Valvular Heart Disease

Arterial and Aortic Valve Calcification Abolished by Elastolytic Cathepsin S Deficiency in Chronic Renal Disease

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Background—Clinical studies have demonstrated that 50% of individuals with chronic renal disease (CRD) die of cardiovascular causes, including advanced calcific arterial and valvular disease; however, the mechanisms of accelerated calcification in CRD remain obscure, and no therapies can prevent disease progression. We recently demonstrated in vivo that inflammation triggers cardiovascular calcification. In vitro evidence also indicates that elastin degradation products may promote osteogenesis. Here, we used genetically modified mice and molecular imaging to test the hypothesis in vivo that cathepsin S (catS), a potent elastolytic proteinase, accelerates calcification in atherosclerotic mice with CRD induced by 5/6 nephrectomy.

Methods and Results—Apolipoprotein-deficient (apoE<sup>−/−</sup>/catS<sup>+/+</sup>) (n=24) and apoE<sup>−/−</sup>/catS<sup>−/−</sup> (n=24) mice were assigned to CRD and control groups. CRD mice had significantly higher serum phosphate, creatinine, and cystatin C levels than those without CRD. To visualize catS activity and osteogenesis in vivo, we coadministered catS-activatable and calcification-targeted molecular imaging agents 10 weeks after nephrectomy. Imaging coregistered increased catS and osteogenic activities in the CRD apoE<sup>−/−</sup>/catS<sup>+/+</sup> cohort, whereas CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> mice exhibited less calcification. Quantitative histology demonstrated greater catS-associated elastin fragmentation and calcification in CRD apoE<sup>−/−</sup>/catS<sup>+/+</sup> than CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> aortas and aortic valves. Notably, catS deletion did not cause compensatory increases in RNA levels of other elastolytic cathepsins or matrix metalloproteinases. Elastin peptide and recombinant catS significantly increased calcification in smooth muscle cells in vitro, a process further amplified in phosphate-enriched culture medium.

Conclusions—The present study provides direct in vivo evidence that catS-induced elastolysis accelerates arterial and aortic valve calcification in CRD, providing new insight into the pathophysiology of cardiovascular calcification. (Circulation. 2009;119:1785-1794.)

Key Words: calcification • aortic valve • atherosclerosis • kidney failure, chronic • elastin

Westernized societies face a growing burden of cardiovascular calcification, a disease of disordered mineral metabolism.<sup>1-4</sup> The interaction of prevalent epidemiological factors such as age, hypercholesterolemia, and renal insufficiency accelerates arterial and aortic valve calcification.<sup>5</sup> Clinical studies have demonstrated that approximately 50% of individuals with chronic renal disease (CRD) die of a cardiovascular cause.<sup>6-8</sup> In addition to the classic risk factors such as age and dyslipidemia, patients with CRD have hyperphosphatemia, which is considered an independent risk factor for cardiovascular death.<sup>9,10</sup> CRD accelerates the development of atherosclerosis and excessive calcification in both the intima and media of atheromatous lesions.<sup>11,12</sup> Although they have different causes, intimal and medial calcification both involve the activation of proinflammatory mechanisms and smooth muscle cell (SMC) proliferation, which likely share common calcification pathways.

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Recent studies suggest that arterial and valvular calcification occurs through highly regulated molecular processes characterized by expression of osteogenic proteins and matrix-degrading proteinases. We have previously implicated proteolytic enzymes expressed by activated macrophages and myofibroblast-like cells in atherosclerotic plaque progression and aortic valve disease.<sup>13-15</sup> During atherogenesis, macro-
phage-derived proteinases such as elastolytic cathepsins or metalloproteinases (MMP-2 and MMP-9) induce release of biologically active, soluble elastin-derived peptides that may promote osteogenic differentiation of myofibroblasts. In addition, elastases degrade medial elastin, which favors calcification through an increase of elastin polarity that in turn enhances elastin affinity for calcium.

Cardiovascular calcification commonly causes devastating complications, including plaque rupture and aortic valve stenosis, which currently have no suitable therapeutic alternative beyond valve replacement. In addition, a recent large-scale intervention trial showed that statin therapy did not prevent the progression of calcific aortic stenosis. This lack of therapeutic options demands the exploration of new pathways that contribute to cardiovascular calcification.

Our recent studies used real-time molecular imaging approaches to establish in vivo that proatherogenic molecular pathways that contribute to cardiovascular calcification. The present study dissected the mechanisms underlying accelerated arterial and valvular calcification in CRD. Specifically, we tested the hypothesis that proinflammatory cathepsin S (catS), a highly potent elastase, contributes to arterial and valvular calcification in mice with atherosclerosis and CRD assessed by in vivo and ex vivo optical molecular imaging, correlative histopathology, and in vitro experiments. These new insights into the pathobiology of arterial and valvular calcification aid the investigation of novel therapeutic strategies to reduce the onset of cardiovascular events, and thus mortality, in CRD.

Methods

An expanded Methods section is available as an online-only Data Supplement.

