

The large G protein alpha-subunit XL α s limits clathrin-mediated endocytosis and regulates tissue iron levels in vivo

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Abbreviations: G α , stimulatory G protein alpha-subunit; XL α s, extra-large G alpha protein; SNX9, sorting nexin-9; Dnm, dynamin; PTH, parathyroid hormone; PTHR, parathyroid hormone receptor type-1; V2R, vasopressin receptor type-2; TfRc, transferrin receptor 1; GFP, green fluorescent protein.

Abstract

Alterations in the activity/levels of the extra-large G protein alpha-subunit (XL α s) are implicated in various human disorders, such as perinatal growth retardation. Encoded by *GNAS*, XL α s is partly identical to the α -subunit of the stimulatory G protein (G α), but the cellular actions of XL α s remain poorly defined. Following an initial proteomic screen, we identified sorting nexin-9 (SNX9) and dynamins, key components of clathrin-mediated endocytosis, as novel binding partners of XL α s. Overexpression of XL α s in HEK293 cells inhibited internalization of transferrin, a process that depends on clathrin-mediated endocytosis, while its ablation by CRISPR/Cas9 in an osteocyte-like cell line (Ocy454) enhanced it. Similarly, primary cardiomyocytes derived from XL α s knockout (XLKO) pups showed enhanced transferrin internalization. Early postnatal XLKO mice showed a significantly higher degree of cardiac iron uptake than wild-type littermates following iron-dextran injection. In XLKO neonates, iron and ferritin levels were elevated in heart and skeletal muscle, where XL α s is normally expressed abundantly. XLKO heart and skeletal muscle, as well as XLKO Ocy454 cells, showed elevated SNX9 protein levels, and siRNA-mediated knock-down of SNX9 in XLKO Ocy454 cells prevented enhanced transferrin internalization. In transfected cells, XL α s also inhibited internalization of the parathyroid hormone and the type-2 vasopressin receptors. Internalization of transferrin and these G protein-coupled receptors (GPCR) was also inhibited in cells expressing an XL α s mutant missing the G α portion, but not G α or an N-terminally truncated XL α s mutant unable to interact with SNX9 or dynamin. Thus, XL α s restricts clathrin-mediated endocytosis and plays a critical role in iron/transferrin uptake in vivo.

Significance Statement

Mutations in the gene encoding XL α s and Gs α (*GNAS*) cause several genetic diseases and various tumors. Although alterations in XL α s activity/levels are implicated in some of these disorders, cellular actions of XL α s have remained poorly defined. We identified dynamins and sorting nexin-9, key components of clathrin-mediated endocytosis, as novel binding partners of XL α s and showed that XL α s, but not Gs α , restricts clathrin-mediated endocytosis and plays a role in iron/transferrin uptake in vivo. Thus, impaired or enhanced endocytosis may be involved in the pathogenesis of some of the *GNAS*-related diseases. Our findings also provide novel insights into the roles of heterotrimeric G proteins and the mechanisms underlying endocytosis, a fundamental cellular process required for nutrient uptake and regulation of cell signaling.

/body

Introduction

Endocytosis is a fundamental cellular process by which fluid or particles from the extracellular space or different macromolecules of the plasma membrane are internalized into transport vesicles¹⁻⁴. It thus plays a role in a wide variety of cellular and physiological functions, including signal transduction, neurotransmission, and development. Mutations in the genes encoding some of the core components of endocytosis cause human diseases, such as familial hypocalciuric hypocalcemia⁵, certain types of Charcot-Marie-Tooth disease⁶, centronuclear myopathy⁷, and late-onset Alzheimer's disease⁸. Moreover, the pathogenesis of certain neurodegenerative diseases critically involves endocytosis and related cellular processes⁹. In addition, intracellular targeting of many clinical drugs relies on the endocytic pathway¹⁰. Endocytosis is tightly regulated and involves coordinated actions of a range of proteins at the plasma membrane.

Signals from many hormones, neurotransmitters, and autocrine/paracrine factors are transduced at the plasma membrane via the action of the stimulatory heterotrimeric G protein^{11,12}. The alpha-subunit of this ubiquitously expressed protein ($G\alpha$) is encoded by the *GNAS* complex locus, mutations of which are responsible for multiple human diseases that affect a variety of organ systems^{13,14}. *GNAS* also gives rise to a large $G\alpha$ variant termed *XL α s*¹⁵. Derived from an upstream, paternally active promoter, *XL α s* uses a separate first exon that splices onto exons 2-13 used by $G\alpha$. *XL α s* is thus partly identical to $G\alpha$ and comprises most functional domains of the latter¹⁶. However, *XL α s* and $G\alpha$ differ markedly in their

amino-terminal domains. Loss or gain of XL α s activity is thought to contribute directly to some of the phenotypes resulting from *GNAS* alterations, including intrauterine growth retardation seen frequently in patients with pseudo-pseudohypoparathyroidism, progressive osseous heteroplasia, platelet Gs-hypofunction abnormalities, and certain types of breast cancers¹⁷⁻²⁰. Nevertheless, the cellular actions of XL α s, unlike the actions of Gs α , have remained poorly defined.

XL α s shows strong plasma membrane avidity and, unlike Gs α , remains anchored to the plasma membrane following activation by G protein-coupled receptors (GPCRs) or GTPase inhibiting mutations^{21,22}. The unique amino-terminal domain of XL α s (XL domain) is larger than and differs markedly from that of Gs α . The XL domain contains multiple proline-rich motifs, suggesting that this domain may be involved in functionally important interactions at the plasma membrane. In this study, we aimed to discover the unique cellular actions of XL α s by identifying protein-protein interactions involving this protein. We revealed two proteins important for endocytosis, sorting nexin 9 (SNX9) and dynamin, as binding partners of XL α s. Our subsequent studies showed that XL α s plays an inhibitory role in endocytosis and regulates iron/transferrin uptake.

Results

XL α s forms complexes with SNX9, Dnm1, and Dnm2

To identify novel binding partners of XL α s, we performed an initial proteomic screen whereby lysates of C3H10T1/2 cells (a mouse cell line functionally similar to mesenchymal stem

cells) overexpressing FLAG-tagged XL α s or YFP were purified on an anti-FLAG affinity resin, followed by LC-MS/MS. As expected, co-purified proteins identified selectively from XL α s-expressing cells included some G protein subunits, as well as ALEX (alternative gene product encoded by the XL-exon), which is known to interact with XL α s²³ (SI Appendix, Table S1). This screen identified sorting nexin 9 (SNX9), a SH3 domain-containing protein critical for endocytosis²⁴, as a binding partner of XL α s. The screen also identified dynamin-1 (Dnm1) and dynamin-2 (Dnm2), which interact with SNX9 and are also critical for endocytosis^{24,25}.

To verify these interactions, we performed co-immunoprecipitation experiments. FLAG-XL α s, SNX9, or both were overexpressed in HEK293T cells and immunoprecipitated from total cell lysates using anti-FLAG antibody. Subsequent immunoblots using anti-SNX9 antibody detected SNX9 only in samples from cells co-expressing XL α s and SNX9 (Fig. 1A). Conversely, the lysates were immunoprecipitated by anti-SNX9 antibody, and co-immunoprecipitated proteins were analyzed by immunoblots using anti-FLAG antibody. XL α s was successfully detected only in samples from cells co-expressing both XL α s and SNX9 (Fig. 1A). We also confirmed the XL α s-Dnm1 and XL α s-Dnm2 interactions by similar co-immunoprecipitation experiments using anti-Dnm1 or anti-Dnm2 antibodies (Fig. 1B, C).

Abundant XL α s mRNA expression has been found by Northern blots in early postnatal mouse heart²⁶. Western blots using a C-terminal G α antibody, which could recognize both G α and XL α s, confirmed that XL α s was abundantly expressed in heart at postnatal day 2 (P2), and that its expression was absent in heart from XL α s knockout (XLKO) mice (Fig. 1D). To determine whether interactions between XL α s and SNX9/dynamins take place at physiological

levels in vivo, we thus used protein lysates of hearts from P2 wild-type (WT) mice, or skeletal muscle from neonates. The lysates were immunoprecipitated with anti-XL α s, anti-Dnm2 or anti-SNX9 antibodies, and goat and rabbit IgG were used as controls. Western blot analysis of the immunoprecipitated proteins by using anti-XL α s antiserum revealed co-immunoprecipitation of XL α s with SNX9 and Dnm2 (Fig. 1E and SI Appendix, Fig. S1).

