was recorded with a TD 20/20 luminometer as an indicator of ATP concentration. After this initial ATP-dependent bioluminescence, ATP-sulfurylase (0.01 U in 1 μl) was added to drive conversion of PPi to ATP and bioluminescence was continuously recorded until a steady state was reached. This value was subtracted from the initial ATP-dependent bioluminescence value to give PPi-dependent bioluminescence. Calibration curves with standard amounts of ATP and PPi (1 nM to 1 μM) were generated for each experiment in the absence or presence of pharmacological inhibitors where relevant to assess possible effects of these inhibitors on the enzyme-linked reactions.

For some experiments, adherent VSMC monolayers were pulsed with 500 nM exogenous ATP after addition of BSS and extracellular samples (100 μl) were taken at specified time points and assayed for ATP and PPi. Total cellular ATP content was determined by permeabilizing the VSMC monolayers with digitonin (50 μg/ml, 10 min, 37°C) and measuring the ATP released into the bathing medium.

High-performance liquid chromatography-based measurement of ENPP1 enzyme activity. ENPP1 enzyme activity in intact VSMC was assayed by measuring the metabolism of MeATP (38). VSMC monolayers were washed twice with 1 ml of PBS (pH 7.4) and then incubated in 1 ml of BSS supplemented with 300 μM MeATP. Samples of the extracellular BSS (100 μl) were taken at various times and heat inactivated (100°C) for 5 min. MeATP and its metabolites were chromatographically resolved with an Alltech C18 Adsorbosphere column that was isocratically eluted (1.3 ml/min) with 0.1 M KH2PO4 pH 6.0, 5% methanol. The eluted nucleotides were detected by absorbance at 254 nm. Chromatogram peak heights were determined with Data Ally v2.06 software, normalized to the initial MeATP concentration, and plotted versus time. Half-life (t1/2) values were determined by a nonlinear regression one-phase exponential decay curve fit with GraphPad Prism v3.0 software.

Alkaline phosphatase activity. Alkaline phosphatase activity in whole cell lysates of VSMC was measured with 1 mM pNPP substrate as previously described (3, 31, 38).

Western blotting. Monolayers of adherent VSMC or HEK-293 cells stably transfected with human ENPP1 were extracted at 4°C with 200 μl/well RIPA buffer containing 0.5% Nonidet P-40, 0.1% SDS in 1× PBS pH 7.4 with freshly added protease inhibitors 100 μM PMSF, 2 μg/ml aprotinin, 500 μM DTT, and 2 μg/ml leupeptin and analyzed by SDS-PAGE, Western blotting, and chemiluminescence detection with horseradish peroxidase (HRP)-coupled secondary antibodies as previously described (13, 38). Primary antibodies were incubated overnight at 4°C in 6% milk with subsequent secondary antibody (2®Ab) incubations performed at room temperature for 1 h: SM-α-actin (1/1,000; mouse 2®Ab 1/5,000), SM22a (1/300; α-rabbit 2®Ab 1/5,000), Calp (1/500; α-mouse 2®Ab 1/5,000), ENPP1 (1/250; α-goat 2®Ab 1/5,000), β-actin (1/500; α-goat 2®Ab 1/5,000), and GAPDH (1/1,000; α-mouse 2®Ab 1/7,500). Where indicated, the signal intensities of the HRP-labeled GAPDH bands were quantified by chemiluminescence imaging with a Typhoon Trio variable-mode imager (GE Healthcare Life Sciences). The human ENPP1 plasmid expression vector was provided by Dr. Robert Terkeltaub (University of California, San Diego).

Statistics. All experiments were repeated at least three times with different preparations of cultured VSMC. All data, unless otherwise stated, represent means ± SE, with statistical significance defined as P < 0.05 by two-tailed distribution with equal-variance Student’s t-test.