Animal Experiments

We studied osteogenic changes in arteries and aortic valves of 30-week-old apolipoprotein E (apoE)-deficient/catS wild-type mice (apoE<sup>−/−</sup>/catS<sup>+/+</sup>; n=24) and apoE-deficient/catS-deficient (apoE<sup>−/−</sup>/catS<sup>−/−</sup>; n=24) mice that consumed an atherogenic diet (Teklad TD 88137; Harlan, Indianapolis, Ind) from 10 weeks of age. At 20 weeks of age, mice in each group were randomized either to continue procedures that are known to aggravate atherosclerosis. At 10 weeks after surgery, mice underwent intravital microscopy and were euthanized for ex vivo imaging and correlative histological analyses.

The Subcommittee on Research Animal Care at Massachusetts General Hospital approved all procedures.

### Blood Biochemical Analyses

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Phosphate, mg/dL</th>
<th>Calcium, mg/dL</th>
<th>Creatinine, mg/dL</th>
<th>Cystatin C, mg/dL</th>
<th>Total Cholesterol, mg/dL</th>
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<tr>
<td>apoE&lt;sup&gt;−/−&lt;/sup&gt;/catS&lt;sup&gt;+/+&lt;/sup&gt;</td>
<td>4.70±0.37†</td>
<td>0.92±0.01</td>
<td>0.25±0.01†</td>
<td>0.25±0.01†</td>
<td>56.33±9.83†</td>
</tr>
<tr>
<td>CRD apoE&lt;sup&gt;−/−&lt;/sup&gt;/catS&lt;sup&gt;+/+&lt;/sup&gt;</td>
<td>7.18±0.49*</td>
<td>0.96±0.50</td>
<td>0.29±0.03†</td>
<td>0.27±0.01†</td>
<td>69.40±2.87†</td>
</tr>
<tr>
<td>apoE&lt;sup&gt;−/−&lt;/sup&gt;/catS&lt;sup&gt;−/−&lt;/sup&gt;</td>
<td>6.28±0.40†</td>
<td>0.78±0.06</td>
<td>0.37±0.01†</td>
<td>0.56±0.13†</td>
<td>467.2±51.1†</td>
</tr>
<tr>
<td>CRD apoE&lt;sup&gt;−/−&lt;/sup&gt;/catS&lt;sup&gt;−/−&lt;/sup&gt;</td>
<td>11.38±0.88</td>
<td>0.94±0.03</td>
<td>0.6±0.04</td>
<td>0.94±0.10†</td>
<td>397.1±24.76†</td>
</tr>
<tr>
<td>apoE&lt;sup&gt;−/−&lt;/sup&gt;/catS&lt;sup&gt;−/−&lt;/sup&gt;</td>
<td>7.18±0.50†</td>
<td>0.88±0.01</td>
<td>0.26±0.02†</td>
<td>0.17±0.01*</td>
<td>842.0±58.55*</td>
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<tr>
<td>CRD apoE&lt;sup&gt;−/−&lt;/sup&gt;/catS&lt;sup&gt;−/−&lt;/sup&gt;</td>
<td>10.28±1.40</td>
<td>0.78±0.21</td>
<td>0.45±0.05</td>
<td>0.21±0.03*</td>
<td>659.6±114.20*</td>
</tr>
</tbody>
</table>

*Indicates significance between CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> and other groups. †Indicates significance between CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> and other groups.

The Committee on Research Animal Care at Massachusetts General Hospital approved all procedures.

Molecular Imaging Agents

### Detection of Elastolytic Activity

A novel peptide-based catS-activatable agent consists of backbone of a catS-cleavable dipeptide substrate (Leu-Arg) and 2 polyethylene glycol chains that contain a fluorochrome in their dendritic arms. After enzymatic cleavage by catS, the fluorochromes separate, which results in signal amplification (excitation/emission 750/780 nm). In vitro validation studies indicated that catS, but not cathepsins B, K, or L, cleaves this probe.

### Detection of Osteogenic Activity

A bisphosphonate-conjugated imaging agent (OsteoSense<sub>680</sub>, VisEn Medical Inc, Woburn, Mass), which generates fluorescence evident through the near-infrared window (excitation/emission 650/680 nm), was used to detect osteogenic activity, as described previously.

### Detection of Inflammation

Cross-linked iron oxide (CLIO-gly) fluorescent nanoparticles, an imaging agent that produces fluorescence visible through the near-infrared window (excitation/emission 750/780 nm), was used to detect macrophages.

### Intravital Dual-Channel Fluorescence Imaging

Mice (n=12 per group) simultaneously received spectrally distinct imaging agents (activatable cathepsin S<sub>750</sub> and OsteoSense<sub>680</sub> or CLIO-gly<sub>750</sub> and OsteoSense<sub>680</sub>) or saline via intravenous injection 24 hours before imaging. We performed dual-channel fluorescence imaging using an Olympus IV100 intravital laser scanning fluorescence microscope developed for imaging small experimental animals.

### Macroscopic Fluorescence Reflectance Imaging

After mice were euthanized, aortas were perfused with saline, dissected, and imaged to map the macroscopic near-infrared osteogenic activity elaborated by the OsteoSense<sub>680</sub> imaging agent with a fluorescence reflectance imaging system equipped with multichannel filter sets (Omega Optical, Brattleboro, Vt) as described previously.