XL α s overexpression inhibits transferrin receptor internalization

Internalization of the transferrin receptor, by which transferrin-bound iron enters into cells, has been extensively studied as a prototype for clathrin-mediated endocytosis. To determine whether XL α s has a role in transferrin internalization, we transfected HEK293T cells with cDNA encoding GFP-tagged XL α s and treated these cells with transferrin-Alexa Fluor 568 for 30 min. Confocal microscopy showed that, while transferrin was internalized in untransfected cells, a much lower amount of transferrin-Alexa Fluor 568 was detected in cells overexpressing XL α s (Fig. 2A). We also performed flow cytometry to quantify transferrin uptake in untransfected and transfected cells. Cells overexpressing XL α s-GFP exhibited significantly lower transferrin uptake compared to untransfected cells (Fig. 2B, C). As expected, dominant negative mutants of Dnm1 and Dnm2 (Dnm1-K44A and Dnm2-K44A) showed significant inhibition of transferrin endocytosis (Fig. 2D-G).

Ablation of XL α s in cultured cells promotes transferrin internalization

To further investigate the role of XL α s in transferrin uptake, we employed the osteocyte-like cell line Ocy454 cells^{27,28}, since XL α s protein expression had been previously shown in bone²⁹. Using anti-XL α s antiserum we found that XL α s is expressed at readily detectable levels in

Ocy454 cells (Fig. 3A). We ablated XL α s in these cells by using CRISPR/Cas9, and Western blots confirmed successful ablation of XL α s in four independent clonal cell lines (Fig. 3A; SI Appendix, Table S2, S3 and SI Appendix, Fig. S2). Consistent with the findings in a previous report³⁰, Gsa protein levels in XLKO cells were modestly but significantly higher than in control cells (Fig. 3A, B). The average level of transferrin uptake, as determined by 30-min treatment with transferrin-Alexa Fluor 568 followed by flow cytometry, was 1.8-fold higher in the XLKO clones than control cells (Fig. 3C, SI Appendix, Fig. S3A). Despite this increase in transferrin uptake, XLKO cells showed similar levels of mRNA encoding the transferrin receptor type-1 (TfRc) to control cells at baseline (Fig. 3D).

Loss of XL α s is associated with enhanced transferrin/iron uptake

To determine whether XL α s plays a physiological role in transferrin uptake, we cultured primary cardiomyocytes isolated from P2 WT and XLKO littermates. After treatment with transferrin-Alexa Fluor 568 for 30 min, followed by flow cytometry analysis, XLKO cardiomyocytes internalized 2.5-fold more transferrin compared to WT cardiomyocytes (Fig. 3E, SI Appendix, Fig. S3B). The baseline TfRc mRNA levels were comparable in XLKO and WT cells (Fig. 3F). Increased level of intracellular iron, which is mediated by transferrin internalization, leads to apoptosis³¹⁻³³. We treated primary cardiomyocytes isolated from P2 WT and XLKO pups with different concentrations of FeCl₃ for 72h to induce iron overload. Significantly higher percentage of XLKO cells underwent apoptosis under different FeCl₃ concentrations compared to WT cells, as judged by the percentage of cells that are annexin V-positive and propidium iodide-negative (Fig. 3G, SI Appendix, Fig. S3C).

To examine whether the ablation of *XLas* could increase iron uptake in vivo, we used XLKO mice and WT littermates and analyzed the cardiac tissue following iron-dextran or vehicle injection for 10 days, starting from birth. Prussian blue staining of heart sections revealed more extensive myocardial iron accumulation in iron-injected XLKO pups than iron-injected WT pups (Fig. 4A). Diaminobenzidine (DAB)-enhanced Perl's staining of hearts from vehicle-injected mice also showed more extensive myocardial iron accumulation in P10 XLKO pups, indicating that the iron level in XLKO heart is elevated even in the absence of iron administration (Fig. 4B). Elevated tissue iron levels are associated with decreased TfRc levels^{34,35}. Accordingly, baseline TfRc mRNA levels were reduced markedly in XLKO hearts (Fig. 4C). In contrast, serum iron levels in P10 XLKO pups were significantly lower than in WT littermates (Fig. 4D), and consistent with serum iron deficiency, TfRc mRNA levels in kidney were elevated (Fig. 4E). qRT-PCR analysis demonstrated that, while *XLas* mRNA was expressed abundantly in P10 heart, it was barely detectable in kidney (Fig. 4F). These results demonstrated that *XLas* ablation increases iron levels in a tissue-specific manner. Together with data from cultured cells, these findings suggest that *XLas* acts as an inhibitor of iron uptake.

XLKO neonates have elevated iron levels in heart and skeletal muscle.

XLKO pups are slightly smaller than wild-type littermates at birth but otherwise display no gross abnormalities; however, these pups develop early postnatal growth retardation and disrupted glucose metabolism^{26,36}. We thus analyzed XLKO neonates with respect to serum and tissue iron levels, focusing on tissues in which *XLas* is either abundantly (e.g. heart and skeletal muscle) or poorly expressed (kidney, liver, lung, and spleen) (Fig. 5A)^{26,37}. While serum iron

levels were similar in newborn XLKO and WT pups (Fig. 5B), Western blot analyses showed that the levels of ferritin – an indicator of tissue iron status – in heart and skeletal muscle were significantly higher in XLKO neonates than in WT littermates (Fig. 5C, D). In contrast, ferritin levels were similar in kidney, liver, lung, and spleen of XLKO and WT littermates (Fig. 5C, D). Accordingly, iron content was significantly increased in neonatal XLKO heart and skeletal muscle (Fig. 5E, F). These results were consistent with the above findings that XL α s inhibits transferrin/iron uptake and indicated a physiological role for XL α s as a negative regulator of tissue iron levels.

XL α s ablation increases SNX9 levels, and SNX9 knockdown rescues the enhanced transferrin uptake observed in XLKO Ocy454 cells.

SNX9 levels are critical for mediating clathrin-mediated endocytosis^{24,38}. Western blots showed that the level of SNX9 protein was significantly increased in P0 XLKO heart and skeletal muscle, but not in kidney, liver, lung, or spleen, compared to that in WT littermates (Fig. 6A, B). The level of SNX9 protein was also elevated in XLKO Ocy454 cells compared to control cells (Fig. 6C, D). Conversely, transient overexpression of XL α s in HEK293T cells resulted in a significant reduction in SNX9 protein levels (SI Appendix, Fig.S4). To examine the role of SNX9 in the action of XL α s, we knocked down SNX9 expression in both XLKO and control Ocy454 cells by using siRNA and confirmed the knockdown by Western blot analysis (Fig. 6C, D). Diminished SNX9 expression resulted in a marked reduction of transferrin uptake in both XLKO and control Ocy454 cells, and essentially abrogated the enhanced transferrin uptake resulting from XL α s ablation (Fig. 6E, SI Appendix, Fig. S5).

The proline-rich N-terminal portion is required for the inhibitory effect of XL α s on transferrin uptake

SNX9 comprises a Src-homology 3 (SH3) domain, which plays an important role in its interaction with dynamins²⁴. SH3 domains interact with proline-rich motifs in other proteins³⁹. We thus examined whether SNX9 is able to interact with G α , which, unlike XL α s, lacks proline-rich motifs. We also constructed an N-terminally truncated XL α s mutant missing all proline-rich motifs and the highly conserved proline-rich region (PostPRR-XL α s). Co-immunoprecipitation experiments and subsequent Western blot analyses using transfected HEK293T cells revealed that SNX9 could be immunoprecipitated with XL α s but not with G α or PostPRR-XL α s (Fig. 7A). We also performed similar co-immunoprecipitation experiments and found that neither G α nor the PostPRR-XL α s mutant was able to interact with Dnm1 and Dnm2 (Fig. 7B, C). We then transfected HEK293T cells with cDNA encoding GFP-tagged G α or PostPRR-XL α s-GFP, and treated these cells with transferrin-Alexa Fluor 568 for 30 min. Confocal microscopy showed that transferrin was internalized in untransfected cells, as well as cells overexpressing G α or PostPRR- XL α s (Fig. 7D). Moreover, flow cytometry using transferrin-Alexa Fluor 568 revealed that, unlike XL α s, neither G α nor PostPRR-XL α s inhibited transferrin uptake in transfected HEK293T cells (Fig. 7E-H).

Morphological Analysis of Coated Profiles in Cells Expressing G α and XL α s

Overexpression of dominant-negative dynamin mutants results in an increase in the percentage of clathrin-coated pits that have elongated necks⁴⁰. To determine whether XL α s

overexpression alters clathrin-coated pit morphology, we performed transmission electron microscopy using HEK293T cells overexpressing GFP-tagged G α or GFP-tagged XL α s, which were incubated with 10 nm gold-conjugated transferrin for 1h at 37°C to aid in the identification of endocytic coated pits. Although gold-conjugated transferrin could be detected in internalized vesicles of both G α - and XL α s-overexpressing cells, the relative abundance of the differently shaped coated pits was significantly different (Fig. 8A). The majority of coated pits observed in G α -overexpressing cells were shallow (Fig. 8B, C), with smaller number of deep pits (Fig. 8D, E) and few elongated pits identified, similar to the findings previously observed in untransfected or empty vector transfected cells⁴⁰. Overexpression of XL α s caused a pronounced shift in the ratio of shallow coated pits to deeply invaginated (Fig. 8F, G) or elongated pits with long necks (Fig 8H, I).

