A G protein–coupled, IP3/protein kinase C pathway controlling the synthesis of phosphaturic hormone FGF23

Qing He,1 Lauren T. Shumate,1 Julia Matthias,1 Cumhur Aydin,1,2 Marc N. Wein,1 Jordan M. Spatz,1 Regina Goetz,1 Moosa Mohammadi,1 Antonius Plagge,4 Paola Divieti Pajevic,5 and Murat Bastpepe1

1Endocrine Unit, Department of Medicine, Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts, USA. 2Department of Endodontics, Gulhane Faculty of Dentistry, University of Health Sciences, Ankara, Turkey. 3Department of Biochemistry & Molecular Pharmacology, New York University School of Medicine, New York, New York, USA. 4Department of Cellular and Molecular Physiology, Institute of Translational Medicine, University of Liverpool, Liverpool, United Kingdom. 5Department of Molecular & Cell Biology, Boston University Goldman School of Dental Medicine, Boston, Massachusetts, USA.

Introduction
Phosphate is necessary for cell metabolism and growth, as well as skeletal development and mineralization, and excess levels of phosphate can lead to soft tissue mineralization (1–5). Fibroblast growth factor 23 (FGF23) is a polypeptide hormone that acts on kidneys to stimulate urinary phosphate excretion and to inhibit the generation of the bioactive vitamin D metabolite, 1,25 dihydroxyvitamin D [1,25(OH)2D] (6, 7). FGF23 deficiency or impaired FGF23 action results in increased levels of serum phosphate, 1,25(OH)2D, and calcium, thus causing increased tendency of soft tissue mineralization, as seen in certain forms of tumoral calcinosis. Conversely, excess production of FGF23 leads to renal phosphate wasting and hypophosphatemia with inappropriately suppressed levels of 1,25(OH)2D, as seen in tumor-induced osteomalia and several inherited disorders of hypophosphatemia, such as X-linked hypophosphatemic rickets. FGF23 production also increases markedly in iron deficiency, driving the hypophosphatemia in patients with autosomal dominant hypophosphatemic rickets. In addition, the progressive increase of FGF23 in renal failure disrupts vitamin D metabolism, contributes to secondary hyperparathyroidism, and leads to impaired bone mineralization. Moreover, FGF23 elevation is directly associated with cardiovascular mortality seen in patients with chronic kidney disease. Recently, high circulating levels of FGF23 have also been associated with increased risk of dementia and Alzheimer’s disease (8).

FGF23 is mainly synthesized by mature osteoblasts and osteocytes in bone (9, 10), but the molecular mechanisms and signaling pathways governing FGF23 production remain poorly understood. Several stimulators of
FGF23 production have been identified, including dietary phosphorous, 1,25(OH)2D, inflammatory cytokines, calcium, and iron deficiency (1–5, 11). In addition, skeletal production of FGF23 is also induced by FGF receptor 1 (FGFR1) signaling that primarily involves activation of the MAPK pathway (12–14). Another stimulator of FGF23 production is parathyroid hormone (PTH) (15–18). The receptor for PTH (PTH1R) is a G protein–coupled receptor (GPCR), which couples to multiple heterotrimeric G proteins. The direct stimulatory action of PTH on FGF23 production, however, is mediated by the α subunit of the stimulatory G protein (Gsα), thus involving cAMP generation.

Gsα is derived from the GNAS complex gene, which also gives rise to the extralarge Go subunit (XLαs) (19). XLαs uses a distinct, paternally active promoter and is partly identical to Gsα, diverging from the latter in its N-terminal region (20, 21). When overexpressed in cells or in mice, XLαs mimics Gsα with respect to cAMP generation both basally and in response to activation of GPCRs, including PTH1R (22–24). Interestingly, XLαs, despite sharing marked identity with Gsα, can mimic or enhance signaling of Gαq, another class of heterotrimeric Go subunits, which stimulate phospholipase C and, thereby, trigger generation of inositol 1,4,5-trisphosphate (IP3) and diacylglycerol and the activation of protein kinase C (PKC) (25). XLαs is expressed in a wide range of tissues, including cells of the osteoblast lineage (26–28). In this study, we addressed whether FGF23 production is regulated by the cellular action of XLαs. We found that XLαs mediates FGF23 production in a cell-autonomous manner via the activation of PKC signaling. Our additional investigations using different mouse models and cell culture experiments showed that PKC activation is critically involved in FGF23 production, integrating signals from different intracellular pathways. We also revealed elevated PKC activity in the skeletal tissue of Hyp mice, a model of X-linked hypophosphatemia (XLH), and partially rescued the FGF23 and phosphate phenotype of those mice by ablating XLαs.