### Histopathological Assessment

**Morphological Characterization**

Tissue samples were frozen in OCT compound, and 5-μm serial sections were cut and stained with hematoxylin and eosin for general...
morphology. Alkaline phosphatase activity (a marker of early osteogenic differentiation) was detected on cryosections according to the manufacturer’s instructions (alkaline phosphatase substrate kit, Vector Laboratories, Burlingame, Calif). Van Gieson stain was used to assess elastin. Von Kossa silver stain was used to histochemically image advanced calcification. Masson trichrome stain was used to evaluate glomerulosclerosis.

Immunohistochemistry
Immunohistochemistry for macrophages (anti-mouse Mac3, BD Biosciences, San Jose, Calif), catS (Santa Cruz Biotechnology, Santa Cruz, Calif), and cystatin C (Abcam, Cambridge, United Kingdom) was performed by the avidin-biotin peroxidase method. Fluorescence immunohistochemistry simultaneously visualized Texas Red–labeled catS and elastin. Images were captured and processed with an epifluorescence microscope (Eclipse 80i, Nikon Instruments, Melville, NY) with a cooled CCD camera (Cascade, Photometrics, Ariz).

Real-Time Reverse-Transcription Polymerase Chain Reaction
Total RNA was isolated from aorta with an RNeasy Mini Kit (Qiagen, Valencia, Calif) from all groups of mice (n=5 per group). Polymerase chain reaction detection and quantification of cathepsins S, B, L, and K and MMP-2 and MMP-9 was done with a MyiQ single-color real-time PCR detection system and iQ SYBR Green Supermix (BioRad, Hercules, Calif). All measurements were duplicated, and the mean value was used. Data are expressed in arbitrary units that were normalized by β-actin.

Primary Human SMC Culture
Human vascular SMCs were treated with human aortic elastin peptides 100 mg/mL (Elastin Products Co, St Louis, Mo), either alone or in the presence of human recombinant catS 1 mg/mL (Calbiochem, San Diego, Calif); catS plus the cathepsin inhibitor cystatin C 1 mg/mL (Calbiochem); or cystatin C 1 mg/mL. Separate plates were treated with
Statistical Analysis

Statistical analyses for comparisons of multiple groups used 1-way ANOVA followed by the Tukey post hoc test. Student t test was performed when 2 groups were compared (GraphPad Prism, version 4.0, GraphPad Software, San Diego, Calif). Data are presented as mean±SEM. P values <0.05 were considered significant.

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results

Phosphate, Creatinine, and Cystatin C Levels Are Increased in CRD ApoE<sup>−/−</sup>/CatS<sup>−/−</sup> Mice

Histopathological analysis 10 weeks after subtotal nephrectomy revealed that the kidneys of hypercholesterolemic CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> mice had a 50% reduction in the number of nephrons and enlarged glomeruli and developed glomerulosclerosis (online-only Data Supplement Figure). Both CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> and CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> groups had significantly increased serum phosphate and creatinine levels compared with apoE<sup>−/−</sup>/catS<sup>+</sup>/ and apoE<sup>−/−</sup>/catS<sup>−/−</sup> mice with normal kidney function, whereas serum calcium levels remained unaffected (Table). Elevation of cystatin C, a marker of impaired glomerular filtration rate and a major endogenous inhibitor of catS, reflects a very early stage of chronic renal dysfunction. ApoE<sup>−/−</sup>/catS<sup>−/−</sup> mice and especially CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> mice had significantly increased cystatin C levels compared with apoE<sup>−/−</sup>/catS<sup>+</sup>/ and CRD apoE<sup>−/−</sup>/catS<sup>−/−</sup> mice lacking catS (Table).

Calcification Is Increased in the Aortas of CRD ApoE<sup>−/−</sup>/CatS<sup>−/−</sup> Mice Compared With CatS-Deficient Mice

Macroscopic fluorescence reflectance imaging was used to map osteogenic activity in mouse aortas (Figure 1). A bisphosphonate-derivatized near-infrared fluorescent imaging
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Augmented Osteogenic and Elastolytic Activity in CRD ApoE"/"/CatS"++ Mouse Compared With CatS-Deficient Mice

Intravital multichannel, high-resolution laser scanning fluorescence microscopy visualized in vivo real-time osteogenic and elastolytic activities in the atherosclerotic carotid artery plaques.24 Intravital microscopy coregistered osteogenic and elastolytic signals in CRD apoE"/"/catS++ mice (Figure 2A). In contrast, CRD apoE"/"/catS−/− mice contained less osteogenic signal in the carotid plaque, where catS elastolytic activity remained undetectable (Figure 2B). Correlative histological analysis showed advanced calcification in CRD apoE"/"/catS++ mouse arteries detected by von Kossa staining (Figure 2C) and alkaline phosphatase activity (Figure 2D), whereas CRD apoE"/"/catS−/− mice showed negligible calcification and alkaline phosphatase activity, which corroborated the molecular imaging results.