Overexpression of XL α s Inhibits G Protein-Coupled Receptor Internalization

Clathrin-mediated endocytosis also mediates the agonist-induced internalization of G protein-coupled receptors (GPCRs). It has been shown that XL α s can couple to multiple GPCRs including the PTH receptor (PTH R)^{41,42}, which undergoes agonist-induced internalization⁴³. We treated HEK293T cells transfected with cDNA encoding PTH R and either GFP-tagged XL α s, GFP-tagged G α , or PostPRR-XL α s-GFP with tetramethylrhodamine-labeled PTH(1-34) (PTH-TMR) (10nM), a PTH R analog that has been previously utilized for monitoring the agonist-induced internalization of this receptor⁴⁴. Confocal microscopy showed that, five minutes after PTH stimulation, PTH R (as detected by the location of PTH-TMR) and G α were translocated into the intracellular space in G α -expressing

cells (Fig. 9A, SI Appendix, Fig. S6A). PTHR also translocated into the intracellular region in PostPRR-XL α s-expressing cells, while the majority of PostPRR-XL α s, as shown previously²¹, remained on the plasma membrane (Fig. 9B). In contrast, PTHR and XL α s-GFP signals were detectable only on the cell surface in XL α s-expressing cells (Fig. 9C, SI Appendix, Fig. S6B). Thus, the relative membrane/cytosol fluorescence intensity – for both red and green channels – was significantly higher in XL α s-overexpressing cells compared to G α -overexpressing cells (Fig. 9D, E, SI Appendix, Fig. S6C, D).

We also employed total internal reflection fluorescence (TIRF) microscopy to monitor PTHR at the plasma membrane and quantify the effect of XL α s on PTHR internalization. HEK293 cells overexpressing dsRed-labeled PTHR and either G α s-GFP or XL α s-GFP were treated with PTH(1-34), and the fluorescence intensity was monitored in live cells. In G α expressing cells, PTH treatment led to diminished fluorescent intensity for both G α and PTHR (SI Appendix, Fig. S7A, B), indicating that these proteins were internalized. In contrast, in XL α s expressing cells the signal intensities remained constant despite PTH treatment, indicating that both XL α s and PTHR remained largely at the plasma membrane (SI Appendix, Fig. S7C, D).

We then tested whether overexpression of XL α s affects internalization of the type-2 vasopressin receptor (V2R), another GPCR that internalizes via clathrin-mediated endocytosis^{45,46}. HEK293T cells were co-transfected with XL α s-GFP and V2R cDNA and treated with tetramethylrhodamine-labeled vasopressin (VP-TMR) for 5 min. The cells co-transfected with G α -GFP and V2R cDNA were used as control. Confocal microscopy

indicated a small degree of V2R internalization in XL α s-overexpressing cells, whereas most V2R signal was detected in the cytoplasmic portion of cells overexpressing G α (SI Appendix, Fig. S8).

To determine whether GPCR internalization is enhanced in the setting of XL α s ablation, we established primary cardiomyocyte cultures from WT and XLKO mice and subsequently transfected these cells with PTHR plasmid. We then treated these cells with PTH-TMR and performed fluorescence confocal microscopy. One minute after PTH-TMR treatment, most of the fluorescence signal appeared close to the plasma membrane in cells from WT mice, whereas a significant amount of signal appeared intracellular in cells from XLKO mice (SI Appendix, Fig. S9A-D). While no differences were detected between XLKO and WT cells at 5 minutes (SI Appendix, Fig. S9E, F), the subcellular distribution of PTH-TMR was significantly different between WT and XLKO cells at 15 minutes. WT cells displayed punctate intracellular fluorescence signal, whereas a significant portion of XLKO cells exhibited focal perinuclear spots (SI Appendix, Fig. S9G-I). The latter pattern of subcellular distribution has been previously described for PTHR, indicating the localization of internalized PTHR at later stages (~30 min after ligand treatment)⁴⁷. In our experiments, most WT cells indeed displayed similar perinuclear spots 30 minute following PTH-TMR treatment, although punctate fluorescence signal was also detectable. XLKO cells, on the other hand, showed markedly diminished fluorescence intensity but continued to have the focal perinuclear spots (SI Appendix, Fig. S9 J, K). These findings suggested that PTHR internalization was enhanced in the setting of XL α s deficiency.

Neither ALEX nor the Gs α portion is required for the inhibitory action of XL α s on endocytosis

ALEX is translated from the XL α s transcript using a different open reading frame and can interact with XL α s²³. We generated an XL α s cDNA mutant in which the initiator methionine for ALEX was mutated to a threonine without changing the coding sequence for XL α s (ALEX(-)XL α s). A similar mutagenesis approach has previously been applied to successfully silence the translation of ALEX from rat XL α s cDNA²³. Confocal microscopy showed that both transferrin and PTHR internalization were inhibited in HEK293T cells transiently expressing ALEX(-)XL α s, similar to cells expressing native XL α s (SI Appendix, Fig. S10A, B). By using flow cytometry, we also demonstrated that the degree of transferrin internalization was significantly lower in cells expressing ALEX(-)XL α s than in untransfected cells (SI Appendix, Fig. S10C, D), thus indicating that ALEX does not play a significant role in the action of XL α s in endocytosis.

We also examined a C-terminally truncated XL α s mutant (N-terminal XL α s), in which the portion containing the residues identical to Gs α are replaced with GFP. Confocal microscopy showed that this mutant was localized to the plasma membrane in most transfected HEK293T cells, although intracellular GFP signal was additionally detected in some cells (Fig. 10A, B). Regardless, HEK293T cells expressing this mutant demonstrated significantly reduced transferrin uptake and PTHR internalization (Fig. 10A, B). Flow cytometry also confirmed that N-terminal XL α s significantly inhibited transferrin uptake (Fig. 10C, D). The degree of inhibition was similar to that for full-length XL α s (Fig. 10E, F), while overexpression of Gs α did

not inhibit transferrin uptake (Fig. 10G, H). These results indicate that the G α portion of XL α s is not required for the inhibition of endocytosis.

Discussion

In this study, we identified SNX9 and dynamin as novel binding partners of the *GNAS*-derived imprinted G-alpha protein XL α s. Our investigations indicated that XL α s acts as an inhibitor of clathrin-mediated endocytosis independent of its G α -like actions. Accordingly, loss of XL α s enhanced the internalization of transferrin, which occurs via clathrin-mediated endocytosis, and resulted in increased iron uptake in cultured cells and in mice. Moreover, agonist-induced internalization of the G protein-coupled PTHR, which is also mediated by clathrin-mediated endocytosis, was more extensive in cells missing XL α s than in wild-type cells. These findings not only reveal a hitherto unknown cellular action for XL α s, but also provide novel insights into heterotrimeric G protein actions and the regulation of endocytosis.

Since endocytosis is key to multiple cellular processes, it is conceivable that ablation or overexpression of XL α s in our experiments led to secondary disruptions in certain cellular processes and, thereby, affected our results. However, evaluation of endocytosis as a primary read-out is less likely to be confounded. It is unlikely that the enhanced transferrin uptake in XLKO Ocy454 cells and XLKO primary cardiomyocytes were secondary to basally increased TfRc levels, as we found that the TfRc mRNA levels were unaltered in those cells compared to WT cells. Likewise, increased TfRc levels cannot account for the increased iron uptake into the hearts of P10 XLKO pups, since the baseline TfRc mRNA abundance was diminished in XLKO

hearts (~16% of WT). The reduction in TfRc mRNA in heart may reflect the increased tissue iron level at baseline, which was demonstrated by our histological analyses (see Fig. 4A).

Strikingly, these findings were obtained despite low serum iron levels in P10 XLKO pups. We are currently unable to offer any explanation for the latter finding, but it is tempting to speculate that the increased deposition of iron in heart and skeletal muscle might be responsible, at least partly, for the low circulating iron levels. Nonetheless, our additional findings obtained from XLKO neonates, which are affected minimally, if at all, by the postnatal defects involving multiple systems, clearly support the conclusion that XL α s plays a critical role in the regulation of tissue iron levels, consistent with an important action of XL α s in clathrin-mediated endocytosis.

The effect of XL α s on endocytosis is possibly through its interactions with SNX9 and dynamin, given that the N-terminally truncated XL α s mutant that is unable to interact with SNX9 or dynamins is also unable to inhibit endocytosis. SNX9 recruits dynamin to the plasma membrane and stimulates its oligomerization, thereby promoting its activity⁴⁸. Overexpression of dominant-negative dynamin mutants results in a dramatic increase in the number of pits with long necks⁴⁰. As indicated in our EM analyses, overexpression of XL α s also led to increased numbers of elongated pits relative to deep or shallow pits, consistent with the hypothesis that XL α s interferes with the actions of SNX9 and dynamin.

