Klotho Deficiency Causes Vascular Calcification in Chronic Kidney Disease

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ABSTRACT

Soft-tissue calcification is a prominent feature in both chronic kidney disease (CKD) and experimental Klotho deficiency, but whether Klotho deficiency is responsible for the calcification in CKD is unknown. Here, wild-type mice with CKD had very low renal, plasma, and urinary levels of Klotho. In humans, we observed a graded reduction in urinary Klotho starting at an early stage of CKD and progressing with loss of renal function. Despite induction of CKD, transgenic mice that overexpressed Klotho had preserved levels of Klotho, enhanced phosphaturia, better renal function, and much less calcification compared with wild-type mice with CKD. Conversely, Klotho-haploinsufficient mice with CKD had undetectable levels of Klotho, worse renal function, and severe calcification. The beneficial effect of Klotho on vascular calcification was a result of more than its effect on renal function and phosphatemia, suggesting a direct effect of Klotho on the vasculature. In vitro, Klotho suppressed Na⁺/H⁺-dependent uptake of phosphate and mineralization induced by high phosphate and preserved differentiation in vascular smooth muscle cells. In summary, Klotho is an early biomarker for CKD, and Klotho deficiency contributes to soft-tissue calcification in CKD. Klotho ameliorates vascular calcification by enhancing phosphaturia, preserving glomerular filtration, and directly inhibiting phosphate uptake by vascular smooth muscle. Replacement of Klotho may have therapeutic potential for CKD.


The high cardiovascular mortality in patients with chronic kidney disease (CKD) is closely associated with vascular calcification (VC).1,2 Risk factors for VC include hypertension, hyperlipidemia, diabetes, plasma phosphate, homocysteine, and osteoprotegerin.3,4 Defects in endogenous anti-calcification factors such as matrix Gla protein, osteoprotegerin, carbonic anhydrase isoenzyme II, fibrillin-1, fetuin-A, fibroblast growth factor 23, and Klotho may play an important role in this dire complication of CKD.5–10 High serum phosphate is associated with significantly increased risk for death.11 Treatment with phosphorus binders improves survival of hemodialysis patients compared with no treatment with matched baseline serum phosphate levels.12

Early diagnosis and treatment is important to retard the progression of CKD. Most biomarkers in current clinical use are not early or sensitive enough.13–16 The need to find a sensitive and early biomarker is of paramount importance for early diagnosis and intervention. Various strategies have been devised to slow progression of renal disease12,17,18 with varying effectiveness.19 We are in

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dire need of additional new agents in preventing the progression of CKD and in ameliorating VC.

*Klotho* was originally identified as an aging suppressor. Its gene product is a single-pass transmembrane protein that functions as a coreceptor for fibroblast growth factor (FGF) 23. Klotho is expressed widely, but its level is highest in the kidney. Klotho is also secreted into the cerebrospinal fluid, blood, and urine by ectodomain shedding mediated by membrane-anchored proteases. Secreted Klotho functions in an endocrine fashion as an enzyme or possibly a hormone. Klotho deficiency in rodents leads to a syndrome of premature aging where ectopic soft tissue calcification is a notable feature. Overexpression of Klotho rescues the Klotho-deficient phenotype including ectopic calcification, suggesting that Klotho may be an inhibitor of ectopic calcification.

Because of the features common to both human CKD and murine experimental Klotho deficiency (*Kl/H11002/H11002*), we postulate that Klotho deficiency may be responsible for the VC in CKD. The literature offers suggestive but limited evidence for a pathogenic role of Klotho in CKD. Renal Klotho mRNA is lower in a five-sixths nephrectomy model of CKD and in human nephrectomy samples from end-stage sclerotic kidneys. A modest amelioration of proteinuria and renal function was observed when Klotho was overexpressed genetically in a chronic glomerulonephritis model or via viral delivery in a chronic angiotension II and a spontaneous hypertension model.