RESULTS

Potentiation of P2-induced VSMC matrix mineralization by cAMP signaling: time course and dependence on extracellular P2 concentration. We recently reported (38) that early-passage (passages 2–4) rat aortic VSMC cultures rapidly accumulate
extracellular PPi via autocrine mechanisms that involve release of intracellular ATP and PPi stores. We extended this culture model to the analysis of VSMC matrix mineralization in response to elevated extracellular Pi in the absence or presence of stimulated cAMP signaling. Only minor mineralization was observed in VSMC treated with either FSK (1 μM) alone or elevated Pi (3 or 5 mM) alone for up to 10 days (Fig. 1, A and C). Treatment with 3 or 5 mM Pi alone for 12 days increased mineral deposition, but not to statistically significant levels. In contrast, when coadministered, FSK + 5 mM Pi acted synergistically to increase the rate and magnitude of matrix calcification, which was significant within 9 days and maintained for up to 12 days (Fig. 1). FSK also potentiated matrix mineralization in VSMC challenged with 3 mM extracellular Pi, but this calcification required more prolonged cotreatment (Fig. 1C). For subsequent experiments, we routinely used VSMC cultures stimulated with 5 mM Pi + 1 μM FSK for 10 days as the model of induced matrix mineralization.

VSMC matrix mineralization is correlated with decreased accumulation of extracellular PPi, and altered expression of PPi homeostatic gene products. In vitro VSMC calcification is often characterized by the induction of osteochondrogenic markers and loss of VSMC differentiation proteins. However, the early-passage VSMC used in our experiments maintained high expression of the smooth muscle contractile marker proteins α-SM-actin, SM22α, and Calp regardless of their treatment protocol or calcification status (Fig. 2A). We observed a transient increase in mRNA (but not to statistically significant levels) encoding the osteoblast differentiation marker Runx2/Cbfa1 in response to elevated Pi alone or Pi + FSK, while FSK alone induced a progressive increase in Runx2 expression over 10 days (Fig. 2B). We also quantified TNAP, ANK, and ENPP1 mRNA levels in VSMC cultured under control or procalcification conditions (Fig. 2B). cAMP stimulation induced a progressive increase in TNAP expression in the absence or presence of elevated Pi. In contrast, the same cAMP stimulus caused a decrease in ANK expression that was maximal within 24 h in the absence of elevated Pi, and further suppressed at 4 and 10 days in the presence of high Pi; elevated Pi alone did not significantly modulate ANK mRNA levels. A significant reduction in ENPP1 transcripts was observed only in VSMC stimulated with both FSK and high Pi, for 10 days. These results suggest that multiple components of the extracellular Pi, homeostatic network are differentially regulated in response to cAMP stimulation alone or in combination with exposure to elevated Pi.

The alkaline phosphatase subtype TNAP is a calcification regulator that is necessary for normal physiological mineralization in bone (11). We confirmed previous reports (15) that FSK stimulation of VSMC causes a gradual and progressive increase in total alkaline phosphatase activity (which includes both TNAP and other alkaline phosphatase subtypes) in whole cell lysates (Fig. 2C). Notably, this cAMP-dependent elevation of alkaline phosphatase activity was modestly attenuated in VSMC additionally cultured with elevated Pi. Notably, elevated extracellular Pi alone did not increase TNAP transcripts or total alkaline phosphatase activity. These observations suggest that the robust mineralization phenotype observed at 10 days in VSMC costimulated with FSK and high Pi cannot be explained solely at the level of increased TNAP expression and alkaline phosphatase activity.

We measured the ability of VSMC to accumulate extracellular PPi after FSK treatment in the absence or presence of elevated Pi. A twofold reduction in the rate of autocrine PPi accumulation was observed in VSMC treated for 1 day with FSK (Fig. 2D). This reduction in extracellular PPi accumulation rate was sustained when VSMC were continuously cultured in FSK-supplemented medium for up to 10 days (Fig. 2D; Figs. 3, B and C). Unexpectedly, VSMC exposed to high Pi (5 mM) alone for 24 h were characterized by a threefold increase in the rate of Pi accumulation (Figs. 2D and 3A). However, this Pi-induced potentiation of PPi accumulation was prevented when VSMC were additionally stimulated with FSK (Figs. 2D and 3A). The effect of hyperphosphatemia was transient; PPi accumulation rates in VSMC cultured with elevated Pi for 4 (Fig. 2D) and 10 (Figs. 2D and 3C) days were...
Fig. 2. VSMC matrix mineralization is correlated with decreased accumulation of extracellular inorganic pyrophosphate (PPi) and altered expression of PPi homeostatic gene products. A: Western blot of VSMC cell extracts probed for SMC marker proteins α-SM-actin, SM22α, and calponin for the indicated days in culture in the absence or presence of 1 μM FSK, 5 mM Pi, or FSK + Pi, with β-actin and GAPDH as loading controls. Signal intensities of the GAPDH bands in lanes probed for SMC marker proteins (Fig. 2A) were quantified by chemiluminescence imaging and normalized relative to the GAPDH band intensity of control VSMC (1st lane). B: quantitative PCR (qPCR) analysis of PPi homeostatic proteins tissue nonselective alkaline phosphatase (TNAP), ANK, and ectonucleotide pyrophosphatase/phosphodiesterase-1 (ENPP1), along with the osteonuclear alkaline phosphatase (TNAP), ANK, and extracellular levels of PPi. Generation at the 2 h time point after transfer of VSMC to basal saline assay medium that were treated for the indicated days in culture in the absence or presence of 1 μM FSK, 5 mM Pi, or FSK + Pi, Data represent means ± SE; n ≥ 3. *P < 0.05 vs. control.