Since SNX9 knockdown rescues the enhanced internalization caused by XL α s deficiency in cultured cells, it appears that XL α s acts mechanistically upstream of SNX9. The increase in the protein level of SNX9 in XL α s-ablated cells and tissues may suggest that the interaction of XL α s

with SNX9 contributes to the regulation of SNX9 levels, which is known to be critical for clathrin-mediated endocytosis^{24,33}. Further studies are warranted to elucidate the precise mechanisms whereby XL α s mediates the action of SNX9.

Our experiments indicated that the interaction of XL α s with SNX9 and dynamin occurs via the portion of the XL domain including multiple proline-rich motifs and the highly conserved proline-rich domain. SNX9 contains an SH3 domain, which may mediate the interaction between this domain and SNX9. Consistent with this possibility, a 15-aa segment (GARRKIHLRPPSPEI) overlapping the conserved proline-rich region of human XL α s is predicted to interact with the SNX9 SH3-domain (according to MoDPepInt; <http://modpepint.informatik.uni-freiburg.de>)⁴⁹. Moreover, the proline-rich region comprises an evolutionarily conserved class I SH3 domain-binding motif⁵⁰. While a direct interaction seems likely, it remains possible that XL α s-SNX9 interaction occurs through another protein, and that these two are part of a larger complex, which also includes dynamin. Dynamin interacts with SNX9 via its own proline-rich lipid-binding domain and this interaction occurs via the SH3 domain of SNX9⁵¹. Considering that SNX9 forms homodimers via its BAR domain⁵², it is tempting to speculate that XL α s and dynamin are brought together via interacting individually with SNX9. Future studies are needed to elucidate the molecular determinants of these interactions.

Considering that the XL α s transcript gives rise to both XL α s and ALEX, our transfection experiments using XL α s cDNA also led to ALEX overexpression. Likewise, the disruption of XL α s sequence is predicted to ablate not only XL α s but also ALEX in vivo. Thus, it is

possible that ALEX may have mediated or contributed to the interaction of XL α s with SNX9 and/or dynamin and the effect of XL α s on endocytosis. However, our mutational analyses using transfected cells suggested that ALEX, which was shown to interact with XL α s²³, is not required for the inhibitory action of XL α s on endocytosis.

XL α s is able to mediate basal and GPCR activated cAMP generation when overexpressed^{21,41,53}. Interestingly, our previous findings have suggested that XL α s promotes basal and GPCR-activated IP3 generation in mouse kidney and cultured cells³⁰. It could thus be argued that the effect of XL α s on endocytosis is secondary to the activation of these signaling pathways. However, this possibility is unlikely, since endocytosis was not inhibited as a result of G α overexpression, which, like XL α s overexpression, enhances basal cAMP signaling⁴². Moreover, C-terminal truncation of XL α s leading to the loss of its G α portion did not abolish the inhibitory action of XL α s in endocytosis. In some transfected HEK293 cells, this truncation mutant (N-terminal XL α s) localized to intracellular sites, as well as the plasma membrane. Similarly, an XL α s construct using the rat XL-domain has previously been studied and was shown to localize exclusively to the plasma membrane in transfected PC12 cells but not in COS7 cells, in which localization was detected in additional subcellular compartments²². Thus, it is possible that the G α -portion of XL α s contributes to the plasma membrane localization of XL α s and may function concurrently with other cell-specific mechanisms.

Genetic mutations in humans and studies of different mouse models implicate loss of XL α s activity, by itself or combined with loss of G α activity, in a number of disorders, including intrauterine growth retardation, heterotopic ossification, platelet defects, and disrupted glucose

and energy metabolism with increased central sympathetic outflow^{18,54-56}. It has also been shown that XL α s hyperactivity contributes to the pathogenesis of breast cancers associated with increased chromosome 20q copy number²⁰. Diseases caused by XL α s alterations could thus result, at least partly, from changes in clathrin-mediated endocytosis. In addition, studies have revealed that SNX9 plays additional actions in membrane trafficking and actin dynamics, thus contributing to a wide range of cellular processes, including clathrin-independent endocytosis, cell division, and tumor metastasis⁵⁷. Since our study strongly suggests that XL α s acts as a regulator of SNX9 activity or levels, it appears likely that altered XL α s function also affects these other SNX9-dependent cellular events.

The G α -portion seems to be unnecessary for the XL α s-mediated inhibition of endocytosis. It thus appears unlikely that this action of XL α s is impaired due to inactivating mutations located within the G α portion (such as those found in patients with pseudo-pseudohypoparathyroidism, who carry paternal GNAS mutations), unless the mutation causes diminished XL α s expression as a result of non-sense mediated decay or protein instability. The same mutations, however, impair the G protein signaling action of XL α s⁴². Selective effects of these GNAS mutations on the different actions of XL α s would have implications in the associated clinical phenotypes.

The modest increase of G α levels in XLKO cells is concordant with a previous study demonstrating elevated G α levels, as well as agonist-induced cAMP production, in XLKO renal brush border membranes³⁰. This mechanism governing the XLKO-induced elevation in G α levels remain unknown. Nonetheless, it is unlikely that the elevated G α levels contribute to

the increased transferrin uptake observed in XLKO cells, as our findings argue against a role for G α overexpression in endocytosis.

In summary, our findings indicate that XL α s plays a role as an inhibitor of clathrin-mediated endocytosis, and that this role of XL α s is upstream of SNX9 and independent of its G protein signaling action. Consistent with this novel cellular action, loss of XL α s results in increased transferrin uptake and iron accumulation in cultured cells and mice.

Methods

Expression plasmids

Plasmids encoding SNX9, Dnm1, Dnm2, Dnm1K44A-GFP, and Dnm2K44A-GFP were obtained from Addgene. cDNA encoding FLAG-tagged XL α s, HA-tagged PostPRR-XL α s, HA-tagged G α , XL α s and G α with GFP tag were described previously^{21,58}. The plasmid encoding PostPRR-XL α s-GFP was constructed by substituting the sequences encoding PostPRR-XL α s for the full-length XL α s in the XL α s-GFP construct. ALEX(-)XL α s-GFP plasmid was constructed by point mutation at ALEX start codon region in the XL α s-GFP construct. The plasmid encoding N-terminal XL α s-GFP was constructed by inserting N-terminal XL α s portion into pcDNA3.1/CT-GFP TOPO vector using CT-GFP Fusion TOPO Expression Kit (Thermo Fisher Scientific). The plasmid encoding the PTHR-dsRed fusion protein (PTHR-dsRed), PTHR, and Vasopressin Type 2 Receptor (V2R) were reported before^{21,59}.

Mice

XLKO mice were generated by disrupting the first exon encoding XL α s on the paternal allele²⁶.

These mice were maintained in a CD1 genetic background. 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 Subcommittee on Research Animal Care.

Mass spectrometry

C3H10T1/2 cells were transfected with FLAG-tagged XL α s or YFP, and the cell lysates were purified by anti-FLAG affinity resin and followed by LC-MS/MS analysis. LC-MS/MS was carried out at the Taplin Biological Mass Spectrometry Facility, Cell Biology Department, Harvard Medical School.

Cell culture and transfection

Primary cardiomyocytes were prepared from P2 mouse hearts as previously described, and cultured in Ham's F-10 medium with 10% horse serum and 5% FBS at 37 °C⁶⁰. HEK293T cells were cultured in Dulbecco's modified Eagle's medium with 10% FBS at 37 °C, while osteocytic cell line Ocy454 cells were maintained in α -minimum essential medium with 10% FBS at 33°C^{27,28}. Primary cardiomyocytes were transiently transfected by using Lipofectamin LTX & PLUS (Invitrogen). HEK293T cells were transiently transfected by using either Lipofectamin 2000 (Invitrogen) for endocytic vesicle profiling by EM, or PolyJet (SignaGen Laboratories) for all other assays.

Generation of XL α s knockout Ocy454 cells by CRISPR/Cas9

Three different guide RNAs targeting XL α s were designed through the sgRNA Designer website (Broad Institute), and cloned into pSpCas9(BB)-2A-GFP vector (Addgene) (SI Appendix, Table

S2). The osteocytic Ocy454 cells were transfected with the plasmids containing *XLas* sgRNAs, and 3 days following transfection, successful delivery of sgRNA plasmids was confirmed by visualizing green fluorescent marker expression by fluorescence microscopy. Transfected cells were sorted using fluorescence activated cell sorting (FACS), and individual GFP-positive cells were cloned into 96-well plates and allowed to expand for 3 weeks. Successful knockout of *XLas* in single cloned Ocy454 cells were assessed by Western blot analysis and sequencing of DNA fragments covering the sgRNA target region (SI Appendix, Table S3, SI Appendix, Fig. S2).