CatS-Associated Elastin Breaks Are More Common in CRD ApoE"/"/CatS++ Plaques Than in Those in CatS-Deficient Mice

Fluorescence immunohistochemistry detected abundant immunoreactive catS expression in CRD apoE"/"/catS++ plaque associated with increased fragmentation of elastin (Figure 3A). apoE"/"/catS−/− and CRD apoE"/"/catS−/− mice had undetectable levels of catS and fewer elastin fragments (Figure 3A), which was verified by quantitative histological assessment (P<0.001; Figure 3B).

Intimal and Medial Calcification Is Associated With CatS Expression and Elastin Degradation in CRD ApoE"/"/CatS++ Mouse Aortas

Advanced calcification in the intima and media was associated with elastin fragmentation in the aortas of CRD apoE"/"/catS++ mice, whereas aortas of CRD apoE"/"/catS−/− mice had preserved elastin and negligible calcification (Figure 4A). Further histopathological analysis of CRD apoE"/"/catS++ plaques suggested a link between catS expression, reduced elastin (van Gieson staining), and calcifying cells in the media and intima (alkaline phosphatase and von Kossa; arrows) compared with CRD apoE"/"/catS−/− mice (Figure 4B). Notably, CRD apoE"/"/catS++ mice had low cystatin C tissue expression, which suggests imbalance that would favor elastin degradation in the arterial wall (Figure 4B). Correlative fluorescence imaging further colocalized immunoreactive catS with osteogenic near-infrared signal in CRD apoE"/"/catS++ mice injected with OsteoSense680 (Figure 4C).

Aortic Valves of CRD ApoE"/"/CatS++ Mice Exhibit Features of Calcific Valve Disease

Gross morphology and dual-channel fluorescence microscopy (Figure 5A) demonstrated advanced calcification (OsteoSense) in inflamed aortic valves (CLIO-gly). Individual mapping showed that signal intensities peaked at the areas of leaflet attachment to the aortic wall (Figure 5A). Histological plaque development. Histological analysis showed that catS deletion did not reduce plaque size (Figure 1D) or macrophage accumulation in CRD mice (Figure 1E).
analysis further demonstrated that aortic leaflets obtained from CRD apoE−/−/catS+/+ mice contained abundant macrophages that expressed catS in association with undetectable elastin (van Gieson negative), whereas CRD apoE−/−/catS−/− mice had preserved valvular elastin and no macrophage-derived catS (Figure 5B). In addition, valves from CRD apoE−/−/catS−/− mice showed substantial calcification (von Kossa), whereas no calcification occurred in CRD apoE−/−/catS−/− valves (Figure 5B). Quantitative analysis showed no significant difference between macrophage accumulations in the 2 CRD groups (Figure 5C).

**CatS Deficiency Does Not Alter Expression Levels of Other Major Cathepsins**

Germline manipulation of a gene in mice could cause “compensatory” changes in other genes that share similar functions with the targeted gene. Therefore, further experiments were conducted to examine the expression of other elastolytic enzymes. Quantitative real-time reverse-transcription polymerase chain reaction analysis demonstrated β-actin–adjusted levels of RNAs encoding cathepsins S, B, L, and K and MMP-2 and MMP-9 in the aortas of CRD apoE−/−/catS+/+ or CRD apoE−/−/catS−/− mice (Figure 6). As expected, CRD apoE−/−/catS−/− mice did not express catS. In addition, catS deletion did not cause statistically significant changes in expression of cathepsins B, L, or K and MMP-2 and MMP-9.

**SMCs Treated With Aortic Elastin Peptide and Recombinant CatS in Phosphate-Enriched Culture Medium Display Greater Osteogenic Potential**

To explore the mechanisms by which catS deletion decreased calcification, we tested in vitro the ability of elastin peptides to promote calcification of primary cultures of human vascular SMCs (Figure 7). Treatment of SMCs in osteogenic medium with elastin peptides significantly increased alkaline phosphatase activity relative to control levels (P<0.01). The addition of catS further increased alkaline phosphatase activity up to 2-fold relative to elastin peptides (P<0.001; Figure 7A and 7B), which suggests that elastin fragments cleaved by catS promote osteogenic activity more potently than randomly cleaved elastin fragments. CatS inhibition by simultaneous addition of cystatin C, an endogenous inhibitor of cathepsins, attenuated the increase in osteogenesis that resulted from cathepsin activity (Figure 7A through 7C). High serum phosphate levels contribute to cardiovascular calcifi-

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**Figure 5** (Continued). (CLIO-gly, green), Individual mapping (bottom) showed maximum signal intensities at the areas of high mechanical stress (arrows). The data represent 3 mice that showed similar results. **B**, Aortic leaflets from CRD apoE−/−/catS+/+ mice contained abundant macrophages (Mac 3+) that expressed catS in association with undetectable elastin (van Gieson negative) and showed evidence of calcification (von Kossa), the characteristics of calcific aortic valve disease (left). In contrast, inflamed leaflets of CRD apoE−/−/catS−/− mice exhibited negligible catS expression, preserved elastin, and no evidence of calcification (right). Bar = 100 μm. **C**, Quantitative assessment showed no significant difference in macrophage accumulation between CRD apoE−/−/catS+/+ and CRD apoE−/−/catS−/− mice. Ao indicates aorta.
cation; therefore, we also tested the effect of increased phosphate on calcification of vascular SMCs. The addition of monosodium phosphate moderately increased calcification with or without cleaved elastin (data not shown); however, with catS, monosodium phosphate promoted calcification more strikingly (35-fold, $p < 0.001$; Figure 7A and 7C). Of note, alkaline phosphatase activity decreases in more prominently calcifying cells.