Similar to those in control cells. Notably, VSMC costimulated for 10 days with FSK plus either 3 mM (Fig. 3B) or 5 mM (Figs. 2D and 3C) Pi were characterized by autocrine PPi accumulation rates even lower than the reduced rate induced by FSK treatment alone. Together, these data indicate that the synergistic actions of cAMP and elevated phosphate on VSMC mineralization (Fig. 1) are well correlated with a markedly attenuated capacity for accumulation of extracellular PPi.

Autocrine accumulation of extracellular PPi is decreased in VSMC stimulated by cAMP: pharmacology, kinetics, and reversibility. The experiments in Fig. 2D and Fig. 3 indicated that the inhibitory effects of FSK on PPi homeostasis were induced within 24 h and then steadily maintained over time. We further characterized the pharmacology and kinetics of this early response of VSMC to FSK. Cells pretreated with 1 μM FSK for 24 h were characterized by two- to threefold lower rates of extracellular PPi accumulation relative to control cells (Fig. 4A). The PPi accumulation rates in both control and FSK-treated VSMC were linear for early response of VSMC to FSK. Cells pretreated with 1 μM FSK for 24 h were characterized by two- to threefold lower rates of extracellular PPi accumulation relative to control cells (Fig. 4A). These data indicate that the reduced capacity for extracellular PPi accumulation by cAMP stimulation involves the regulation of gene expression, rather than posttranslational modification, of PPi homeostatic proteins. The suppression of PPi homeostasis by FSK reflected its specific action as a direct stimulator of cAMP accumulation because equimolar dd-FSK, an analog that does not activate adenylate cyclase, was without effect (Supplemental Fig. S1B). Moreover, similar decreases in PPi accumulation rate were observed when cAMP signaling was stimulated with the phosphodiesterase inhibitor IBMX (200 μM) or the membrane-permeant cAMP analog CPT-cAMP (100 μM) (Fig. 4E). As noted in Fig. 2, the cAMP stimulus also modestly increased TNAP expression and alkaline phosphatase activity within 24 h. However, the reduced rate of extracellular PPi accumulation observed in FSK-treated VSMC was not reversed by inclusion of 5 mM levamisole, a TNAP inhibitor, in the medium used to assay PPi accumulation (Fig. 4F). This indicates that the increased alkaline phosphatase activity observed in Fig. 2C was not responsible for the

The online version of this article contains supplemental material.
cAMP-sensitive effector protein (but not PKA) (12), did not mimic the reduction in extracellular PPi accumulation (Supplemental Fig. S1D) induced by the 8-pCPT-cAMP analog that activates both PKA and Epac signaling (Fig. 4E). Together, these data demonstrate that stimulation of cAMP signaling negatively regulates the ability of VSMC to generate extracellular PPi.