Cell lysis, immunoprecipitation and Western blotting analysis

HEK293T cells 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 cocktail tablets (Roche). For immunoprecipitations, equal amounts of cell lysate were incubated with the indicated antibodies for 16–18 h at 4 °C with rotation. Protein A/G-agarose beads (Santa Cruz) were then added to the lysates to capture the immune complex for one hour. After washing with HNTG buffer for four times and phosphate-buffered saline (PBS) for one time, the immune complexes were eluted from the beads by boiling in 2× SDS sample buffer. For immunoblot analysis, cell lysates and immunoprecipitated proteins were resolved by 10% SDS-polyacrylamide gel electrophoresis (SDS-PAGE) and transferred to nitrocellulose membranes (Bio-rad). Western blots were then incubated with specific antibodies. Antibody against FLAG was purchased from Sigma. Antibodies against SNX9, Dnm1 and Dnm2 were from Santa Cruz Biotechnology. Polyclonal antiserum against mouse *XLas* was described

previously⁶¹. Gs α antibody, which recognizes Gs α , XL α s and PostPRR-XL α s, was purchased from Millipore. L-Ferritin antibody was purchased from Novus Biologicals.

Confocal microscopy

HEK293T cells were co-transfected with GFP-tagged XL α s or Gs α , together with PTHR or V2R plasmids. Forty-eight hours after transfection, the cells were washed three times with 10mM Hepes pH7.5 with 0.1% BSA and then treated with PTH-TMR (10 nM) or VP-TMR (1 μ m) for 5 min at 37°C to visualize internalization of PTHR and V2R. Primary cardiomyocytes from P2 WT and XLKO mice were transfected with PTHR plasmid, and treated with PTH-TMR (10 nM) for 1 min, 5 min, 15 min, or 30 min at room temperature. PTH-TMR was synthesized at the MGH Biopolymer Core facility, and VP-TMR was described previously⁶². For transferrin receptor internalization, HEK293T cells transfected with XL α s-GFP or Gs α -GFP were serum starved for one hour and treated with transferrin-Alexa Fluor 568 (ThermoFisher Scientific) (10 μ g/ml) for 30 min. Cells were washed three times with cold PBS and fixed with 4% paraformaldehyde (PFA) in PBS for 20 min. HEK293T cells co-transfected with HA-tagged Gs α or PostPRR-XL α s were treated with PTH-TMR (10 nM) for 5 min. After fixation with 4% PFA for 20 min, cells were permeabilized with 0.2% Triton X-100 in PBS and subsequently incubated for 30 min with a blocking solution containing 0.2% Triton X-100, 1% BSA and 5% goat serum in PBS. Cells were then immunoreacted to a rabbit anti-HA antibody (Santa Cruz Biotechnology), followed by Alexa Fluor 488-conjugated donkey anti-rabbit IgG (Life technologies). Fluorescent intensity was visualized and analyzed with a Zeiss LSM 510 Confocal Microscope (Ragon Institute) and Zeiss Zen software. To quantify the fluorescence intensity ratio

between the plasma membrane and cytosol in XL α s-GFP or G α s-GFP transfected cells, a line was drawn across each one of the cells. The line intensity profiles were obtained by using ImageJ software, as described^{63,64}. The results shown are averages \pm SEM from ten different cells from at least three independent experiments.

TIRF microscopy

TIRF microscopy analysis of PTHR internalization was performed as previously described²¹. Briefly, HEK293T cells were cultured on FluoroDish (World Precision Instruments, Inc.) and transiently transfected with cDNA encoding G α s-GFP or XL α s-GFP, as well as PTHR-dsRed. Forty-eight hours after transfection, cells were stimulated with 10 nM PTH(1-34) and fluorescent signal intensities in individual live cells with brightest GFP signal were analyzed by a total internal reflection (TIRF) objective over 50 min.

Flow cytometric analysis for transferrin uptake and apoptosis

For transferrin uptake assay, HEK293T cells were transfected with G α s-GFP, XL α s-GFP, PostPRR-XL α s-GFP, Dnm1K44A-GFP, or Dnm2K44A-GFP. Forty-eight hours after transfection, cells were serum starved for one hour and subsequently incubated with transferrin Alexa Fluor 568. Thirty minutes after the addition of transferrin-Alexa Fluor 568, the transfected HEK293T cells, Ocy454 cells, and primary cardiomyocytes isolated from P2 mice were washed with PBS and dissociated from the culture plates. Cells were then subjected to flow cytometry by using FACSariaII (BD Biosciences) at MGH Center for Regenerative Medicine Flow Cytometry Core. The results were analyzed by FlowJo software (FlowJo LLC) for the median values of transferrin uptake in GFP-positive and GFP-negative cell populations.

For apoptosis analysis in primary cardiomyocytes with iron overload, the cells were treated with or without 150, 300, 600 μM FeCl_3 as previously described³³. After seventy-two hours of incubation, the cells were gently detached by 0.05% Trypsin-EDTA (Invitrogen) and stained with Annexin V-FITC Apoptosis Detection Kit (abcam), and Annexin V-positive/PI-negative cells were gated by flow cytometric assay to quantify the apoptotic cell number.

cDNA synthesis and qRT-PCR analysis

Total RNA was prepared using the RNeasy Plus Mini Kit (QIAGEN). One microgram of total RNA was used to synthesize first-strand cDNA using ProtoScript II First-strand cDNA synthesis kit (New England Biolabs). qRT-PCR analysis was performed with specific primers and FastStart Universal SYBR Green Master (Roche) with β -actin as a reference gene. Primers used for qRT-PCR were: β -actin (F) GATCTGGCACACACCTTCT and (R) GGGGTGTTGAAGGTCTCAAA; TfRc (F) ATGCCCTCTCTGGTGACATTTGGA and (R) ACCCTCCACAAGCACACTCTTTCT; and XL α s (F) CTCATCGACAAGCAACTGGA and (R) CCCTCTCCGTAAACCCATT.

In vivo iron-loading experiments

Iron dextran was injected i.p daily (400mg per kg body weight per day) for a total duration of 10 days starting from neonatal age, i.e. P0-P9. Mice injected with vehicle (0.9% sodium chloride solution) were used as control. Mice were sacrificed at P10 for the analysis. Hearts were removed and fixed in 4% PFA and embedded in paraffin (MGH Center for Skeletal Research). 5 μm sections were stained with Iron Stain Kit (Sigma) using staining protocol recommended by the manufacturer. The deposition of iron was visualized as blue depositions using a bright field

microscope. For heart tissues with vehicle injection, a modified diaminobenzidine-enhanced Perls' stain containing cobalt chloride was used⁶⁵.

Iron analysis

Serum iron and tissues nonheme iron concentrations were determined as described previously⁶⁶. Tissue iron is reported as micrograms of iron per gram of wet weight tissue.

Transmission electron microscopy

HEK293T cells were transfected with XL α s-GFP or Gs α -GFP plasmids for 48 hours. The percentage of GFP positive cells was determined to assess the transfection efficiency, and over 95% cells were GFP positive. Cells were incubated with Transferrin - 10nm Gold Conjugate (Cytodiagnosics) in PBS supplemented with 1mM MgCl₂, 1 mM CaCl₂, 5 mM glucose and 0.2% BSA) for 1 hour, and then washed and fixed in with 2.5% glutaraldehyde/2% PFA in 0.1 M cacodylate buffer (pH 7.4) for 2 hours at room temperature. Cells were then processed for thin-section electron microscopy using a Tecnai G2 Spirit Bio TWIN electron microscope (FEI Company) at the Harvard Medical School EM facility.

Statistical analysis

The means \pm SEM of multiple independent measurements were calculated. The unpaired two-tailed Student's t-test was used to determine the significance of differences between means. *P* values smaller than 0.05 (**p*<0.05, ***p*<0.01, ****p*<0.001) were considered to be significant.