Discussion

The present study provides evidence that catS promotes arterial and valvular calcification in hypercholesterolemic mice with CRD. Key findings documented here (1) show the suppression of arterial and aortic valve calcification in catS-deficient mice; (2) demonstrate in vivo that arterial calcification is associated with catS activity as detected by real-time visualization of spectrally distinct near-infrared signals amplified by catS-activatable and calcification-targeted molecular imaging agents; (3) correlate catS expression with calcifying cells and elastolysis in atheroma and inflamed aortic valves; and (4) provide mechanistic in vitro evidence that human vascular SMCs treated with elastin fragmented by catS undergo osteogenic changes, a process augmented in phosphate-enriched culture medium. Clinical and preclinical studies suggest that calcification of arteries or valves can cause devastating complications, including plaque rupture and aortic valve stenosis. These results support the hypothesis that elastolysis promotes osteogenesis. The present study observations suggest that antiinflammatory therapies and/or maintenance of elastin integrity by limitation of elastolytic activity might prevent cardiovascular calcification and its complications when introduced early.

The present study extends our previous work on the pathogenesis of cardiovascular calcification, which demonstrated that atherosclerotic calcification and calcific aortic valve disease share similar risk factors and proinflammatory molecular and cellular processes, as determined by advanced molecular imaging approaches. Notably, the present study used molecular imaging of early calcification and
elastolytic activity to address new mechanisms underlying accelerated calcification in patients with CRD and suggests that calcification is a multifactorial process induced by proinflammatory stimuli that promote accumulation of elastolytic macrophages. Because mature aortic valves have an elastin-rich, multilayered structure and can develop inflammatory lesions that recapitulate features of atherosclerotic plaques, we propose that similar mechanisms of catS-associated elastin degradation contribute to the development of calcific aortic valve disease. Aortic valve calcification impairs the movement of aortic valve leaflets, which affects cardiac function, and can only be alleviated through costly and invasive procedures. Therefore, early diagnosis of and interference with aortic valve calcification could provide enormous clinical benefits.

CatS, one of the most potent mammalian elastases abundantly expressed by macrophages and SMCs in atheroma, contributes significantly to proteolysis of elastic laminae. Previous studies suggested that elastic fibers resist degradation due to numerous cross-links and the highly hydrophobic characteristics of tropoelastin chains. However, during progression of atherosclerosis, when disruption of the balance between cathepsins and their inhibitor cystatin C occurs, powerful proteases such as catS may degrade elastin, generating soluble peptides. These elastin-derived peptides serve as biologically active molecules (so-called matrikines or elastokines) that are highly chemotactic for macrophages and can regulate cell migration and proliferation, as well as release of bone-regulating proteins from SMCs and valvular myofibroblasts, which leads to plaque growth and calcification. In addition, human genetic studies link mutations in the elastin gene and calcific valvular aortic stenosis.

Previous studies established the contribution of catS to the pathogenesis of atherosclerosis and aortic stenosis. The present study used genetically modified mice and molecular imaging to seek direct in vivo evidence for the role of catS in calcification. We showed in vivo that lack of catS elastolytic activity is associated with decreased calcification in atherosclerotic plaques and aortic valves. Histopathological validation studies also showed that calcification decreased significantly in catS-deficient mice with CRD.

The present study further demonstrated an in vitro preparation that permits exploration of the mechanisms of vascular cell calcification, which suggests that treatment of primary human SMCs with human aortic elastin peptide and recombinant catS induces calcification of vascular cells. Moreover, the amplified osteogenic responses in phosphate-enriched culture medium suggest that catS-associated elastin degradation promotes arterial calcification in the hyperphosphatemic milieu of chronic renal impairment. These in vitro results and in vivo findings in hyperphosphatemic mice with CRD coincide with clinical studies that imply that an imbalance of the mineral metabolism causes vascular calcification in patients with renal failure. Clinical reports further suggest that elevated serum phosphate concentrations are associated with a substantially greater risk of end-stage CRD, and that risk increases up to 5-fold for each 1.0-mg/dL increment in the mean serum phosphate concentration.

We used cystatin C as an established marker of the glomerular filtration rate to validate our model of CRD. The present study also demonstrated that apoE deficiency increased cystatin C, which agrees with clinical evidence that patients with documented atherosclerosis have elevated levels of this inhibitor. Although circulating cystatin C increased in CRD apoE/ mice, local expression in atherosclerotic lesions appears to decrease, in agreement with our previous report; however, the mechanism of this paradox remains unknown. Because a wide variety of tissues produce cystatin C, systemic cystatin C production, rather than local changes in cystatin C expression in atherosclerotic plaques, may determine its elevated serum concentrations.