We will test three hypotheses: (1) CKD is a state of Klotho deficiency; (2) low Klotho is an early marker of CKD; and (3) Klotho deficiency contributes to VC and Klotho replacement ameliorates CKD via multiple mechanisms.

**RESULTS**

**CKD Is a State of Klotho Deficiency**

The pattern of calcification of soft tissue in CKD is indistinguishable from that seen in Klotho deficiency in rodents. We found similar increases in tissue calcium content in *Kl/H11002/H11002* and CKD animals (Figure 1, A and B). We next asked whether CKD is a state of endocrine Klotho deficiency. End-stage CKD patients and animals have reduced Klotho in kidneys, but there is no data on blood or urine Klotho in CKD. Klotho was undetectable in homozygous Klotho deficiency (*Kl/H11002/H11002*) and was notably decreased in kidney and barely detectable in the blood and urine of CKD mice (Figure 1C), indicating that CKD is a state of “pan deficiency” of Klotho. Because of the lack of a reliable assay for human plasma Klotho at the time of the study, we measured urinary Klotho in CKD patients.
as a surrogate. Humans (Table 1) with various stages of CKD (National Kidney Foundation classification) have lower levels of Klotho in blood, kidney, and urine (Figure 1C), high plasma FGF23, hyperphosphatemia (Table 2), and ectopic calcification (Figure 1, A and B). A critical question is whether Klotho deficiency is a mere marker or whether it contributes to the pathophysiology of CKD because the latter raises the possibility of therapeutic replacement. To this end, we examined whether Klotho levels affect CKD and its complications. Baseline Klotho was lower in Klotho mice compared with WT and was highest in Tg-Kl mice (Figure 2A and Supplemental Figure 2A). Klotho was decreased in all lines of mice when CKD was induced. The Klotho level in Tg-Kl-CKD mice was lower than Tg-Kl-Sham mice but still equivalent to that of WT-Sham mice (Figure 2A and Supplemental Figure 2A). Tg-Kl mice have higher plasma Klotho levels and more organs expressing Klotho protein. In the kidneys of Tg-Kl mice, almost all of the renal structures express Klotho protein (Supplemental Figure 2B).

WT-CKD mice had hypertension, anemia, increased plasma creatinine (Pc), declined creatinine clearance (Clc), increased proteinuria (Supplemental Table 1), and more severe renal histologic damage (Supplemental Figure 3). All of the changes were slightly exaggerated in Klotho mice but were much improved in the Tg-Kl mice (Supplemental Table 1 and Supplemental Figure 3). Klotho mice had more severe and Tg-Kl mice had milder CKD than WT mice, although all were subjected to the same insult. Hence, amelioration of CKD per se can be a potential factor for less severe soft tissue calcification when Klotho levels are maintained.

Elevation of parathyroid hormone (PTH) in WT-CKD mice was blunted by Klotho overexpression and worsened by Klotho deficiency (Figure 2B). CKD decreased plasma 1,25D3 modestly in WT mice (Figure 2C), which is compatible with the moderate CKD (Supplemental Table 1). The decreased 1,25D3 in Klotho mice is compatible with Klotho being a potent suppressor of 1,25D3 production (Figure 2C). Our in vivo data do not exclude the possibility that Klotho’s beneficial effect may be through various calcitropic hormones. The direct effect of Klotho will be examined below.

One determinant of soft tissue calcification is plasma phosphate (Pi) concentration. Both Klotho and WT animals with CKD had higher levels of plasma Pi and higher fractional excretion of phosphorus (FEphos) than Sham animals (Supplemental Table 1). In contrast, Tg-Kl-CKD mice did not show much hyperphosphatemia; their FEphos were already high in baseline and did not increase further with CKD (Supplemental Table 1). Therefore, a second mechanism by which Klotho can lessen soft tissue calcification might be by lowering plasma phosphate levels through promotion of phosphaturia.