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References

- 1 Doherty, G. J. & McMahon, H. T. Mechanisms of endocytosis. *Annu Rev Biochem* **78**, 857-902, doi:10.1146/annurev.biochem.78.081307.110540 (2009).
- 2 McMahon, H. T. & Boucrot, E. Molecular mechanism and physiological functions of clathrin-mediated endocytosis. *Nat Rev Mol Cell Biol* **12**, 517-533, doi:10.1038/nrm3151 nrm3151 [pii] (2011).
- 3 Elkin, S. R., Lakoduk, A. M. & Schmid, S. L. Endocytic pathways and endosomal trafficking: a primer. *Wien Med Wochenschr* **166**, 196-204, doi:10.1007/s10354-016-0432-7 10.1007/s10354-016-0432-7 [pii] (2016).
- 4 Kumari, S., Mg, S. & Mayor, S. Endocytosis unplugged: multiple ways to enter the cell. *Cell Res* **20**, 256-275, doi:10.1038/cr.2010.19 cr201019 [pii] (2010).
- 5 Nesbit, M. A. *et al.* Mutations in AP2S1 cause familial hypocalciuric hypercalcemia type 3. *Nat Genet* **45**, 93-97, doi:10.1038/ng.2492 ng.2492 [pii] (2013).
- 6 Zuchner, S. *et al.* Mutations in the pleckstrin homology domain of dynamin 2 cause dominant intermediate Charcot-Marie-Tooth disease. *Nat Genet* **37**, 289-294 (2005).
- 7 Bitoun, M. *et al.* Mutations in dynamin 2 cause dominant centronuclear myopathy. *Nat Genet* **37**, 1207-1209 (2005).
- 8 Harold, D. *et al.* Genome-wide association study identifies variants at CLU and PICALM associated with Alzheimer's disease. *Nat Genet* **41**, 1088-1093, doi:10.1038/ng.440 ng.440 [pii] (2009).
- 9 Nixon, R. A. Endosome function and dysfunction in Alzheimer's disease and other neurodegenerative diseases. *Neurobiol Aging* **26**, 373-382, doi:S0197-4580(04)00294-5 [pii] 10.1016/j.neurobiolaging.2004.09.018 (2005).
- 10 Bareford, L. M. & Swaan, P. W. Endocytic mechanisms for targeted drug delivery. *Adv Drug Deliv Rev* **59**, 748-758, doi:S0169-409X(07)00096-8 [pii] 10.1016/j.addr.2007.06.008 (2007).
- 11 Oldham, W. M. & Hamm, H. E. Heterotrimeric G protein activation by G-protein-coupled receptors. *Nat Rev Mol Cell Biol* **9**, 60-71, doi:nrm2299 [pii] 10.1038/nrm2299 (2008).
- 12 Weinstein, L. S., Liu, J., Sakamoto, A., Xie, T. & Chen, M. Minireview: GNAS: normal and abnormal functions. *Endocrinology* **145**, 5459-5464 (2004).
- 13 Turan, S. & Bastepe, M. GNAS Spectrum of Disorders. *Current osteoporosis reports* **13**, 146-158, doi:10.1007/s11914-015-0268-x (2015).
- 14 Weinstein, L. S., Chen, M. & Liu, J. Gs(alpha) mutations and imprinting defects in human disease. *Ann N Y Acad Sci* **968**, 173-197 (2002).
- 15 Kehlenbach, R. H., Matthey, J. & Huttner, W. B. XL alpha s is a new type of G protein. *Nature* **372**, 804-809 (1994).
- 16 Hayward, B. E., Moran, V., Strain, L. & Bonthron, D. T. Bidirectional imprinting of a single gene: GNAS1

- encodes maternally, paternally, and biallelically derived proteins. *Proc Natl Acad Sci U S A* **95**, 15475-15480 (1998).
- 17 Shore, E. M. *et al.* Paternally inherited inactivating mutations of the GNAS1 gene in progressive osseous heteroplasia. *N Engl J Med* **346**, 99-106, doi:10.1056/NEJMoa011262 346/2/99 [pii] (2002).
- 18 Richard, N. *et al.* Paternal GNAS Mutations Lead to Severe Intrauterine Growth Retardation (IUGR) and Provide Evidence for a Role of XLalphas in Fetal Development. *J Clin Endocrinol Metab* **98**, E1549-1556, doi:10.1210/jc.2013-1667 (2013).
- 19 Izzi, B. *et al.* Methylation defect in imprinted genes detected in patients with an Albright's hereditary osteodystrophy like phenotype and platelet Gs hypofunction. *PLoS One* **7**, e38579, doi:10.1371/journal.pone.0038579 (2012).
- 20 Garcia-Murillas, I. *et al.* An siRNA screen identifies the GNAS locus as a driver in 20q amplified breast cancer. *Oncogene* **33**, 2478-2486, doi:10.1038/onc.2013.202 onc2013202 [pii] (2014).
- 21 Liu, Z., Turan, S., Wehbi, V. L., Vilardaga, J. P. & Bastepe, M. Extra-long Galphas variant XLalphas protein escapes activation-induced subcellular redistribution and is able to provide sustained signaling. *J Biol Chem* **286**, 38558-38569, doi:10.1074/jbc.M111.240150 M111.240150 [pii] (2011).
- 22 Pasolli, H. A., Klemke, M., Kehlenbach, R. H., Wang, Y. & Huttner, W. B. Characterization of the extra-large G protein alpha-subunit XLalphas. I. Tissue distribution and subcellular localization. *J Biol Chem* **275**, 33622-33632, doi:10.1074/jbc.M001335200 M001335200 [pii] (2000).
- 23 Klemke, M., Kehlenbach, R. H. & Huttner, W. B. Two overlapping reading frames in a single exon encode interacting proteins--a novel way of gene usage. *Embo J* **20**, 3849-3860. (2001).
- 24 Soulet, F., Yarar, D., Leonard, M. & Schmid, S. L. SNX9 regulates dynamin assembly and is required for efficient clathrin-mediated endocytosis. *Mol Biol Cell* **16**, 2058-2067, doi:E04-11-1016 [pii] 10.1091/mbc.E04-11-1016 (2005).
- 25 Urrutia, R., Henley, J. R., Cook, T. & McNiven, M. A. The dynamins: redundant or distinct functions for an expanding family of related GTPases? *Proc Natl Acad Sci U S A* **94**, 377-384 (1997).
- 26 Plagge, A. *et al.* The imprinted signaling protein XL alpha s is required for postnatal adaptation to feeding. *Nat Genet* **36**, 818-826, doi:10.1038/ng1397 ng1397 [pii] (2004).
- 27 Spatz, J. M. *et al.* The Wnt Inhibitor Sclerostin Is Up-regulated by Mechanical Unloading in Osteocytes in Vitro. *J Biol Chem* **290**, 16744-16758, doi:10.1074/jbc.M114.628313 (2015).
- 28 Wein, M. N. *et al.* HDAC5 controls MEF2C-driven sclerostin expression in osteocytes. *J Bone Miner Res* **30**, 400-411, doi:10.1002/jbmr.2381 (2015).
- 29 Pignolo, R. J. *et al.* Heterozygous inactivation of Gnas in adipose-derived mesenchymal progenitor cells enhances osteoblast differentiation and promotes heterotopic ossification. *J Bone Miner Res* **26**, 2647-2655, doi:10.1002/jbmr.481 (2011).
- 30 He, Q., Zhu, Y., Corbin, B. A., Plagge, A. & Bastepe, M. The G protein alpha subunit variant XLalphas promotes inositol 1,4,5-trisphosphate signaling and mediates the renal actions of parathyroid hormone in

- vivo. *Sci Signal* **8**, ra84, doi:10.1126/scisignal.aaa9953
8/391/ra84 [pii] (2015).
- 31 Papanikolaou, G. & Pantopoulos, K. Iron metabolism and toxicity. *Toxicol Appl Pharmacol* **202**, 199-211, doi:S0041-008X(04)00314-X [pii]
10.1016/j.taap.2004.06.021 (2005).
- 32 Oudit, G. Y. *et al.* Taurine supplementation reduces oxidative stress and improves cardiovascular function in an iron-overload murine model. *Circulation* **109**, 1877-1885, doi:10.1161/01.CIR.0000124229.40424.80
01.CIR.0000124229.40424.80 [pii] (2004).
- 33 Chen, M. P., Cabantchik, Z. I., Chan, S., Chan, G. C. & Cheung, Y. F. Iron overload and apoptosis of HL-1 cardiomyocytes: effects of calcium channel blockade. *PLoS One* **9**, e112915, doi:10.1371/journal.pone.0112915
PONE-D-14-08458 [pii] (2014).
- 34 Zecca, L., Youdim, M. B., Riederer, P., Connor, J. R. & Crichton, R. R. Iron, brain ageing and neurodegenerative disorders. *Nat Rev Neurosci* **5**, 863-873, doi:nrn1537 [pii]
10.1038/nrn1537 (2004).
- 35 Enns, C. A. Pumping iron: the strange partnership of the hemochromatosis protein, a class I MHC homolog, with the transferrin receptor. *Traffic* **2**, 167-174, doi:tra020303 [pii] (2001).
- 36 Fernandez-Rebollo, E. *et al.* Loss of XLalphas (extra-large alphas) imprinting results in early postnatal hypoglycemia and lethality in a mouse model of pseudohypoparathyroidism Ib. *Proc Natl Acad Sci U S A* **109**, 6638-6643, doi:10.1073/pnas.1117608109
1117608109 [pii] (2012).
- 37 Krechowec, S. O. *et al.* Postnatal changes in the expression pattern of the imprinted signalling protein XLalphas underlie the changing phenotype of deficient mice. *PLoS One* **7**, e29753, doi:10.1371/journal.pone.0029753
PONE-D-11-12984 [pii] (2012).
- 38 Ma, M. P. & Chircop, M. SNX9, SNX18 and SNX33 are required for progression through and completion of mitosis. *J Cell Sci* **125**, 4372-4382, doi:10.1242/jcs.105981
jcs.105981 [pii] (2012).
- 39 Kay, B. K., Williamson, M. P. & Sudol, M. The importance of being proline: the interaction of proline-rich motifs in signaling proteins with their cognate domains. *FASEB J* **14**, 231-241 (2000).
- 40 Damke, H., Binns, D. D., Ueda, H., Schmid, S. L. & Baba, T. Dynamin GTPase domain mutants block endocytic vesicle formation at morphologically distinct stages. *Mol Biol Cell* **12**, 2578-2589 (2001).
- 41 Bastepe, M. *et al.* Receptor-mediated adenylyl cyclase activation through XLalpha(s), the extra-large variant of the stimulatory G protein alpha-subunit. *Mol Endocrinol* **16**, 1912-1919, doi:10.1210/me.2002-0054 (2002).
- 42 Linglart, A. *et al.* Coding GNAS mutations leading to hormone resistance impair in vitro agonist- and cholera toxin-induced adenosine cyclic 3',5'-monophosphate formation mediated by human XLalphas. *Endocrinology* **147**, 2253-2262, doi:en.2005-1487 [pii]
10.1210/en.2005-1487 (2006).
- 43 Huang, Z., Chen, Y. & Nissenson, R. A. The cytoplasmic tail of the G-protein-coupled receptor for parathyroid hormone and parathyroid hormone-related protein contains positive and negative signals for