ENPP1 ectonucleotidase activity is maintained at control levels in VSMC stimulated by cAMP or elevated extracellular Pi. Reduced levels of ENPP1 mRNA were observed only in VSMC cultured for 10 days with both FSK and high Pi (Fig. 2B). However, Western blot analysis indicated that total ENPP1 protein expression was reduced by FSK treatment in the absence or presence of elevated Pi, at all time points, while a modest increase in ENPP1 protein was observed in cells stimulated with high Pi, for 1 day, with levels decreasing below baseline at 4 and 10 days (Fig. 5A). To gauge the possible functional significance of these decreases in ENPP1 protein levels, we used an HPLC-based method to monitor the metabolism of extracellular MeATP, a specific substrate for ENPP family ecto-ATPases (38), by intact VSMC subjected to the various combinations and durations of cAMP or high phosphate stimuli (Fig. 5B). Figure 5B, top, illustrates the chromatograms of extracellular medium samples at 0, 10, 30, or 60 min after addition of 300 μM MeATP to control VSMC and indicates that these cells metabolize 50% of the nucleotide within 12 min to produce AMP, Ado, and (not pictured) inosine. No decreases in MeATP clearance rate (relative to control) were observed in any of the treated VSMC cultures (Fig. 5, C and D). Indeed, most of the treated cultures cleared MeATP at modestly faster rates (i.e., lower 1/2 values). Thus the functional activity of ENPP1, as a cell surface ectonucleotidase, is maintained at control levels in FSK- and Pi-treated VSMC despite the reduction in ENPP1 protein in whole cell lysates.

To further characterize this dissociation between ENPP1 activity in intact cells and ENPP1 protein levels in cell lysates, we compared the abilities of control versus FSK-treated (1 day) VSMC to metabolize a pulse of 500 nM exogenous ATP and thereby produce extracellular PPi, in excess over that derived from endogenous sources (Fig. 5, C and D). Control VSMC rapidly metabolized the exogenous ATP (Fig. 5E) and increased extracellular PPi, by approximately twofold over that derived solely from autocrine metabolism (Fig. 5C). As noted above, FSK-treated VSMC were characterized by a twofold reduction in their ability to generate extracellular PPi, from endogenous stores (Fig. 5D). However, these cells hydrolyzed the 500 nM exogenous ATP at a control rate (Fig. 5E) to produce an additional 370 nM PPi over that derived from the autocrine pathway (Fig. 5D). Thus reduced expression of ENPP1 as a functional cell surface nucleotidase does not play a major role in the attenuation of extracellular PPi accumulation by VSMC stimulated by either increased cAMP signaling (Fig. 5, B and D) or elevated Pi (Fig. 5B).

Autocrine ATP release is decreased in VSMC costimulated by cAMP and elevated extracellular Pi. Although early and sustained decreases in both ANK expression and PPi accumulation rate were induced by cAMP stimulation in the absence and presence of costimulation by high phosphate, VSMC subjected to both stimuli were characterized by even lower rates of autocrine PPi generation (Fig. 2D). This suggested that the latter calcifying conditions induced modulation of additional pathways that generate extracellular PPi. Increased reduced rate of PPi accumulation observed in VSMC treated with FSK for only 24 h.

We attempted to determine whether the inhibitory effects of cAMP on PPi accumulation required PKA signaling pathways using H-89 and KT-5720, but neither of these PKA inhibitors reversed the effect of FSK (Supplemental Fig. S1C). Surprisingly, VSMC treated with H-89 or KT-5720 alone, in the absence of FSK, exhibited a greater than twofold reduction in extracellular PPi generation similar to that induced by FSK alone. H-89 and KT-5720 can inhibit multiple kinases in addition to PKA (34), 8-pCPT-2′-O-Me-cAMP, a membrane-permeant cAMP analog that selectively activates the Epac

![Figure 3](http://ajpcell.physiology.org/)