Results
Serum FGF23 levels are significantly reduced in P10 XLαs-knockout mice, with resultant increase in serum phosphate and 1,25(OH)2D levels. Serum phosphate levels have been found to be elevated in some pediatric patients with paternal GNAS defects and in 10-day-old XLαs-knockout (XLKO) pups (29–36). We found that, at this age, XLKO pups were indeed hyperphosphatemic and, additionally, displayed modest hypocalcemia with only slightly elevated PTH levels that were not significantly different from the levels in WT littermates (Figure 1, A–C). In addition, both C-terminal and intact FGF23 levels were significantly reduced in XLKO mice at postnatal day 10 (P10) (Figure 1D and E). Similarly, XLKO mice also had modestly reduced C-terminal FGF23 levels at 4 weeks and 2 months of age, compared with WT littermates, although the difference did not reach statistical significance (Supplemental Figure 1, A and B; supplemental material available online with this article; https://doi.org/10.1172/jci.insight.125007DS1). Moreover, serum level of 1,25(OH)2D, whose synthesis is known to be suppressed by FGF23, was markedly increased in XLKO mice (Figure 1F). Quantitative reverse transcription PCR (qRT-PCR) analysis on total RNA isolated from P10 WT and XLKO femurs revealed that FGF23 mRNA levels in XLKO bone were less than 40% of the levels in WT bone (Figure 1G). The expression levels of Phex and Dmp1, 2 genes in which inactivating mutations cause FGF23 excess and hypophosphatemic rickets, were also diminished in XLKO bones (Supplemental Figure 1C). 1,25(OH)2D level is controlled mainly by activities of the renal enzymes 25-hydroxyvitamin D 1α-hydroxylase (Cyp27b1), which synthesizes 1,25(OH)2D, and 25-hydroxyvitamin D 24-hydroxylase (Cyp24a1), which metabolizes 1,25(OH)2D. We found that the abundance of Cyp27b1 mRNA was increased over 2.7-fold, while the expression of Cyp24a1 mRNA was increased 1.8-fold in P10 XLKO kidneys compared with WT (Figure 1H), implying that the increased 1,25(OH)2D levels may reflect enhanced synthesis. FGF23 acts to decrease the abundance of type II sodium–dependent phosphate cotransporter Npt2a in the renal brush border membrane. Western blots showed that the protein abundance of Npt2a in XLKO renal brush border membrane was markedly increased (Figure 1, I and J). Immunofluorescence staining of kidney sections from P10 WT and XLKO mice also showed a pronounced increase in Npt2a staining in XLKO (Figure 1K), consistent with the hyperphosphatemia in XLKO pups.

Recombinant FGF23 injection rescues hyperphosphatemia in XLKO mice. To address whether the phenotype of XLKO mice resulted from reduced FGF23 levels, WT and XLKO mice were injected i.p. twice daily for 4 days with vehicle or full-length FGF23 harboring mutations responsible for autosomal dominant hypophosphatemic rickets (FGF23R176Q/R179Q); these mutations inhibit proteolytic inactivation of FGF23. Upon FGF23R176Q/R179Q administration, the serum phosphate levels declined significantly in both WT and XLKO mice, and the elevated phosphate levels in XLKO mice were normalized to the levels in vehicle-injected
WT mice (Figure 2A). The blood ionized calcium levels in WT mice were significantly decreased upon FGF23 injection. On the other hand, the calcium level was surprisingly elevated and corrected to normal in XLKO mice by FGF23 administration, suggesting that the decreased calcium level observed in XLKO mice may be secondary to the elevated phosphate level (Figure 2B). Moreover, WT mice displayed the expected decrease in Cyp27b1 mRNA and the increase in Cyp24a1 mRNA expression, as measured by qRT-PCR (Figure 2, C and D). On the other hand, there was a more dramatic response to FGF23 in XLKO mice. Cyp27b1 mRNA levels were repressed over 90% in XLKO mice, and Cyp24a1 mRNA levels were induced by approximately 3.5-fold (Figure 2, C and D), predicting a decline of the elevated 1,25(OH)2D levels in XLKO mice. These results demonstrated that the phosphate and vitamin D phenotype in XLKO mice results from FGF23 deficiency.