We screened for ectopic calcification in multiple organs. As expected, there was no staining in Sham animals (not shown). In CKD, there was calcification in the kidneys and aortas of both WT and Klotho mice (Figure 2D). In contrast, Tg-Kl-CKD animals had very little or no calcification (Figure 2D). The modest and patchy calcification in the vasculature of WT CKD mice might be due to the modest renal failure and/or short duration of follow-up. The percentage of mice with detectable calcification for each CKD group was: Klotho mice, 69.2% (9 of 13) versus WT 57.1% (8 of 14); and Tg-Kl, 25% (4 of 16) versus WT 53.3% (8 of 15). Calcium content in aortas (Figure 3A) and kidneys (Figure 3B) was higher in CKD than Sham in both the WT and Klotho mice. The calcium content in all organs is inversely related to Klotho levels: highest in Klotho mice, intermediate in WT, and lowest in Tg-Kl (Figure 3, A and B).

In humans with CKD, both plasma Cr and Pi levels are predictors of soft tissue calcification. Soft tissue cal-

### Table 1. Summary of ages and eGFRs of normal subjects and CKD patients

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Normal</th>
<th>CKD Overall</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>47.7 ± 3.1</td>
<td>52.9 ± 2.2</td>
<td>41.5 ± 3.8</td>
<td>49.0 ± 3.7</td>
<td>59.6 ± 4.0</td>
<td>55.8 ± 5.4</td>
<td>60.1 ± 6.0</td>
</tr>
<tr>
<td>Gender (male/female)</td>
<td>6/7</td>
<td>18/22</td>
<td>1/7</td>
<td>5/4</td>
<td>4/4</td>
<td>6/2</td>
<td>2/5</td>
</tr>
<tr>
<td>eGFR (mL/min per 1.73 m²)</td>
<td>105.46 ± 4.81</td>
<td>58.80 ± 6.90</td>
<td>116.88 ± 3.26</td>
<td>75.44 ± 2.97</td>
<td>46.00 ± 3.35</td>
<td>22.38 ± 4.81</td>
<td>10.16 ± 1.26</td>
</tr>
</tbody>
</table>

eGFR is calculated with the Modification of Diet in Renal Disease equation.

**P < 0.01 versus normal subjects by one-way ANOVA followed by Student-Newman-Keul’s test.

**P < 0.05 versus normal subjects by one-way ANOVA followed by Student-Newman-Keul’s test.

### Table 2. Blood Pi and creatinine clearance in Klotho mice and WT CKD mice

<table>
<thead>
<tr>
<th></th>
<th>Klotho/−/− Model</th>
<th>WT</th>
<th>Klotho/−/− Model</th>
<th>Sham</th>
<th>CKD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serum Pi (mg/dl)</td>
<td>5.9 ± 0.4</td>
<td>8.1 ± 0.5</td>
<td>6.3 ± 0.6</td>
<td>7.1 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>Clc (µL/min/g body wt)</td>
<td>15.41 ± 1.03</td>
<td>10.32 ± 2.14</td>
<td>10.22 ± 2.74</td>
<td>6.15 ± 1.13</td>
<td></td>
</tr>
</tbody>
</table>

The data are represented as the means ± SEM (n ≥ 4).

**P < 0.01 versus Sham by unpaired t test.

**P < 0.05 versus WT by unpaired t test.
Calcium content is positively related to plasma Pi and Cr in all mice (Figure 3C). When we divided the animals into subgroups on the basis of their genetic Klotho status, despite the overlap, one could see that for a given plasma Pi and Cr concentration, Tg-Kl mice had the lowest soft tissue calcium content, and Kl/H11001/H11002 had the highest, with WT in between (Figure 3C). Therefore, differences in plasma Pi or Cr are insufficient to explain the different levels of ectopic calcification in the various Klotho background. The data suggest that Klotho has a direct protective effect on soft tissue calcification above and beyond that of the renal effects of phosphaturia and preservation of glomerular filtration.