Collectively, our findings suggest the potential multistep mechanism that accelerates cardiovascular calcification in Figure 8. Schematic of the proposed multistep mechanism of accelerated atherosclerotic and valvular calcification in CRD. In atherosclerotic artery and inflamed aortic valve, macrophage-derived catS degrades elastin. Biologically active elastin-degradation products initiate calcification of mesenchymal cells (eg, vascular SMCs or valvular myofibroblast-like cells). Furthermore, CRD-associated hyperphosphatemia accelerates calcification of mesenchymal cells through phosphate-induced release of matrix vesicles and apoptosis, which results in more advanced calcification.
CRD (Figure 8). In atherosclerotic lesions and inflamed valves, macrophage-derived catS and other elastolytic enzymes participate in degradation of elastin matrix. On disruption of the elastic lamina, mesenchymal cells (arterial SMCs or valvular myofibrolast-like cells) proliferate, which causes lesion formation and growth. In addition, elastolysis-triggered release of biologically active elastin-degradation products (matrikines) and various uremia-specific proinflammatory factors may attract more macrophages, which in turn produce more proteolytic enzymes, thus forming an amplification loop and promoting further expansion of the lesion. Mesenchymal cells, activated by elastin-degradation products, undergo osteogenic differentiation. The systemic mineral imbalance, such as hyperphosphatemia in patients with CRD, further accelerates calcification of vascular SMCs or valvular myofibrolasts through phosphate-induced release of matrix vesicles and apoptosis.13,47

The increased risk of mortality and morbidity associated with cardiovascular calcification drives the development of new therapeutic strategies to prevent and potentially reverse this process. Future therapeutic interventions in calcification-prone individuals may target inflammation and phosphate balance. New therapeutic options may also include selective inhibition of catS. More importantly, identification of high-risk patients requires new imaging modalities or biomarkers that target the origin of calcification and provide a powerful tool in personalized preventive cardiovascular medicine. A better understanding of the molecular and cellular mechanisms of cardiovascular calcification will lead to improved therapies for unstable coronary plaques and calcific aortic valve lesions while the disease remains silent or reversible.24 Although calcification in atherosclerosis typically involves the intima intima, CRD calcification occurs primarily in the media. Therefore, development of high-resolution imaging of calcification in different arterial layers may distinguish the origin of calcification and provide a powerful tool in personalized preventive cardiovascular medicine. A better understanding of the molecular and cellular mechanisms of cardiovascular calcification will lead to improved therapies for unstable coronary plaques and calcific aortic valve lesions. Ongoing efforts that combine rigorous assessment of arterial and valvular pathology and further development of imaging technologies will provide novel insights into optimum therapeutic strategies for treatment of calcific vasculopathy/valvulopathy, particularly in patients with CRD.

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Disclosures
Drs Weissleder and Jaffer are shareholders of VisEn Medical, Woburn, Mass. The remaining authors report no conflicts.

References


CLINICAL PERSPECTIVE

Aging societies face a growing burden of vascular and valvular calcification. Half of all individuals with chronic renal disease succumb to cardiovascular complications. Despite its vast clinical significance, the mechanisms of accelerated cardiovascular calcification, particularly in chronic renal disease, remain obscure, and we currently lack therapies to prevent its progression. Recent clinical trials showed no benefit of statin therapy on progression of calcific aortic valve stenosis, a growing clinical challenge without alternatives to costly invasive treatments. Hence, the need to discover new pathways that contribute to cardiovascular calcification and to develop new therapeutic strategies to prevent or reverse calcification has driven our recent research investigations. The present study provides support for the hypothesis that elastin breakdown products produced by cathepsin S, a proteinase regulated by inflammation and overexpressed in diseased arteries and valves, can trigger osteogenesis. These results indicate that antiinflammatory therapies and preservation of elastin integrity might prevent cardiovascular calcification and its complications when introduced early. Therapeutic interventions in calcification-prone patients with chronic renal disease may target inflammation and phosphate balance. New therapeutic options may also include inhibition of elastolytic cathepsins, particularly cathepsin S. Although calcification in atherosclerosis typically occurs in the intima, chronic renal disease calcification primarily involves the media. Therefore, development of high-resolution imaging of calcification in different arterial layers may distinguish the cause of calcification and provide a powerful tool in personalized medicine. More importantly, identification of high-risk patients requires new imaging modalities to detect calcifying atherosclerotic plaques and aortic valve lesions at stages during which the disease remains silent or reversible.
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Supplemental Methods

Animal experiments

We studied osteogenic changes in arteries and aortic valves of 30-week-old apoE<sup>-/-</sup>/catS<sup>+/+</sup> (n=24) and apoE<sup>-/-</sup>/catS<sup>-/-</sup> (n=24) mice that consumed an atherogenic diet (Teklad TD 88137; 42% milk fat, 0.2% total cholesterol, Harlan, Indianapolis, IN) from 10 weeks of age. At 20 weeks of age, mice in each group were randomized either to continue with the atherogenic high-cholesterol diet or a CRD group (12 mice per group). Age-matched wild-type C57/BL6 mice (Jackson Laboratory, Bar Harbor, ME) with normal renal function (n=6) and CRD (n=6) served as controls. We used a two-step procedure to create CRD: left hemi-nephrectomy followed by right total nephrectomy one week later, procedures known to aggravate atherosclerosis.<sup>1,2</sup> At 10 weeks after surgery, mice underwent intravital microscopy and were sacrificed for ex vivo imaging and correlative histological analyses. The Subcommittee on Research Animal Care at Massachusetts General Hospital approved all procedures.