**XLαs ablation does not impair PTH-induced FGF23 production or cAMP generation but dampens IP3 and PKC levels in osteocytes.** PTH stimulates FGF23 production via a Gsα/cAMP–mediated mechanism (15–17), and PTH1R has been shown to couple to XLαs (22, 23). Injection with human PTH (aa 1–34) (50 nmol/kg) significantly augmented serum C-terminal FGF23 levels in both WT and XLKO pups after 2 hours, and the levels were comparable between the 2 genotypes (Figure 3A). Skeletal FGF23
mRNA expression was also significantly increased upon 2 hours of PTH treatment in both WT and XLKO mice, with no evidence of impaired PTH-induced FGF23 production in XLKO (Figure 3B). XLαs, like Gαs, can stimulate generation of the second messenger cAMP. We thus examined the cAMP levels in Ocy454 cells, an osteocyte-like cell line (37), in which we have previously ablated XLαs by using CRISPR/Cas9 (38). Both the basal and PTH-induced levels of cAMP were higher in XLKO Ocy454 cells than in control cells (Supplemental Figure 2A). These enhanced cAMP levels in XLKO cells are consistent with our previous finding that Gαs protein level is moderately elevated in XLKO Ocy454 cells than in control cells (38). We have previously demonstrated that ablation of XLαs represses IP3 generation and the total levels of several PKC isoforms, including PKCα and PKCδ, in renal proximal tubules (25). Similarly, the analysis of P10 XLKO femur samples revealed reduced levels of PKCα and PKCδ (Figure 3, C and D). As expected, XLαs expression was undetectable in XLKO femurs, while Gαs expression appeared moderately increased (Figure 3C). Consistent with our in vivo results, FGF23 mRNA levels, as well as PKCα and PKCδ protein levels, were markedly reduced in XLKO Ocy454 cells (Figure 3, E–G). Moreover, the intracellular level of myo-inositol-1-phosphate (IP1), an indicator of IP3 generation (39), was also significantly repressed in XLKO cells (Supplemental Figure 2B).

**PKC activation induces FGF23 production.** Because IP3/PKC, but not cAMP, signaling was diminished upon XLαs ablation, we then examined whether activation of PKC could rescue FGF23 expression in XLKO Ocy454 cells. Treatment with phorbol 12-myristate 13-acetate (PMA), a potent PKC activator, resulted in elevated FGF23 mRNA levels in both control (3.1-fold) and XLKO cells (7.3-fold), compared with vehicle-treated cells (Figure 4A). To further confirm the effect of PKC signaling on FGF23 production in vivo, we injected P9 WT and XLKO pups i.p. with saline (as control) or PMA (500 ng/g body weight).
and analyzed the mice after 24 hours. Skeletal FGF23 mRNA levels, as well as serum FGF23 levels, were significantly increased in both WT and XLKO mice upon PMA injection, concurrently with a significant reduction in serum phosphate levels (Figure 4, B–D). Taken together, these results strongly suggested that activation of PKC stimulates FGF23 production.

Constitutively active Gαq/PKC signaling stimulates FGF23 production. One of the most important stimulators of PKC is the Gαq/11 signaling pathway, which can be triggered by multiple GPCRs (40, 41). Because stimulation of PKC signaling by PMA stimulated FGF23 production in vitro and in vivo, we addressed whether activation of Gαq signaling also leads to FGF23 production in osteoblasts and osteocytes. Rosa26-floxed stop-GNAQ<sub>Gαq</sub> mice (42), which drive expression of a constitutively active Gαq mutant in cells that undergo Cre-mediated recombination, were crossed with osteocalcin-Cre–transgenic (Ocn-Cre–transgenic) mice, which express Cre recombinase in osteoblasts and their descendants. Serum C-terminal FGF23 levels, as well as skeletal FGF23 mRNA expression, were dramatically increased in P10 GNAQ<sub>Gαq</sub> Ocn-Cre mice (Figure 5, A and B), while the intact levels were only moderately increased (Figure 5C), indicating that the majority of overproduced FGF23 in the double-transgenic mice was coupled with increased FGF23 cleavage.
In fact, phosphate levels were not changed in GNAQ Q209L Ocn-Cre mice (Figure 5D). We also crossed GNAQ Q209L with dentin matrix phosphoprotein 1–Cre (Dmp-Cre) mice, in which Cre is expressed in mature osteoblasts and osteocytes, and found a similar but milder increase of FGF23 production in GNAQ Q209L Dmp1-Cre mice (Figure 5, E–G); however, phosphate remained unchanged between control and double-transgenic mice (Figure 5H). We also analyzed serum C-terminal and skeletal FGF23 mRNA levels in 2-month-old control and GNAQ Q209L Dmp1-Cre mice and found that FGF23 production remained elevated in double-transgenic mice (Supplemental Figure 3, A and B). Taken together, these results strongly suggested that Gq/11 signaling is able to promote FGF23 production.

