Podocytes are specialized epithelial cells in the kidney glomerulus that play important structural and functional roles in maintaining the filtration barrier. Nephrotic syndrome results from a breakdown of the kidney filtration barrier and is associated with proteinuria, hyperlipidemia, and edema. Additionally, podocytes undergo changes in morphology and internalize plasma proteins in response to this disorder. Here, we used fluid-phase tracers in murine models and determined that podocytes actively internalize fluid from the plasma and that the rate of internalization is increased when the filtration barrier is disrupted. In cultured podocytes, the presence of free fatty acids (FFAs) associated with serum albumin stimulated macropinocytosis through a pathway that involves FFA receptors, the Gβ/Gγ complex, and RAC1. Moreover, mice with elevated levels of plasma FFAs as the result of a high-fat diet were more susceptible to Adriamycin-induced proteinuria than were animals on standard chow. Together, these results support a model in which podocytes sense the disruption of the filtration barrier via FFAs bound to albumin and respond by enhancing fluid-phase uptake. The response to FFAs may function in the development of nephrotic syndrome by amplifying the effects of proteinuria.
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Introduction

The kidney glomerular filter functions to remove small molecular wastes from the blood without the loss of large plasma proteins into the urine. The filter is composed of 3 layers: fenestrated endothelial cells, the glomerular basement membrane (GBM), and epithelial cells known as podocytes (1). The GBM is thought to act as a size- and charge-selective filter or gel. On the outer aspect of the GBM, podocytes spread out across capillary loops and form a tight interdigitating network of membrane extensions known as foot processes. The space between adjacent foot processes is covered by a specialized cell junction complex that allows the passage of fluid and solutes.

The exact mechanism of glomerular filtration is not completely understood and has been the subject of modeling studies (2–5). All of these models predict that the size selectivity of the GBM is not 100% effective and is, to a certain degree, permeable to plasma proteins. In an average human, approximately 180 liters of blood is filtered by the kidney daily. Even if the GBM filtration barrier is disrupted. In cultured podocytes, the presence of free fatty acids (FFAs) associated with serum albumin stimulated macropinocytosis through a pathway that involves FFA receptors, the Gβγ complex, and RAC1. Moreover, mice with elevated levels of plasma FFAs as the result of a high-fat diet were more susceptible to Adriamycin-induced proteinuria than were animals on standard chow. Together, these results support a model in which podocytes sense the disruption of the filtration barrier via FFAs bound to albumin and respond by enhancing fluid-phase uptake. The response to FFAs may function in the development of nephrotic syndrome by amplifying the effects of proteinuria.

It was proposed over 40 years ago that podocytes internalize and remove proteins that cross the GBM (6, 7). Numerous studies using electron microscopy have shown increased numbers of protein-containing vesicles in podocytes under nephrotic conditions in which there is significant leakage of proteins across the GBM (8–18). Previously, we showed that expression of the neonatal Fc receptor, a transcytosis receptor for Ig and albumin, allows podocytes to handle these proteins by internalization and transcytosis (19).

Fluid-phase uptake in cells occurs through 2 distinct processes (20). Micropinocytosis is a nonspecific process that results in small vesicles of less than 0.1 μm in diameter and involves both coated and noncoated vesicles (21). A second, more specialized process called macropinocytosis only occurs in certain cell types. It involves the formation of large vesicles measuring 0.2–5 μm in diameter that form at sites of membrane ruffling (22). Macropinocytosis is clathrin independent, but requires actin, RAC1, and PI 3-kinase (P13K). In certain cells like immature DCs and macrophages, macropinocytosis is a constitutive process (23, 24); in other cells, it is induced by extracellular stimuli, such as growth factors (25). Macropinocytosis allows for efficient internalization of extracellular fluids (up to 1 cell volume of fluid/hour), and because of the larger size of the vesicles, it is also more efficient for the uptake of large-sized molecules.

Here, we discovered that podocytes internalize fluid via macropinocytosis and that the rate can be increased by free fatty acids (FFAs) bound to albumin. Distinct from other known regulators of macropinocytosis, we found that lipid-binding GPCRs and Gβγ subunits regulate macropinocytosis in podocytes. Macropinocytosis may function to maintain the GBM by removing proteins that cross the GBM. In a proteinuric setting, however, this response...
to FFAs may function as a maladaptive one, leading to podocyte dysfunction and death. Loss of albumin during proteinuria and the subsequent increase of unbound FFAs have been implicated in nephrotic syndrome as an inducer of ANGPTL4 expression in podocytes (26). Our work suggests that FFAs may be involved in the development of nephrotic syndrome not only by inducing ANGPTL4, but also by directly affecting podocytes.