Blood biochemical analyses

Blood was collected from the heart into chilled dry tubes and spun in a refrigerated centrifuge, and serum was stored at -80°C. Serum levels of total cholesterol, cystatin C, creatinine, phosphate, and calcium were assessed (n=5 per group).

Creatinine assay

Mouse blood samples (n=5 per group) were spinned for 10 minutes at 10,000 rpm and separated serum was again centrifuged for 60 min at 15,000 rpm to remove emulsionated fat. Cleared serum was assayed for creatinine levels using the standard
spectrophotometric Jaffe method according to manufacturer’s instructions (QuantiChrom Creatinine Assay kit, Bioassay Systems). Creatinine concentration was determined from absorption values at 490-530 nm.

**ELISA**

Serum samples from all groups of mice (n=5 per group) were collected and used for cystatin C ELISA. Briefly, 96-well immunosorb plates (NUNC Co., Naperville, IL) were coated with cystatin C polyclonal IgG (10 µg/mL; Cortex Biochem) in NaHCO₃ (pH 8.2) overnight at 4°C. After wash and 3% BSA blocking, plates were incubated with diluted mouse serum samples and were again incubated overnight at 4°C. Cystatin C mAb’s (1 µg/mL) were used as detecting antibody followed with peroxidase-conjugated goat anti-mouse IgG/IgM (Kirkegaard and Perry Laboratories, Gaithersburg, MD). ELISA plates were developed with OPD (Sigma Chemical Co.). Recombinant mouse cystatin C was used as standard for each plate.

**Molecular imaging agents**

**i) Detection of elastolytic activity.** A novel peptide-based cathepsin-S-activatable agent consists of backbone of a cathepsin-S-cleavable dipeptide substrate (Leu-Arg) and two polyethylene glycol (PEG) chains in their dendritic arms containing a fluorochrome. Following enzymatic cleavage by cathepsin S, the fluorochromes separate, resulting in signal amplification (ex/em 750/780 nm). *In vitro* validation studies indicated that cathepsin S, but not cathepsins B, K, or L, cleave this probe.

**ii) Detection of osteogenic activity.** Bisphosphonate-conjugated imaging agent (OsteoSense680, VisEn Medical Inc., Woburn, MA) elaborates fluorescence evident
through the near-infrared window (ex/em 650/680 nm) detected osteogenic activity as previously described.\textsuperscript{4-6}

\textit{iii) Detection of inflammation.} Cross-linked iron oxide (CLIO-gly) fluorescent nanoparticle, an imaging agent that elaborates fluorescence visible through the near-infrared window (ex/em 750/780 nm) detected macrophage accumulation.

\textbf{Intravital laser scanning fluorescence imaging}

Mice (n=12 per group) simultaneously received two spectrally distinct imaging agents (activatable cathepsin S/750 and OsteoSense680 or CLIO750 and OsteoSence680) or saline via intravenous injection 24 hours before imaging. We performed dual-channel fluorescence imaging using an Olympus IV100 intravital laser scanning fluorescence microscope (Olympus Corporation, Tokyo, Japan) specifically developed for imaging small experimental animals as previously described.\textsuperscript{4,5,7} Images were acquired using an Olympus 4x UplanApo (N.A. 0.16) objective and the Olympus Fluoview FV300 program version 4.3. Samples were excited with a 633 nm HeNe-R laser (Model 05LHP925; Melles Griot) and a 748 nm infrared diode laser (Model FV10-LD748, Olympus Corporation, Tokyo, Japan) and images collected using custom build dichroic mirrors SDM-570 and SDM-750, and emission filters BA 650-700 nm and BA 770 nm IF respectively (Olympus Corporation, Tokyo, Japan). Images were acquired serially to avoid cross talk between channels and processed and analyzed using ImageJ software (v.1.41, NIH, Bethesda, MD).

\textbf{Macroscopic fluorescence reflectance imaging}

After mice were euthanized, aortas were perfused with saline, dissected, and imaged to map the macroscopic near-infrared osteogenic activity elaborated from
OsteoSense680 imaging agent using a fluorescence reflectance imaging system equipped with multichannel filter sets (Omega Optical, Brattleboro, VT) as previously described (n=12 per group).^5

**Histopathological assessment**

**i) Morphological characterization.** Tissue samples were frozen in OCT compound (Sakura Finetech, Torrance, CA) and 5-µm serial sections were cut and stained with hematoxylin and eosin for general morphology. Alkaline phosphatase activity (marker of early osteoblastic differentiation) was detected on cryosections according to the manufacturer’s instructions (Alkaline Phosphatase Substrate Kit; Vector Laboratories, Burlingame, CA). Van Gieson stain assessed elastin. Von Kossa silver stain histochemically imaged advanced calcification. Masson trichrome stain evaluated glomerulosclerosis.