Because adult XLKO mice, unlike their early postnatal counterparts, displayed only a modest reduction of FGF23 levels, and because constitutively active Gq signaling promoted FGF23 synthesis both early postnatally and in adulthood, we compared mRNA levels of XLαs, as well as Gqα and G11α, in P10 and 8-week-old mouse femurs. qRT-PCR experiments revealed that the level of XLαs in 8-week-old femur was only 1.8% ± 0.9% of that in P10 femur, suggesting a dramatic decline of XLαs expression with age. In contrast, the levels of Gqα and G11α at 8 weeks were 63.1% ± 1.8% and 75.3% ± 2.4% of the levels at P10, respectively (Supplemental Figure 3C).

The Gq/11/PKC signaling–induced FGF23 production is dependent on MAPK signaling. Both control and XLKO Ocy454 clonal cells transduced with adenovirus encoding XLαs showed marked elevation of FGF23 mRNA levels compared with cells transduced with adenoviral YFP used as control (Figure 6A, Supplemental Figure 4A). In addition, treatment of these cells individually with isozyme nonselective PKC inhibitors (bisindolylmaleimide I [Bisindol], Ro-31-8220, or Ro-32-0432) significantly, albeit incompletely, blocked the XLαs overexpression–induced FGF23 production, demonstrating that XLαs regulates FGF23 production via PKC signaling (Figure 6B). The rise of FGF23 mRNA levels by PMA treatment was completely blocked by treatment with these PKC inhibitors (Figure 6C). Similar results were obtained with Saos-2 cells, a human osteosarcoma cell line (Supplemental Figure 4B). PMA also stimulates production of inflammation mediators, such as IL-6, which has been recently shown to
directly stimulate FGF23 production (43). PMA treatment of Ocy454 cells significantly increased IL-6 mRNA levels, and 2 of the PKC inhibitors, Bisindol and Ro-32-0432, repressed PMA-stimulated IL-6 induction (Figure 6D). However, Ro-31-8220, which could inhibit both PMA- and XLαs overexpression–induced FGF23 production, further increased the PMA-induced IL-6 mRNA level rather than repressing it (Figure 6D), strongly suggesting that PKC activation–mediated FGF23 production was not associated with IL-6 expression. The level of ERK1/2 phosphorylation (p-ERK1/2) was dramatically repressed in XLKO bones and in XLKO Ocy454 cells (Figure 6, E–H). PMA treatment also stimulated p-ERK1/2 levels markedly in control and XLKO Ocy454 cells (Figure 6, I and J). In addition, MEK inhibitor U0126 inhibited PMA-induced FGF23 elevation, suggesting that MAPK signaling is downstream of PKC activation and plays an important role in mediating PKC activation–mediated FGF23 production (Figure 6K). Because FGFR1 signaling is a known mediator of FGF23 production in bone, we also examined FGFR1 expression in P10 femurs and clonal Ocy454 cells and revealed significantly reduced FGFR1 mRNA levels in XLKO bones and cells (Supplemental Figure 5, A and B). We then induced FGFR1 transcription in Ocy454 cells through the CRISPR/Cas9 synergistic activation mediator (44), using several activator sgRNAs. Two of the FGFR1 promoter–targeting sgRNAs (activator 1 and activator 2) resulted in significantly increased FGFR1 mRNA expression in WT and XLKO cells (Supplemental Figure 5C). These sgRNAs also raised FGF23 mRNA levels in both WT and XLKO cells and fully rescued the reduced FGF23 levels in XLKO cells (Supplemental Figure 5D). Nevertheless, FGFR1 mRNA expression levels were not altered in femurs from GNAQ<sup>Q209L</sup> Ocn-Cre or GNAQ<sup>Q209L</sup> Dmp1-Cre double-mutant mice (Supplemental Figure 5, E and F), which, as shown above, displayed elevated serum and skeletal mRNA levels of FGF23. These results suggested that the G<sub>q/11</sub>/PKC activation–induced FGF23 synthesis may not involve elevation of FGFR1 levels.