- endocytosis. *J Biol Chem* **270**, 151-156 (1995).
- 44 Ferrandon, S. *et al.* Sustained cyclic AMP production by parathyroid hormone receptor endocytosis. *Nat Chem Biol* **5**, 734-742 (2009).
- 45 Bouley, R. *et al.* Heterologous downregulation of vasopressin type 2 receptor is induced by transferrin. *Am J Physiol Renal Physiol* **304**, F553-564, doi:10.1152/ajprenal.00438.2011
ajprenal.00438.2011 [pii] (2013).
- 46 Feinstein, T. N. *et al.* Noncanonical control of vasopressin receptor type 2 signaling by retromer and arrestin. *J Biol Chem* **288**, 27849-27860, doi:10.1074/jbc.M112.445098
M112.445098 [pii] (2013).
- 47 Conway, B. R. *et al.* Quantitative analysis of agonist-dependent parathyroid hormone receptor trafficking in whole cells using a functional green fluorescent protein conjugate. *J Cell Physiol* **189**, 341-355, doi:10.1002/jcp.10028 [pii]
10.1002/jcp.10028 (2001).
- 48 Lundmark, R. & Carlsson, S. R. Regulated membrane recruitment of dynamin-2 mediated by sorting nexin 9. *J Biol Chem* **279**, 42694-42702, doi:10.1074/jbc.M407430200
M407430200 [pii] (2004).
- 49 Kundu, K., Mann, M., Costa, F. & Backofen, R. MoDPepInt: an interactive web server for prediction of modular domain-peptide interactions. *Bioinformatics* **30**, 2668-2669, doi:10.1093/bioinformatics/btu350
btu350 [pii] (2014).
- 50 Ferraro, E., Peluso, D., Via, A., Ausiello, G. & Helmer-Citterich, M. SH3-Hunter: discovery of SH3 domain interaction sites in proteins. *Nucleic Acids Res* **35**, W451-454, doi:gkm296 [pii]
10.1093/nar/gkm296 (2007).
- 51 Lundmark, R. & Carlsson, S. R. Sorting nexin 9 participates in clathrin-mediated endocytosis through interactions with the core components. *J Biol Chem* **278**, 46772-46781 (2003).
- 52 Yarar, D., Surka, M. C., Leonard, M. C. & Schmid, S. L. SNX9 activities are regulated by multiple phosphoinositides through both PX and BAR domains. *Traffic* **9**, 133-146, doi:TRA675 [pii]
10.1111/j.1600-0854.2007.00675.x (2008).
- 53 Klemke, M. *et al.* Characterization of the extra-large G protein alpha-subunit XLalphas. II. Signal transduction properties. *J Biol Chem* **275**, 33633-33640, doi:10.1074/jbc.M006594200
M006594200 [pii] (2000).
- 54 Shore, E. M. & Kaplan, F. S. Inherited human diseases of heterotopic bone formation. *Nat Rev Rheumatol* **6**, 518-527, doi:10.1038/nrrheum.2010.122
nrrheum.2010.122 [pii] (2010).
- 55 Freson, K. *et al.* GNAS defects identified by stimulatory G protein alpha-subunit signalling studies in platelets. *J Clin Endocrinol Metab* **93**, 4851-4859, doi:10.1210/jc.2008-0883 (2008).
- 56 Xie, T. *et al.* The alternative stimulatory G protein alpha-subunit XLalphas is a critical regulator of energy and glucose metabolism and sympathetic nerve activity in adult mice. *J Biol Chem* **281**, 18989-18999 (2006).
- 57 Bendris, N. & Schmid, S. L. Endocytosis, Metastasis and Beyond: Multiple Facets of SNX9. *Trends Cell Biol* **27**, 189-200, doi:S0962-8924(16)30177-5 [pii]
10.1016/j.tcb.2016.11.001 (2017).

- 58 Aydin, C. *et al.* Extralarge XL(alpha)s (XXL(alpha)s), a variant of stimulatory G protein alpha-subunit (Gs(alpha)), is a distinct, membrane-anchored GNAS product that can mimic Gs(alpha). *Endocrinology* **150**, 3567-3575, doi:10.1210/en.2009-0318 en.2009-0318 [pii] (2009).
- 59 Bouley, R. *et al.* Downregulation of the vasopressin type 2 receptor after vasopressin-induced internalization: involvement of a lysosomal degradation pathway. *Am J Physiol Cell Physiol* **288**, C1390-1401, doi:00353.2004 [pii] 10.1152/ajpcell.00353.2004 (2005).
- 60 Patten, R. D. *et al.* 17beta-estradiol reduces cardiomyocyte apoptosis in vivo and in vitro via activation of phospho-inositide-3 kinase/Akt signaling. *Circ Res* **95**, 692-699, doi:10.1161/01.RES.0000144126.57786.89 01.RES.0000144126.57786.89 [pii] (2004).
- 61 Liu, Z. *et al.* Transgenic overexpression of the extra-large Gsalpha variant XLalphas enhances Gsalpha-mediated responses in the mouse renal proximal tubule in vivo. *Endocrinology* **152**, 1222-1233, doi:10.1210/en.2010-1034 en.2010-1034 [pii] (2011).
- 62 Chen, S. *et al.* Visualizing microtubule-dependent vasopressin type 2 receptor trafficking using a new high-affinity fluorescent vasopressin ligand. *Endocrinology* **152**, 3893-3904, doi:10.1210/en.2011-1049 en.2011-1049 [pii] (2011).
- 63 Ueda, H., Fujita, R., Yoshida, A., Matsunaga, H. & Ueda, M. Identification of prothymosin-alpha1, the necrosis-apoptosis switch molecule in cortical neuronal cultures. *J Cell Biol* **176**, 853-862, doi:jcb.200608022 [pii] 10.1083/jcb.200608022 (2007).
- 64 Armstrong, S., Pereverzev, A., Dixon, S. J. & Sims, S. M. Activation of P2X7 receptors causes isoform-specific translocation of protein kinase C in osteoclasts. *J Cell Sci* **122**, 136-144, doi:10.1242/jcs.031534 jcs.031534 [pii] (2009).
- 65 Canali, S. *et al.* Endothelial cells produce bone morphogenetic protein 6 required for iron homeostasis in mice. *Blood* **129**, 405-414, doi:10.1182/blood-2016-06-721571 blood-2016-06-721571 [pii] (2017).
- 66 Zumbrennen-Bullough, K. B. *et al.* MicroRNA-130a is up-regulated in mouse liver by iron deficiency and targets the bone morphogenetic protein (BMP) receptor ALK2 to attenuate BMP signaling and hepcidin transcription. *J Biol Chem* **289**, 23796-23808, doi:10.1074/jbc.M114.577387 M114.577387 [pii] (2014).

Figure legends

Figure 1. XL α s can be co-immunoprecipitated with SNX9, Dnm1, and Dnm2. (A-C) XL α s-FLAG was co-expressed with (A) SNX9, (B) Dnm1, or (C) Dnm2 in HEK293T cells. Cells transfected with pcDNA plasmid were used as control. Total cell extracts were immunoprecipitated with the (A) anti-SNX9, (B) anti-Dnm1, (C) anti-Dnm2 or anti-FLAG antibodies. The immunoprecipitated proteins were analyzed subsequently by immunoblot using anti-FLAG or (A) anti-SNX9, (B) anti-Dnm1, (C) anti-Dnm2 antibodies. (D) Protein lysates from P2 WT and XLKO hearts were immunoblotted with a G α antibody recognizing both XL α s and G α . (E) Heart tissue lysates from P2 WT mice were immunoprecipitated with anti-XL α s, anti-Dnm2, or anti-SNX9 antibodies, and then, immunoblot was performed using XL α s antiserum. Goat IgG and the rabbit IgG served as negative controls for immunoprecipitation. Heart tissue lysates from P2 WT and XLKO mice were used for immunoblotting to identify the specific XL α s band. These results are representative of at least three independent experiments.