Fig. 3. cAMP signaling decreases the rate of extracellular PPi accumulation by VSMC cultured with control or elevated levels of extracellular Pi. Time course of extracellular levels of PPi, generation following transfer of VSMC to basal saline assay medium that were treated for 1 day in the absence (Con) or presence of 5 mM Pi, or 5 mM Pi + FSK (A); 10 days in the absence (Con) or presence of 3 mM Pi, 1 μM FSK, or 3 mM Pi + FSK (B); or 10 days in the absence (Con) or presence of 5 mM Pi, 1 μM FSK, or 5 mM Pi + FSK (C). Data represent means ± SE; n ≥ 3. *P < 0.05 vs. control.
TNAP (Figs. 2C and 4F) and decreased ENPP1 (Fig. 5B) activity are unlikely mechanisms for this further reduction in PPi accumulation rate. We therefore compared the abilities of the variously stimulated VSMC cultures to release ATP as the autocrine substrate for ENPP1-catalyzed production of extracellular PPi. As we previously reported, autocrine ATP release from cultured VSMC is efficiently coupled to the ENPP1 ecto-ATPase such that only minor accumulation of ATP can be measured in the extracellular culture medium (38). Thus we utilized the ENPP1 competitive substrate MeATP (Fig. 5B) as a pharmacological tool to spare hydrolysis of endogenously released ATP and stabilize its extracellular accumulation. We observed a significant and progressive reduction in the ability of VSMC to release ATP when costimulated with FSK and elevated Pi for 4 and 10 days (Fig. 6). In contrast, ATP release was not significantly changed in cells treated with only FSK.

VSMC exhibited a threefold increase in autocrine ATP release capacity when stimulated with high Pi alone for 1 day, followed by a return to control ATP release rates as the Pi stimulus was extended to 4 or 10 days. This latter pattern of ATP release was well correlated with the biphasic change in extracellular Pi accumulation rates observed in VSMC stimulated with elevated extracellular Pi (Fig. 2D). Notably, no changes in total intracellular ATP content were observed in VSMC grown under any of the culture conditions (data not shown).

Matrix mineralization of VSMC costimulated by cAMP and elevated extracellular Pi is suppressed by exogenous ATP. The above experiments suggested that the ability of cAMP and high-phosphate costimulation to synergistically attenuate ATP release by VSMC reduces their capacity for extracellular PPi generation and may thereby contribute to robust mineralization. To test this hypothesis, we compared extracellular Ca2+ deposition (by Alizarin Red S staining) in VSMC costimulated with FSK and elevated Pi for 10 days in the absence or presence of exogenously added PPi, ATP, CTP, or Ado (each at 50 μM) (Fig. 7). As expected (37), exogenous PPi completely suppressed the matrix mineralization induced by cAMP and high Pi costimulation. Notably, exogenous ATP similarly suppressed this mineralization phenotype. To assess the possible contribution of P2 receptor signaling in ATP-induced rescue of VSMC from matrix mineralization, the VSMC cultures were alternatively supplemented with CTP, a nucleotide triphosphate that does not activate P2 receptors but can serve as a substrate for ENPP1-mediated hydrolysis and PPi generation. CTP mimicked the abilities of exogenous ATP or Pi to suppress VSMC mineralization. Inhibition of mineralization by exogenous ATP could also reflect a contribution of Ado, a metabolite of extracellular ATP hydrolysis that signals through various G protein-coupled Ado receptors. However, exogenous Ado did not reverse the VSMC matrix mineralization induced by cAMP + high-Pi treatment.

**DISCUSSION**

This study describes novel mechanisms by which cAMP and elevated extracellular Pi act synergistically to induce VSMC calcification. Our experiments suggest that the synergy between these stimuli in driving matrix mineralization is medi-
ated in part by suppression of two autocrine pathways for extracellular PPi accumulation: 1) the ANK-dependent efflux of cytosolic PPi and 2) a molecularly undefined ATP release pathway coupled to ENPP1-catalyzed ATP hydrolysis and PPi generation. The decreased activities of these two mechanisms by which VSMC increase extracellular PPi levels are coordinated with the increased activity of TNAP, a PPi-degrading ectoenzyme and well-characterized inducer/marker of physiological calcification in bone and pathological mineralization in arteries. These observations support a model in which ANK- and ATP release-dependent mechanisms serve as critical regulators of extracellular PPi generation and perturbation in their expression or function facilitates VSMC calcification. These findings also raise significant questions regarding the intracellular signaling pathways by which cAMP and elevated Pi act separately and convergently to regulate the expression and activity of the multiple gene products involved in extracellular PPi homeostasis. It will also be important to determine whether modulation of these two pathways for PPi accumulation does, or does not, occur in human VSMC and human disease states characterized by vascular calcification.