Pi Uptake and Pi-induced Mineralization and Dedifferentiation in Cultured Cells

Elevated plasma Pi is associated with VC in experimental animals and in CKD patients. Pi influx is believed to be mediated by NaPi-3 group of Na+/H+ coupled transporters (Pit-1).
and Pit-2) in vascular smooth muscle cells (VSMC). Runx2 expression has been postulated to be an early step of mineralization for osteoblasts and may represent ectopic osteogenesis when expressed in other cells. Pit1 and Pit2 mRNA was increased in KI+/− and decreased in Tg-Kl compared with WT mice (Figure 4A). Klotho deficiency increased Runx2 and decreased the smooth muscle marker SM22, whereas overexpression of Klotho had the opposite effect. Therefore, Klotho may control the balance between differentiation and dedifferentiation of VMSC. In the aorta, Pit1, Pit2, and Runx2 mRNA was upregulated, and SM22 mRNA was downregulated in CKD in both the KI+/− and WT background compared with Sham (Figure 4B). Klotho overexpression completely blocked the changes in Pit1, Pit2, Runx2, and SM22 mRNA induced by CKD (Figure 4B), suggesting that Klotho may maintain VSMC differentiation.

To illustrate whether Klotho directly inhibits VC, we used rat VSMC (A10 cells) to examine for mineralization induced by high ambient Pi. Treatment of A10 cells with recombinant soluble Klotho protein slightly decreased calcium content of A10 cells in 1 mM Pi (Figure 5, A through C, and Supplemental Figure 4A) but significantly reduced the mineralization induced by 2 mM Pi (Figure 5, A through C, and Supplemental Figure 4A) in a dose-dependent fashion (Figure 5, B and C). To examine whether high Pi and Klotho also influence mineralization in other cells, a kidney (MDCK), osteoblast (MC-3T3-E1), and adipocyte cell line (3T3-L1) were used. Calcium content was increased by high Pi in cultured MDCK and MC-3T3-E1 but not in 3T3-L1 (Figure 6A and Supplemental Figure 4B, C through D). These in vitro results indicate that Klotho directly inhibits high Pi-induced calcification in a cell type-specific fashion.

We next examined the effect of Klotho on Pi influx in cultured cells. Phosphate transport in A10 cells is primarily Na+−dependent (85 to 95% of Pi influx) (Figure 6D). The ambient Pi effect on Pi uptake is dose-dependent (Figure 5E). Klotho significantly suppressed Na+−dependent but not Na+−independent Pi transport (Figure 5, D through F). High ambient Pi did not affect calcium influx in A10 cells, and Klotho did not modulate calcium influx either in normal or high Pi culture medium (Supplemental Figure 5). This finding is compatible with the model proposed by Giachelli where Pi uptake activates a series of cellular processes that result in extracellular calcium phosphate deposition. There was inhibition of Pi influx in kidney and osteoblastic cells but not in adipocytes (Figure 6B). Both Pit1 and Pit2 (−10× lower abundance than Pit1) transcripts are present in A10 cells (NaPi-2, NaPi-2a, and NaPi-2c are not detectable by reverse transcription-PCR; data not shown). High Pi treatment increased both Pit1 and Pit2 mRNA in A10 cells, and Klotho blocked this increase (Figure 7A). A similar inhibition by Klotho was also found in osteoblast cells and adipocytes except for Pit1 in adipocytes (Figure 6C).

High Pi induced upregulation of Runx2 and downregulat-
tion of SM22 mRNA and protein in A10 cells (Figure 7), suggesting that dedifferentiation of smooth muscle occurred with high Pi. Klotho reversed these changes suggests and blocked Pi-induced dedifferentiation of A10.