Skeletal PKC activity and MAPK signaling are elevated in a mouse model of XLH. XLH is the most common form of inherited rickets, which is driven by hypophosphatemia caused by excess FGF23 production (45). Hyp mice, a murine model of XLH, also have dramatically elevated FGF23 levels. To assess the level of overall PKC activity in Hyp mice bones, we used Western blot analysis using an antibody recognizing proteins phosphorylated at PKC consensus sites. Our results showed significantly increased
levels of some of these PKC-phosphorylated proteins in Hyp bones (Figure 7, A and B), consistent with enhanced PKC activity. The level of p-ERK1/2 in Hyp bones was also significantly increased (Figure 7, A and C). A single injection of P10 WT and Hyp littermates with the PKC inhibitor Ro-32-0432 revealed, 24 hours later, a mild trend toward lower serum FGF23 and higher serum phosphate levels in Hyp mice compared with vehicle-injected mice (Supplemental Figure 6, A and B). Because ablation of XLαs reduced PKC activation and FGF23 production in vivo, we then intercrossed XLKO and Hyp mice. At P10, XLKO/Hyp double-mutant mice were still hypophosphatemic and displayed increased FGF23 levels compared with WT mice. However, compared with Hyp mice, the XLKO/Hyp double mutants showed a moderate but significant decrease in C-terminal FGF23 levels, as well as intact FGF23 levels (Figure 7, D and E). Likewise, serum phosphate levels were significantly increased in the XLKO/Hyp double mutants compared with Hyp littermates (Figure 7F). These results suggested that suppression of XLαs/PKC signaling could alleviate the biochemical phenotype of Hyp mice.
Discussion

Our study shows that the unique Gα subunit XLαs, which, in spite of being mostly identical to Gsa, promotes IP3/PKC signaling, is required for FGF23 production in early postnatal mice. Our investigations also revealed that the IP3/PKC signaling pathway, presumably downstream of an as-yet-unidentified GPCR, is an important mediator of skeletal FGF23 production through a mechanism dependent on MAPK signaling (Figure 8).

Excess FGF23 production was observed in response to the activation of PKC, stimulated by XLαs overexpression, phorbol esters, or constitutive Gq/11 activation. PKC activation has been shown to promote MAPK signaling in osteoblastic cells (46). We also observed elevated ERK1/2 phosphorylation upon PMA treatment of Ocy454 cells, and the baseline level of ERK1/2 phosphorylation was diminished in XLKO bones, which concurrently had reduced PKCα and PKCδ levels. Taken together with the finding that MAPK inhibitor U0126 blocked the PKC activation–induced FGF23 production, it appears that PKC mediates FGF23 production by promoting, at least partly, the MAPK signaling pathway. In contrast, our findings from PKC inhibitor experiments strongly suggest that PKC-mediated FGF23 production is independent of IL-6.

PKC inhibitors blunted the effect of XLαs overexpression but entirely abrogated the effect of PMA treatment on FGF23 mRNA levels in Ocy454 cells. This finding may reflect the possibility that the XLαs overexpression caused a much stronger PKC activation than did the PMA treatment. Alternatively, XLαs overexpression may have promoted FGF23 production additionally through the cAMP signaling pathway because it can result in significantly increased basal cAMP production (47, 48). However, we found that PMA treatment did not fully restore the levels of ERK1/2 phosphorylation in XLKO cells, suggesting that the action of XLαs entails additional pathways that may converge on MAPK signaling. One of those may be FGFR signaling. Fgfr1 mRNA levels were diminished in XLKO bones, and overexpression of Fgfr1, which presumably enhanced MAPK signaling, could override the suppressed FGF23 synthesis caused by XLαs deficiency. This finding may suggest that the presumably diminished FGFR1 levels contribute to the low FGF23 levels in XLKO cells. Future studies are needed to fully understand the Gq/IP3/PKC pathway—indeed role of XLαs in the regulation of FGFR1/MAPK signaling and FGF23 synthesis. Nonetheless, it is important to note that our mice in which Gq/PKC signaling was constitutively activated in bone showed a pronounced FGF23 overproduction in the
absence of elevated Fgfr1 expression. Thus, it appears that the IP3/PKC signaling–mediated FGF23 production does not require elevation of FGFR1 levels.

FGF23 increases urinary phosphate excretion by repressing the activity of NaPi-2a and NaPi-2c cotransporters to reduce renal phosphate reabsorption to maintain systemic phosphate homeostasis. In mice expressing the constitutively active Gqα mutant in bone cells, serum phosphate levels were not altered, despite the modestly increased levels of serum intact FGF23 in the mutant mice. It is possible that the urinary phosphate excretion was increased in those mice, but our assay was unable to detect the change in serum phosphate. In contrast, the PMA-injected mice displayed low serum phosphate compared with vehicle-injected mice. The latter finding may reflect a direct effect of PMA on the renal proximal tubules because PKC activation promotes renal phosphate excretion (49).