Our finding that stimulation of cAMP signaling for <24 h induced an ~50% decrease in the rate of extracellular PPi accumulation was well correlated with a similar rapid decrease in ANK mRNA levels. In contrast, there were no significant changes in the expression or activity of the other major PPi homeostatic proteins or functions—autocrine ATP release, ENPP1, or TNAP—during this early response to cAMP stimulation. Importantly, we previously reported (38) that a probe-necid-sensitive mechanism provided ~50% of the extracellular PPi-generating capacity of noncalcified VSMC. Together, our previous and new data suggest that reduced expression/transferring of ANK to plasma membrane is the major mechanism underlying the rapid attenuation of extracellular PPi generation in cAMP-stimulated VSMC. Unequivocal support for this conclusion will require quantification of ANK protein levels and localization in cultured VSMC. However, pilot studies with commercially available ANK antibodies failed to detect specific signals in whole cell lysates of these cells.

ANK is a 50-kDa plasma membrane protein with 8–12 predicted transmembrane domains that functions as either a direct PPi transporter or a regulator of an as-yet unidentified...
PP_i transport protein (41, 53). The identification of ANK as a major target for rapid suppression by cAMP signaling is significant given previous findings that increased cAMP facilitates in vitro mineralization by osteoblasts and VSMC (15, 48, 49). However, these earlier studies emphasized the stimulatory effects of cAMP on induction/activity of proosteogenic transcription factors, such as Runx2/Cbfa-1 and osterix, which secondarily elicit—after several days—increased expression of effector proteins such as TNAP, matrix Gla protein (MGP), and osteopontin that directly modulate calcification. We also observed a gradual increase in TNAP mRNA (Fig. 2B) and enzyme activity (Fig. 2C) over 10 days of stimulation of VSMC by FSK. Analysis of Runx2 mRNA levels in the same extracts of FSK-stimulated VSMC showed a similar temporal trend of gradual (although not statistically significant) elevation (Fig. 2B). VSMC treated with elevated Pi, + FSK (or Pi alone) exhibited a transient increase in Runx2 expression that returned to baseline levels before the robust matrix calcification. This transient increase is similar to the findings of Speer et al. (46), who recently reported that Runx2 expression within the in situ aortic VSMC of MGP-null mice is maximal at 2 wk before the massive vascular calcification that characterizes 4-wk-old MGP-null animals. Transient elevation of Runx2 is likely sufficient to increase the levels of osterix, a transcription factor that regulates expression of multiple gene products involved in matrix mineralization (23). In our VSMC model, ANK transcript levels were maximally decreased within 24 h after FSK treatment and this was temporally correlated with an at least twofold decrease in autocrine accumulation of extracellular PP_i that was insensitive to the TNAP inhibitor levamisole. Thus decreased expression of ANK and reduced PP_i generation precede increased expression of TNAP and Runx2 in cAMP-stimulated VSMC.

Another consequence of sustained cAMP stimulation on PP_i homeostasis was observed only when VSMC were costimulated by high extracellular Pi, and this involved a progressive decrease in autocrine ATP release. These changes in autocrine ATP release observed in cAMP- and Pi-treated VSMC likely reflect chronic modulation of the expression or activity of a molecularly undefined ATP release pathway (26). How this autocrine pool of ATP is exported from VSMC and how this export is attenuated by the combined phosphate and cAMP stimuli remain as key questions. Recent studies have focused on a variety of ATP-permeable channels or channel-like activ-
ities as the major pathways for ATP export in multiple cell types (16, 17, 25, 26, 29, 42). Attenuated expression or activity of such channels likely underlies the decreased ATP release rate observed in calcifying VSMC. Regardless of the molecular basis for autocrine ATP release by VSMC, our experiments support the functional significance of this endogenous pool of ATP by showing that exogenous Pi can suppress the calcification of VSMC costimulated with cAMP and high Pi. A similar action of exogenous nucleotides in inhibiting mineralization has been described in primary rat osteoblasts (37).