DISCUSSION

This is the first report that CKD is a state of Klotho deficiency in the kidney, plasma, and urine and that Klotho downregulation is not merely an early biomarker for kidney damage but also plays a pathogenic role in the progression of CKD as well as one of the principal complications of CKD, namely VC. Klotho bestows its anti-calcification effect possibly via at least three mechanisms: a phosphaturic hormone, the preservation of GFR, and a direct effect on soft tissues including the vascular smooth muscle (Figure 8). The potential utility of Klotho in clinical practice is at least two-fold. First, Klotho can serve as an early and sensitive biomarker of CKD. Second, Klotho replacement therapy may be in the horizon in slowing progression of CKD as well as preventing and reversing complications.

CKD Is a State of Klotho Deficiency

Our animals have disease equivalent to human CKD stage 3 to 4, which comprises up to approximately 85% of human CKD. Decreased renal Klotho expression was shown in human renal tissue from end stage kidneys and animals with five-sixths nephrectomy. Because secreted Klotho exerts multiple effects on distant sites, it is crucial to explore Klotho protein levels in blood and urine. We found commensurate Klotho deficiency in the kidney, plasma, and urine in rodent CKD and in urine in human CKD. The mechanism of how kidney disease lowers Klotho expression is unknown presently but can potentially involve ischemia, oxidative stress, angiotensin II, and inflammation. CKD lowered Klotho even in the Tg-Kl mice, despite the fact that the transgene was driven by a constitutive promoter. This can be due to the fact that...
endogenous renal Klotho expression actually constitutes 50% of the renal Klotho in the transgenic animals.\textsuperscript{36} In addition, CKD may have a translational or post-translational effect on the transgenic Klotho.

**Pathogenic Role of Klotho in Progression of CKD and Its Complications**

The data clearly show that Klotho is more than a mere marker for CKD. Klotho overexpression lessens progression of CKD, improves Pi metabolism, and protects the vasculature from calcification. Previous studies showed that overexpressing Klotho by viral-based gene transfer\textsuperscript{34} or genetic manipulation\textsuperscript{33} attenuated progressive renal injury, but the Klotho status and systemic complications of CKD were not studied. Because Klotho is present in multiple body fluids,\textsuperscript{25,27,36,57} the restoration of Klotho clearly exerts multiple systemic effects in addition to renoprotection.

Disturbed mineral metabolism is implicated in hyperparathyroidism, osteodystrophy, and vascular calcification in CKD.\textsuperscript{38–61} Pi overload accelerates calcification in CKD, and control of Pi reduces calcification in CKD.\textsuperscript{62–64} Klotho exerts its phosphaturic effects by inhibiting renal NaPi-2a and NaPi-2c in the renal proximal tubule.\textsuperscript{25,38} Maintenance of high Klotho in CKD preserves phosphaturia and lessens phosphate retention. Hyperphosphatemia is also an important contributor to VC observed in Klotho-deficient mice.\textsuperscript{65}

\textit{Tg-Kl} animals have better renal function when subjected to the same renal insult. The mechanisms whereby Klotho protects kidney from injury are unknown but potentially include anti-oxidation, anti-apoptosis,\textsuperscript{55–56} and anti-senescence.\textsuperscript{33} In addition to preservation of phosphaturia and GFR, Klotho has a direct effect on the vasculature. Pathologic calcium phosphate deposition in the blood vessels and heart is found in aging,\textsuperscript{66} diabetes,\textsuperscript{67,68} hyperlipidemia,\textsuperscript{69} and CKD.\textsuperscript{3–4,7} NaPi-3 proteins (Pit1 and Pit2) are broadly expressed and believed to play housekeeping as well as pathologic roles in different cells.\textsuperscript{70–73} Extracellular Pi stimulates calcification in VSMC through inorganic Pi influx by NaPi-3.\textsuperscript{74–75} and cell-
surface Pit2 reorganization.73,76 High ambient Pi accelerates mineralization44,49 and stimulates surrogate markers of osteogenesis in VSMC,49,77 spawning the hypothesis that high Pi stimulates “ossification” of VMSC.77 Soluble Klotho not only suppresses baseline NaPi-3 activity but also abrogates high Pi-induced upregulation of NaPi-3 mRNA and activity and suppresses calcification and maintains differentiation of VMSC. Pit1 might also act through mechanisms independent of Pi influx,78 and suppression of Pit1 may affect cell proliferation.79 One minor caveat of the A10 in vitro model is that we do not know whether cultured rat cells mimic all features of human VSMC in vivo.