We detected increased levels of phosphorylated proteins by PKC in Hyp bones, suggesting elevated PKC activity in this mouse model of XLH. Consistent with our finding, a microarray analysis of Hyp bones revealed 41 genes upregulated by more than 2-fold (50), and a number of them are positively regulated by PKC activation in bone or in other cell types, including Egr2, Eln, Prkg2, Cyp11a1, Lipg, Gem, and F3 (51–54). The underlying cause of elevated skeletal PKC activity in XLH is currently unknown. Nevertheless, our results obtained from intercrosses between Hyp and XLKO, as well as from the injection of a PKC inhibitor into Hyp and control mice, suggest that the increased PKC activation in XLH contributes to the elevated FGF23 production.

Based on our PTH injection experiments, the novel FGF23 synthesis mechanism involving G protein/PKC activation does not mediate the action of PTH. This is consistent with previous studies showing that PTH-induced FGF23 production occurs via cAMP-mediated mechanisms (15–18, 55). In contrast, 1,25(OH)2D- and phosphate-induced FGF23 production may depend, at least partly, on the G protein/PKC pathway, given that the significantly elevated 1,25(OH)2D and phosphate levels in XLKO pups were insufficient to maintain the normal level of FGF23. Likewise, XLKO pups have been reported to have serum iron deficiency (38), and therefore, it appears that lack of XLα also impedes the effect of iron deficiency on FGF23 production. Consistent with these conclusions, MAPK signaling has been implicated in FGF23 synthesis in response to both iron deficiency and phosphate (56–58). Nonetheless, further studies are needed to address whether XLα or IP3/PKC signaling modulates the actions of these major FGF23 regulators.

Adult XLKO mice displayed only mildly reduced serum FGF23 levels as opposed to P10 XLKO, which had significantly decreased FGF23 production. The outcome of XLα ablation on FGF23 levels may be masked by the systemic alterations previously documented in adult XLKO mice, such as increased levels of circulating catecholamines (59). It is also possible, however, that XLα is not expressed at significant levels in adult osteocytes/osteoblasts and, therefore, has a minor role in FGF23 synthesis. XLα protein or mRNA is readily detectable in adult mouse bone and adult human bone marrow stromal cells (26, 28), but we found a dramatic decline of XLα mRNA levels from P10 to age 8 weeks in mouse femurs, supporting the latter possibility. In contrast, the levels of Gqα or G11α did not change as dramatically with age, making it plausible that the Gq family of α subunits take over XLα’s role as a mediator of FGF23 production in adulthood.
Genetic mutations affecting the paternal $\text{GNAS}$ allele result in complete loss of $\text{XL}\alpha$s in most tissues because of the genomic imprinting of its promoter. Thus, our findings predict that children with paternal $\text{GNAS}$ disruption, i.e., pseudo-pseudohypoparathyroidism, can have reduced FGF23 production and resultant hyperphosphatemia. Accordingly, certain pediatric patients carrying such genetic defects have been reported to have normal or elevated serum phosphate with mildly elevated PTH levels (29–35). However, it should be noted that patients with paternal $\text{GNAS}$ mutations also have $G_{\alpha}\alpha$ haploinsufficiency, which may contribute to those findings or could mask the phenotypic expression of $\text{XL}\alpha$s deficiency alone.

In summary, we discovered a potentially novel mechanism of FGF23 synthesis involving an as-yet-unidentified GPCR that signals via the IP3/PKC pathway feeding into MAPK signaling (Figure 8). Further elucidation of the underlying mechanisms may identify novel drug targets for treating the diseases caused or affected by dysregulated FGF23 production. As such, it will be important to identify the GPCR(s) that couples to $\text{XL}\alpha$s and/or $G_{\alpha}\alpha^{q/1}$ in this context. Targeting that receptor by an agonist or an antagonist may allow FGF23 levels to be fine-tuned as needed.

**Methods**

**Mice.** XLKO mice were generated by disrupting the first exon of $\text{XL}\alpha$s on the paternal allele, thus resulting in the global ablation of this protein (60). These mice were maintained on a CD1 genetic background. $\text{GNAQ}^{Q209L}$-transgenic mice were generated and described previously (42); they were maintained on a C57BL/6 background. Ocn-Cre, Dmp1-Cre, and Hyp mice were also on a C57BL/6 background and purchased from The Jackson Laboratory. Both male and female Hyp mice were included in the analyses, which were performed on P10.