Increases in extracellular Pi potentiate vascular calcification in two ways: 1) by depositing within the extracellular matrix surrounding VSMC in the form of poorly soluble calcium phosphate crystals that include HA and other forms and 2) by triggering intracellular signaling pathways as secondary response to enhanced influx via Pi transporters. HA crystal formation requires several days, and these crystals, when deposited adjacent to cells, have the potential to trigger additional modulation of cell function including inflammation, cellular damage, and apoptosis (6). However, high extracellular Pi can also elicit rapid changes in VSMC and other cell types that precede the obvious deposition of extracellular Pi-based crystals. Elevated extracellular Pi, rapidly (within minutes to hours) stimulates MAP kinase and inhibits Akt kinase cascades in various cells (including VSMC), which, in turn, can induce transcriptional or posttranscriptional responses that impact cellular functions involved in the suppression or potentiation of mineralization (1, 2, 45). These latter responses to high extracellular Pi likely involve elevated influx of Pi, via the type III Na-dependent Pi cotransporter Pit-1 to increase cytosolic Pi concentration (normally 0.5–1 mM) (28, 46). Our data indicate that elevated extracellular Pi also rapidly induces increased accumulation of extracellular Pi in noncalcified VSMC via upregulation of an autocrine ATP release pathway. However, these increased rates of ATP release and Pi accumulation were not sustained and returned to control values as the Pi stimulus was extended to 4 or 10 days.

Although there was a transient and modest increase in Runx2 expression in VSMC stimulated by high Pi alone (Fig. 2B), this was insufficient to induce a calcifying phenotype even after 10 days of sustained treatment. Other investigators have reported that elevated Pi alone can induce calcification in different VSMC models (33, 44). Notably, ex vivo organ cultures of freshly isolated aortic rings, which maintain VSMC in a physiological contractile phenotype, are remarkably resistant to high Pi-induced calcification in the absence of either deliberate mechanical damage or supplementation with exogenous alkaline phosphatase (30). Our VSMC cultures maintained high expression of multiple contractile marker proteins even when induced to calcify by costimulation with high phosphate and cAMP. Together, these observations in aortic rings and early-passage VSMC cultures suggest that contractile phenotype VSMC may support ectopic calcification reactions when subjected to stimuli that both suppress extracellular PPi levels and induce cellular damage. It is also important to note that changes in expression of smooth muscle versus osteogenic marker genes in VSMC cultures during procalcification stimulation are often multiphasic because of changes in the relative fractions of VSMC at different phenotypic states. Previous studies in osteoblasts and chondrocytes have additionally indicated that changes in extracellular PPi, per se can modulate the expression of ANK, ENPP1, and TNAP via complex negative and positive feedback loops (10, 11, 19, 22). Thus the very early reduction in extracellular PPi accumulation and ANK expression observed in FSK-treated VSMC may elicit feedback pathways that favor increased expression of ANK and ENPP1; the time course analyses of ANK and ENPP1 mRNA in Fig. 2B suggest such trends. Moreover, Huang et al. (15) observed that ANK and ENPP1 mRNA levels were increased in murine VSMC cultured for 7 days with 25 μM FSK + 5 mM glycerophosphate as an organic Pi donor.

It is noteworthy that extracellular PPi, homeostasis in VSMC and its perturbation by elevated phosphate involve the coordinated activities of at least three plasma membrane transport proteins, ANK, Pit-1, and the undefined ATP release channels, as well as two plasma membrane ectoenzymes, ENPP1 and TNAP. These proteins may be organized in functionally or structurally defined signaling complexes. Indeed, Wang et al. recently reported (51) that Pit-1 and ANK can be reciprocally coimmunoprecipitated from the plasma membrane extracts of chondrocytes, suggesting that the expression and function of these integral membrane proteins are linked. Given that decreased expression of ANK in cAMP-stimulated VSMC is correlated with suppression of the early high phosphate-induced increase in autocrine ATP release, it is tempting to speculate that ANK may also act as a direct or indirect positive regulator of ATP release channels.

ACKNOWLEDGMENTS

We thank Saneliso N. Masuku and Gregg DiNuoscio for technical assistance; Dr. Jeffery A. Beamish for calponin and SM22a antibodies; Dr. Cathy Carlin for GAPDH antibody; and Andrew E. Blum and Dr. Ozgur Ogut for useful discussions.

GRANTS

This work was supported in part by National Institutes of Health (NIH) Grants KO1-GM-36387 (G. R. Dubyak) and RO1-DK-69681 (W. C. O’Neill) and a grant from the Genzyme Renal Innovations Program (W. C. O’Neill). D. A. Prosdocimo was supported by NIH Grant T32-HL-07887.
REFERENCES