FGF23 signal transduction generally requires transmembrane Klotho as a coreceptor.21,80 CKD subjects have high levels of full-length FGF23 and upregulation of this signal pathway.81 We did not measure FGF23 levels in our animals. It is possible that part of the beneficial effects of Klotho on soft tissue in CKD result from improvement of FGF23 signal transduction.

Potential Clinical Utility
These preclinical studies lay the foundation for two major potential applications. Extensive effort has been devoted to search for early biomarker for kidney diseases focusing mostly on acute kidney disease82 and less on CKD.83 Proteins such as adiponectin,84 γ-glutamyltransferase,85 cystatin C,16 N-acetylβ-D-glucosaminidase,86 fatty acid-binding protein 1,87 and endothelin-188 were proposed as biomarkers. We documented that patients with early stage CKD (stage 1 and 2) already have significantly lower urinary Klotho, and urinary Klotho is progressively lowered with declining eGFR. Urinary Klotho protein might be an ideal early biomarker for CKD. One important goal of CKD treatment is to prevent or postpone the progression to end stage. Klotho supplementation might be a good strategy not only to preserve remnant kidney function but also to minimize complications of CKD through multiple mechanisms.

CONCISE METHODS

Human Study
A total of 53 human subjects were included in this study: 13 normal volunteers and 40 CKD patients (Table 1) at different stages according to the National Kidney Foundation.14 This study was approved by the Institutional Review Board of the University of Texas Southwestern Medical Center at Dallas. All of the human subjects were given and accepted an informed consent form. None of the human subjects were receiving treatment with Pi binder, calcium, or active vitamin D or...
analogs or renal replacement therapy when their urine samples were collected. For measurement of urinary Klotho protein, 4 ml of fresh urine was concentrated to 0.2 ml through Amicon Ultra-4 filters with 100-kD cutoff (Millipore, Billerica, Massachusetts). The concentrated urines (with identical urine creatinine) along with recombinant murine Klotho (rMKl) protein of known concentration were subjected to immunoblot. Specific signals on the basis of bands on films were obtained with free Image J program (National Institutes of Health), and the Klotho protein concentrations in urine samples were quantified using the rMKl as a standard curve.

Animal Models
All of the work on mice was conducted following the Guide for the Care and Use of Laboratory Animals by the National Institutes of Health and was approved by the Institutional Animal Care and Use Committee at the University of Texas Southwestern Medical Center.
The mice used for preparation of CKD model were: (1) one line of transgenic mice with overexpression of Klotho, EFmKL46 (Tg-Kl), whose genetic background is a mixture of C57BL/6 and 129 and (2) heterozygous for Klotho-deficient mice (Kl+/−), whose genetic background for is C57BL/6 and C3H/1. WT littermates were generated during cross-breeding for Tg-Kl and Kl+/− mice. Kl+/− mice and WT littermates used in this study ranged from 6 to 8 weeks; Kl+/−, Tg-Kl, and WT mice were approximately 12 weeks in age. CKD model was generated using uninephrectomy plus ischemia-reperfusion injury in contralateral kidney. Sham mice underwent laparotomy and manual manipulation of the kidneys. After recovery, the mice were housed in normal cages and fed with 1.0% phosphorus diet for 4 weeks with free access to tap water followed by 2.0% phosphorus diet for 8 weeks. For the metabolic study, the mice were transferred to individual metabolic cages. After acclimatization, 24-hour urine was collected, blood was drawn, and tissues were harvested. Plasma and urine chemistry were analyzed by Vitros Chemistry Analyzer (Ortho-Clinical Diagnosis, Rochester, New York) by the Animal Core Facility University of Texas Southwestern Medical Center. BP was measured by a computerized tail-cuff system (BP-2000; Visitech Systems, Apex, North Carolina) in conscious animals throughout our study. Plasma intact PTH and 1,25-(OH)2 vitamin D3 were measured using Apex, North Carolina) in conscious animals throughout our study. Plasma intact PTH and 1,25-(OH)2 vitamin D3 were measured using ELISA kits from Alpco (Salem, New Hampshire) and Immunodiag-nostic Systems (Scottsdale, Arizona), respectively.