**Chemical compounds.** Recombinant human FGF23 containing naturally occurring pathogenic Arg-to-Gln mutations at its $^{176}\text{RTHR}^{179}$ proteolytic cleavage site, FGF23$^{R176Q/R179Q}$ (aa 25–251), was generated in-house (61). Synthetic human PTH (aa 1–34) was synthesized by The Peptide/Protein Core Facility at Massachusetts General Hospital. The broad-range PKC inhibitor Bisindol was purchased from MilliporeSigma; another 2 PKC inhibitors, Ro-32-0432 and Ro-31-8220, were from Santa Cruz Biotechnology. MEK inhibitor U0126 was purchased from Cell Signaling Technology. PMA, forskolin, and all other reagents were purchased from MilliporeSigma.

**Measurement of serum biochemistries.** Serum concentrations of phosphate, $\text{Ca}^{2+}$, PTH, and $1,25(\text{OH})_2\text{D}$ were examined by using blood samples obtained from the carotid artery, as described previously (24). C-terminal and intact FGF23 concentrations were measured with the Mouse/Rat FGF-23 (C-Term) and Mouse/Rat FGF-23 (Intact) ELISA kits (Quidel).

**Cell culture.** The Ocy454 cells, which were previously described (37), were maintained in $\alpha$–minimum essential medium ($\alpha$-MEM, Gibco) with 10% FBS at 33°C and differentiated into osteocyte-like cells by growing at 37°C for 1 week (37, 62). XLKO and control clonal Ocy454 cells were generated previously (38) and used here for protein and mRNA analyses. Saos-2 cells were obtained from ATCC (ATCC HTB-85) and cultured at 37°C in McCoy’s 5a medium (Gibco) supplemented with 15% FBS. To test the effects of PMA and different inhibitors, the cell culture was changed to $\alpha$-MEM with 2% FBS overnight before treating with 1 $\mu$M PMA, with or without inhibitor (10 $\mu$M Bisindol, 10 $\mu$M Ro-32-0432, 10 $\mu$M Ro-31-8220, or 10 $\mu$M U0126) for 6 hours.

**Generation of FGFR1 transcriptionally activated Ocy454 cells by CRISPR/sgRNA-directed synergistic activation mediator.** Four sgRNAs targeting the Fgfr1 gene were designed through the Synergistic Activation Mediator Cas9 activator design tool (http://sam.genome-engineering.org/database/) and subcloned into the lentiviral sgRNA(MS2)zeo vector (Addgene). Based on the efficiency of Fgfr1 activation, 2 activation guides, FGFR1 activator 1 and activator 2, were selected for further analysis. Viral packaging was performed in 293T cells (ATCC) using standard protocols by cotransfection of the lentiviral plasmid along with psPAX2 (Addgene) and MD2.G (Addgene) using PolyJet DNA Transfection Reagent (SignaGen Laboratories). XLKO and control Ocy454 cells were transduced with lentiviral dCas9-VP64, MS2-P65-HSF1, together with lentiviral FGFFR1 activator 1, activator 2, or sgRNA(MS2)zeo, and then selected with blasticidin (5 $\mu$g/mL), hygromycin (100 $\mu$g/mL), and zeocin (200 $\mu$g/mL) to enrich for cells stably expressing the lentivirus. Cells were maintained in the selection medium throughout the duration of the experiment.

**cDNA synthesis and qRT-PCR analysis.** Total RNA isolated from kidneys and femurs of P10 mice, as well as that from Ocy454 and Saos-2 cells, was prepared with the RNeasy Plus Mini Kit (Qiagen), and cDNA was synthesized with the ProtoScript II First Strand cDNA Synthesis Kit (New England BioLabs), as
previously described (63). qRT-PCR analysis on FGF23 was tested by using FGF23-FAM and Actb-VIC TaqMan primers and TaqMan Fast Advanced Master Mix (Applied Biosystems). qRT-PCR analysis on all other genes was performed with specific primers (Supplemental Table 1) and PowerUp SYBR Green Master Mix (Applied Biosystems) with Actb as a reference gene.