Figure 2. XL α s represses TfRc internalization and transferrin uptake. (A) Confocal microscopy analysis of XL α s-GFP expressing cells incubated with transferrin-Alexa Fluor 568 (10 μ g/ml) for 30 min. Scale bar, 10 μ m. (B-G) Flow cytometry analysis of transferrin uptake in different transfected cells. Representative plots of transferrin uptake in cells transiently expressing (B) XL α s-GFP, (D) Dnm1 K44A-GFP, and (F) Dnm2 K44A-GFP. (C, E, G) Quantification of the median values of transferrin-Alexa Fluor 568 in GFP+ and GFP- cell populations. Data are mean \pm SEM of three independent experiments (n=12 per group). *, p<0.05; **, p<0.01.

Figure 3. Ablation of XL α s enhances transferrin uptake and iron overload-induced apoptosis. (A) Western blot analysis of XL α s and G α in clonal control and XLKO Ocy454 cells. (B) Densitometry analysis of G α immunoreactivity shown in panel A. (C) Ocy454 cells were untreated or treated with transferrin-Alexa Fluor 568 for 30 min, and then analyzed by flow cytometry for transferrin uptake for quantification of the median values of transferrin-Alexa Fluor 568 in treated and untreated cells. (D) TfRc mRNA expression levels in control and XLKO Ocy454 cells. qRT-PCR was performed by using β -actin as a reference control (n=8 for control cells and n=16 for XLKO cells from four independent experiments). (E) Transferrin uptake in primary cardiomyocytes from P2 WT and XLKO mice. Cells were untreated or treated with transferrin-Alexa Fluor 568 for 30 min and then analyzed by flow cytometry for the median values of transferrin uptake. (F) TfRc mRNA expression in primary cardiomyocytes. qRT-PCR was performed by using β -actin as a reference control (WT: n=13; XLKO: n=10 for primary cardiomyocytes isolated from three different litters). Data represent mean \pm SEM. *p<0.05, **p<0.01. (G) Primary cardiomyocytes from WT and KO mice were untreated or treated with FeCl₃ for 72 hours, and the percentage of apoptotic cells was also analyzed by flow cytometric analysis of Annexin V/PI double staining. Results are expressed as the means \pm S.E.M of four independent experiments (n=18 in WT group; n=14 in XLKO group). **p < 0.01 as compared with control group.

Figure 4. P10 XLKO mice exhibit low serum iron levels with increased iron accumulation in heart. (A) Prussian blue staining of iron dextran-injected WT and XLKO mice shows more myocardial iron-overload in XLKO samples. (B) DAB Perls' enhanced Prussian blue staining of vehicle treated samples shows more iron deposition in XLKO samples at baseline. Arrows indicate positive stained cells. Images are representative of 6-8 mice per genotype from four independent litters. (C) qRT-PCR analysis of TfRc using total RNAs isolated from P10 mouse hearts. (D) Serum iron levels in P10 WT and XLKO mice. (E) TfRc mRNA levels in P10 WT and XLKO kidneys. (F) qRT-PCR analysis of XL α s in P10 kidneys and hearts. qRT-PCR was performed by using β -actin as a reference control. Data represent mean \pm SEM, *, $p < 0.05$; **, $p < 0.01$, ***, $p < 0.001$; $n = 9-12$.

Figure 5. XLKO neonates exhibit elevated L-Ferritin expression and iron deposition in heart and skeletal muscle. (A) qRT-PCR analysis of XL α s in tissues from WT neonates (P0). (B) Serum iron levels in P0 WT and XLKO. (C) Protein lysates from P0 heart, skeletal muscle, kidney, liver, lung and spleen were immunoblotted for L-Ferritin antibody. α -Tubulin was used as loading control. (D) Densitometric analysis of the relative abundances of L-Ferritin in different tissues. Data represent mean \pm SEM of 3 independent measurements. (E, F) Iron content in (E) heart and (F) skeletal muscle. Mean and SEM are indicated as horizontal bars. *, $p < 0.05$; **, $p < 0.01$; $n = 9-12$.

Figure 6. Ablation of XL α s increases SNX9 expression, and suppression of SNX9 expression rescues the enhanced transferrin uptake in XLKO cells. (A) Protein lysates from P0 heart, skeletal muscle, kidney, liver, lung and spleen were immunoblotted with SNX9 antibody. (B) Densitometric analysis of the relative abundances of SNX9 in different tissues. (C) Control and XLKO Ocy454 cells were transfected with siRNA directed against SNX9 or with control siRNA. Cell lysates were immunoblotted with SNX9 and α -Tubulin antibodies. (D) Results from (C) were quantified by densitometry. Data represent mean \pm SEM of at least three independent measurements; *, $p < 0.05$. (E) siRNA transfected Ocy454 cells were untreated or treated with transferrin-Alexa Fluor 568 for 30 min, and then analyzed by flow cytometry for transferrin uptake. Data are mean \pm SEM of three independent experiments ($n = 9-12$ per group); *, $p < 0.05$; **, $p < 0.01$.

Figure 7. G α and the XL α s mutant lacking the N-terminal region (PostPRR-XL α s) cannot interact with SNX9 or dynamins, or inhibit transferrin uptake. HEK293T cells were transfected with (A) SNX9, (B) Dnm1, or (C) Dnm2 plasmid, together with XL α s, PostPRR-XL α s, or G α plasmid, and the lysates of transfected cells were subjected to immunoprecipitation by using anti-SNX9 antibody. Subsequent immunoblots were performed by using the C-terminal anti-G α antibody, which could recognize XL α s, PostPRR-XL α s, and G α , as well as with (A) SNX9, (B) Dnm1, and (C) Dnm2 antibodies. Whole cell lysates were analyzed by using C-terminal anti-G α antibody to confirm successful transfection. Images are representative of

three independent experiments. (D) Confocal microscopy analysis of HEK293T cells transiently expressing Gs α , or PostPRR-XL α s-GFP. Scale bar, 10 μ m. (E, G) Representative plots of transferrin uptake in (E) Gs α -GFP, (G) PostPRR-XL α s-GFP transfected cells. (F, H) Quantification of the median values in GFP⁺ and GFP⁻ cells. Data are mean \pm SEM from three independent experiments (n=9 per group).

Figure 8. Electron microscopy analysis of coated pit profiles in cells expressing Gs α or XL α s. (A) Quantification of the percentage of elongated, deep and shallow pits in Gs α or XL α s overexpressing cells. 39-45 pits were randomly selected per group for quantification. Shallow coated pits (C-shaped pits, not closing), deep coated pits (with short neck, the length of neck is smaller than the diameter of pit), and elongated pits (the length of neck is greater than the diameter of pit) were identified by their morphology and with the help of ImageJ software (National Institutes of Health). The data shown are averages \pm SEM of three independent experiments; *, p<0.05; ***, p<0.001 vs. that in Gs α -expressing cells. (B-I) Representative coated pits from HEK293T cells overexpressing Gs α or XL α s. The images for Gs α group represent shallow pits (B, C) and deep pits (D, E). For XL α s group, (F, G) were scored as deep pits, while (H, I) were scored as elongated pits. Scale bar, 100nm.

Figure 9. Overexpression of XL α s prevents internalization of the G protein-coupled PTHR. (A, B) Confocal microscopy analysis of PTHR internalization in Gs α , XL α s, or PostPRR XL α s overexpressing cells. PTHR was co-transfected with (A) Gs α -GFP, (B) XL α s-GFP, or (C) PostPRR XL α s-GFP in HEK293T cells. The cells were treated for 5 min with PTH-TMR (10 nM), which internalizes the receptor. Scale bar, 10 μ m. (D) Fluorescence intensities along the white lines in A-C were plotted as intensity histograms. Y-axis, intensity level; X-axis, line distance. (E) Relative ratios of fluorescence intensity between plasma membrane and cytosolic area of PTHR and GFP were quantified by dividing the plasma membrane intensity to the cytosolic fluorescence intensity, using ImageJ. Data are mean \pm SEM from ten different cells. *, p<0.05; **, p<0.01.

Figure 10. N-terminal XL α s inhibits transferrin uptake and PTHR internalization. (A) Confocal microscopy analysis of N-terminal XL α s-GFP expressing cells incubated with transferrin-Alexa Fluor 568 for 30 min. (B) Confocal microscopy analysis of PTHR internalization in N-terminal XL α s-GFP expressing cells. Scale bar, 10 μ m. Representative plots on transferrin uptake in (C) N-terminal XL α s-GFP, (E) XL α s-GFP, and (G) Gs α -GFP. (D, F, H) Quantification of the median values of transferrin-Alexa Fluor 568 in GFP⁺ and GFP⁻ cell populations. Data are mean \pm SEM of two independent experiments (n=8 per group). **, p<0.01.