**Von Kossa Staining and Calcium Content**

The calcium content in soft tissues was measured using the o-cresolphthalein complexone (OCPC) method (Sigma, St. Louis, Missouri). Quantitation (µg/mg protein) was normalized to protein concentration determined by Bradford protein assay. Kidney, heart, and aorta were stained with Von Kossa and counterstained with nuclear Fast Red for evaluation of calcium precipitation. Positive signal for calcium precipitation would be seen in black or brown-black.

**PCR**

For real time PCR, total RNA was extracted from mouse tissues (kidney and aorta) and cell lines (rat vascular smooth muscle cells, A10; mouse osteoblast-like cells, MC-3T3-E1; mouse adipocytes, 3T3-L1). Complimentary DNA was generated. Primers for quantitative PCR (qPCR) are shown in Supplemental Table 4 with conditions described previously. The detailed methods are described in the supplemental materials.

**Cell Culture**

Rat vascular muscle cell (A10), mouse osteoblasts (MC-3T3-E1), mouse adipocytes (3T3-L1), and canine kidney cell (MDCK) were cultured and maintained in condition as described previously. The cells were treated with Pi and/or soluble Klotho protein (amino acid number 31 to 982) as previously described. At given time points, the cells were harvested for Von Kossa staining, OCPC assay, RNA extraction, and for 32P-phosphate and 45Ca uptake (detailed protocol in Supplemental Methods).

**Kidney Histology and Immunohistochemistry**

Four-µm sections of frozen kidney tissues were stained with hematoxylin and eosin and observed by a renal pathologist (JZ) blinded to the experimental conditions using an Axioplan 2 Imaging System (Carl Zeiss, Thornwood, New York). For immunofluorescence study, a monoclonal rat antibody (KM2076) against human Klotho (1:250) was used for staining and followed by secondary antibodies conjugated to fluorescein isothiocyanate (detailed methods in the supplemental materials). Rhodamine-phalloidin (1:50) (Molecular Probes, Eugene, Oregon) for staining β-actin filaments was applied for double staining. The sections were visualized with a Zeiss LSM-510 laser scanning microscope.

**Quantifying Klotho in the Kidney, Urine, and Blood of Mice**

Kidney total lysates were prepared as described. Thirty µg of protein of kidney lystate was solubilized in Laemmli sample buffer; approximately 40 µl of fresh urine were immediately mixed in Laemmli sample buffer after collection. Urine samples with identical amounts of urine creatinine were subjected to SDS-PAGE. One hundred µl of mouse serum were subjected to immunoprecipitation with 4 µl of rabbit anti-serum of human Klotho, followed by immunoblot analysis with anti-Klotho antibody (KM2076) (1:2500), goat anti-rabbit antibody conjugated with horseradish peroxidase (1/5000 dilution) for IgG heavy chain, and monoclonal mouse antibody for β-actin (1/5000 dilution; Sigma). Specific signal was visualized using the ECL kit (PerkinElmer LAS, Inc., Boston, Massachusetts).

**Statistical Analyses**

The data are expressed as the means ± SEM (n = 8 or more unless indicated otherwise). The detailed analyses were described in the supplemental materials.

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**DISCLOSURES**

None.
REFERENCES


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