**ii) Immunohistochemistry.** We employed immunohistochemistry for macrophages (anti-mouse Mac3, BD Biosciences, San Jose, CA) and cathepsin S (Santa Cruz Biotechnology, Santa Cruz, CA). Immunohistochemistry used avidin-biotin peroxidase method. The reaction was visualized with a 3-amino-9-ethyl-carbazol substrate (AEC, Sigma Chemical, Saint Louis, Missouri). Adjacent sections were treated with nonimmune IgG provided controls for antibody specificity. Images were captured with a digital camera (Nikon DXM 1200-F, Nikon Inc, Melville, NY). Fluorescence immunohistochemistry visualized simultaneously Texas Red-labeled cathepsin S and elastin. Images were captured and processed with the epifluorescence microscope (Eclipse 80i, Nikon Instruments, Melville, New York) with a cooled CCD camera (Cascade, Photometrics, AZ).
**Real time RT-PCR**

Total RNA was isolated from aorta by RNeasy Mini Kit (Qiagen) from all groups of mice (n=5 per group). Primer sequences were as follows: cathepsin-S, 5’-TCCCTCAGTGCTCAGAACCT-3’ and 5’-TGCTTTTTCAGGGCATCTT-3’; cathepsin-B, 5’-AAAAAGGCCTGGTTCAGGT-3’ and 5’-GGGAGTAGCCAGCTTCACAG-3’; cathepsin-K, 5’-AGACGCTTACCCGTATGTGG-3’ and 5’-GGACACAGAGACGGGTCTTA-3’; cathepsin-L, 5’-GTGGACTTTTCAGGCATCTT-3’ and 5’-TATCCACCAGGCCCTGTGTCA-3’; MMP 2, 5’-CCCCATGAAGCCTTTGTTTTACC-3’ and 5’-TTGTAGGAGGTGCCCTGGA-3’; MMP 9, 5’-AGGTGGACCATGAGGTGAAC-3’ and 5’-CGGTTGAAGCAAAGAAGGAG-3’. PCR detection and quantification of cathepsin S, B, L, and K used MyiQ Single-Color Real-Time PCR Detection System and iQ SYBR Green Supermix (BioRad). All measurements were duplicated and the mean value was used. Data are expressed in arbitrary units that were normalized by β-actin.

**Primary human smooth muscle cell culture**

Human vascular smooth muscle cells were plated on 12-well cell culture plates, maintained in DMEM containing 10% fetal bovine serum, allowed to reach 80%-90% confluence and then replaced with fresh calcification-promoting medium containing 0.9 mM NaH$_2$PO$_4$. Cells were treated with human aortic elastin peptides (molecular weight >1000), 100 mg/ml (Elastin Products Company), either alone or in the presence of human recombinant cathepsin S, 1 mg/ml (Calbiochem); cathepsin S plus the cathepsin inhibitor cystatin C, 1 mg/ml (Calbiochem); or cystatin C, 1 mg/ml. Separate plates were treated with 2 mM NaH$_2$PO$_4$ in addition to the above treatments. After 4 days of treatment, cells were washed twice with 100 mM TRIS pH 8.0 and stained for alkaline phosphatase activity. Cells were then fixed in 4% PFA for 15 minutes and re-stained for
the presence of calcium phosphate crystals using Von Kossa method. Stained cells were imaged with a color CCD camera (Nikon DXM 1200-F, Nikon Inc.), and the red stain indicative of alkaline phosphatase activity and the black silver staining indicative of calcium phosphate crystals were quantified as a percentage of total area using imaging software (IPLab version 3.9.3; Scanalytic Inc., Rockville, MD).

**Quantification**

Macrophages were counted as a mean number of mac-3-positive cells per 10 high-power fields (x400) in the aortic root plaques or aortic valve lesions. Only cells expressing an antigen of interest (defined as red reaction product associated with blue hematoxylin nuclear counterstain) were counted as previously described.\(^8\)

**Statistical analysis**

Statistical analyses for comparison of multiple groups used one-way ANOVA followed by the Tukey post-hoc test was performed by using GraphPad Prism (v. 4.0, GraphPad Software, San Diego, CA). Student \( t \) test was performed when two groups were compared. Data are presented as mean ±SEM. \( P \)-values less than 0.05 were considered significant.
Supplemental Figure

Figure Legend

Histological evidence of kidney insufficiency in CRD mice.

Histopathological analysis (Masson trichrome) reveals normal kidney appearance in apoE<sup>−/−</sup>catS<sup>+/+</sup> mice. CRD apoE<sup>−/−</sup>catS<sup>+/+</sup> and CRD apoE<sup>−/−</sup>catS<sup>−/−</sup> mice developed thickening of capsule membrane (arrows) and have enlarged glomeruli due to increased Bowman’s space, characteristic of renal insufficiency. Bar=50µm.
References


8. Aikawa E, Whittaker P, Farber M, Mendelson K, Padera RF, Aikawa M, Schoen FJ. Human semilunar cardiac valve remodeling by activated cells from fetus to
adult: implications for postnatal adaptation, pathology, and tissue engineering.

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