**Cell/tissue lysis and Western blot analysis.** Cells and femur tissues were lysed by using HNTG lysis buffer (20 mM HEPES, pH 7.4; 150 mM NaCl; 10% glycerol; 1% Triton X-100, 1.5 mM MgCl₂; 1.0 mM EGTA) containing Complete Protease inhibitor mixture tablets (Roche). Lysates were resolved by 10% SDS-PAGE and transferred to nitrocellulose membranes (Bio-Rad). Western blots were then incubated with specific antibodies. Antibody against p-ERK was purchased from MilliporeSigma (catalog M8159) and tubulin antibody from Abcam (catalog ab6046). Antibodies against phospho-PKC substrates (catalog 2261S), total ERK (catalog 9102S), PKCα (catalog 9960S), and PKCδ (catalog 9960S) were from Cell Signaling Technology. Gsa antibody, which recognizes both Gsa and XLαs, was purchased from MilliporeSigma (catalog 06-237).

**Histology, immunohistochemistry, and immunofluorescence staining.** Kidney sections from P10 XLKO and WT mice were stained with Npt2a antibody (64) at 4°C overnight and then stained with Alexa Fluor 568–conjugated donkey anti-rabbit antibody (Life Technologies) at room temperature for 1 hour. Immunoreactivity was visualized and analyzed with a Nikon Eclipse Ni microscope and SPOT Microscope Imaging Software or with a Zeiss LSM 510 confocal microscope and Zeiss Zen software.

**Isolation of renal brush border membranes.** Brush border membrane portions were prepared from the kidneys of P10 WT and XLKO mice as described previously (65) with minor modifications. Isolated brush border membrane proteins were lysed in a Tris-buffered solution containing 150 mM NaCl and 1% Triton X-100. Measurement of protein concentrations in the samples with antibodies specific for Npt2a (64) and Villin (Santa Cruz Biotechnology, sc-58897) were performed as described previously (24).

**IP₃ and cAMP assays.** The amount of IP₃, a downstream metabolite of IP3, in control and XLKO Ocy454 cells was tested using the IP₃ HTRF assay kit (Cisbio) as previously described (25). For cAMP assay, confluent control and XLKO Ocy454 cells in 96-well plates were treated with different concentrations of PTH, forskolin, or vehicle, with 2 mM 3-isobutyl-1-methylxanthine for 30 minutes at room temperature, before lysing the cells for RIA measurement.

**Recombinant FGF23 R176Q/R179Q, PTH, PMA, and Ro-32-0432 injections.** The recombinant FGF23 compound (61, 66) or vehicle was injected i.p. into WT and XLKO mice (250 ng/g body weight) from P6 to P10 at 12-hour intervals (67). The mice were sacrificed 12 hours after the last injection, and blood and kidneys were collected for analysis. To test PTH-induced FGF23 production in WT and XLKO mice, mice were injected subcutaneously with either PTH (aa 1–34) (50 nmol/kg) or vehicle (10 mM citric acid, 150 mM NaCl, 0.05% Tween 80, pH 5.0) for 2 hours before analysis (55). To test the effect of PMA on FGF23 production, WT and XLKO mice were injected i.p. with vehicle or PMA (500 ng/g body weight) (68, 69) at P9 and sacrificed 24 hours later. Blood and femurs were collected to measure serum FGF23 and phosphate levels, as well as bone FGF23 mRNA levels. PKC inhibitor Ro-32-0432 (6 mg/kg body weight) or vehicle was i.p. injected into P9 WT and Hyp mice for 24 hours. Blood was collected to measure serum FGF23 and phosphate levels.

**Statistics.** All data are presented as mean ± SEM as indicated in the figure legends. The unpaired, 2-tailed Student’s t test was used to determine the significance of differences between 2 groups, and 1-way ANOVA followed by Tukey’s multiple-comparisons test was used to determine statistical significance among 3 or more groups. Welch’s t test (2 tailed) was used for multiple comparisons involving groups with unequal variances, followed by Bonferroni’s correction (that is, P values were multiplied by the number of comparisons). P values smaller than 0.05 (*P < 0.05, **P < 0.01, and ***P < 0.001) were considered significant.

**Study approval.** All the animal experiments were conducted in accordance with the accepted standards of the Institutional Animal Care and Use Committee, and the studies were approved by the Massachusetts General Hospital (MGH) Subcommittee on Research Animal Care.

**Author contributions**

QH and MB designed the research. QH, LTS, JM, and CA performed the experiments. MNW, JMS, RG, MM, AP, and PDP provided important reagents and tools. QH and MB interpreted the original data with feedback from all the other authors. QH and MB wrote the manuscript.
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Address correspondence to: Murat Bastepe, 50 Blossom St. Thier 10, Boston, Massachusetts 02114, USA. Phone: 617.726.3966; Email: bastepe@helix.mgh.harvard.edu.

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