Results
Podocytes are highly endocytic in vivo. Electron micrographs of the kidney often reveal intracellular vesicles in podocytes (8–14). Twenty-four hours after injection with fluorescently labeled fluid-phase tracers (70 kDa FITC-Ficoll), confocal imaging of the kidney glomerulus showed fluorescence labeling, suggesting endocytic uptake (Figure 1A). To examine fluid-phase uptake during proteinuria, we carried out similar experiments with a mouse model of nephrotic syndrome, the laminin β2-KO (Lamb2−/−) mouse (27–29). The uptake of FITC-Ficoll was markedly increased in the Lamb2−/− mice and occurred in cells that were labeled with podocin, a podocyte-specific marker (Figure 1, B and C). The increased uptake in the nephrotic mice was not simply the result of more tracers crossing the disrupted GBM and reaching the podocytes; the uptake of 10 kDa FITC-dextran, which readily passes through intact as well as disrupted GBM was also increased during proteinuria (Figure 1, D–F). Increased uptake of FITC-albumin and FITC-dextran (data not shown) by podocytes also occurred in Adriamycin-treated mice, a different model of nephrotic syndrome, as compared with that observed in untreated control mice (Figure 1, G and H). These results suggested that uptake of extracellular fluid is stimulated in podocytes during proteinuria.

Albumin stimulates macropinocytosis in podocytes. To study fluid-phase endocytosis in podocytes in vitro, we incubated immortalized podocytes in culture with 70 kDa FITC-dextran. In the absence of any stimulus, moderate amounts of uptake were detected by both immunofluorescence and flow cytometry when podocytes were incubated at 37°C, but not at 4°C (Figure 2, A–C). To mimic the increased exposure to plasma proteins during proteinuria, we incubated podocytes with highly abundant plasma proteins. The addition of BSA dramatically increased the uptake of FITC-dextran (Figure 2, A–C). This effect was specific to albumin,
To assess the level of macropinocytosis in podocytes, we compared podocytes with immature DCs, which are known to exhibit a high rate of constitutive macropinocytosis (31). While DCs showed higher levels of uptake compared with untreated podocytes, BSA induced a rate of macropinocytosis in podocytes that surpassed that of DCs (Figure 3C). Macropinocytosis in DCs was not affected by BSA, suggesting that regulation of macropinocytosis in podocytes is distinct from that in other cell types. Indeed, incubation with EGF and PDGF, which are known activators of macropinocytosis (25, 32), did not stimulate macropinocytosis in podocytes, even though downstream targets like ERK were activated (Figure 3D).

FFAs bound to albumin are the stimuli for podocyte macropinocytosis. A major function of albumin is to bind hydrophobic molecules (33). In contrast to conventional BSA, FFA-free BSA did not induce macropinocytosis (Figure 4A), while lipids isolated from BSA or clinical-grade human serum albumin (HSA) stimulated macropinocytosis (Figure 4B). This suggested that plasma lipids bound to albumin were the causative factors stimulating macropinocytosis.
The activity in the lipid extracts was resistant to boiling or hydrolysis in acid or base (data not shown). Incubating the lipids with hydroxylamine (cleavage of ester bonds), methanolic HCl (cleavage of ester, glycosidic, and amide bonds), or periodate (oxidation of sugar moieties) also did not significantly reduce activity (data not shown).

We tested candidate lipid molecules to identify the active lipid compound(s). Initial assays using bioactive lipids (lysophosphatidic acid, prostaglandins, lipopolysaccharide, sphingosylphosphorylcholine, etc.) or lipids with various polar head groups (choline, ethanolamine, n-dansyl-ethanolamine, n-pyrenesulfonyl-ethanolamine) did not result in stimulation of macropinocytosis (data not shown). However, several different FFAs, including oleic acid, eicosaatrienoic acid (ETA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) stimulated macroinocytosis in a dose-dependant manner (Figure 4C). When combined, the different FFAs had an additive effect and induced dextran uptake to levels comparable to those in BSA lipid extracts (Figure 4D). Thus, several different FFAs can stimulate macropinocytosis in podocytes.

Stimulation of macropinocytosis by albumin-associated FFAs is mediated by lipid-binding GPCRs and Gβγ. Since many lipids induce their effects through specific receptors, we searched podocyte expression datasets (34) for expression of lipid receptors, focusing on GPCRs. This showed that podocytes express a variety of lipid-binding GPCRs, including FFA receptors 1, 2, and 3 (FFAR1, FFAR2, and FFAR3) (data not shown). The ligands of FFAR1 are medium- and long-chain fatty acids, whereas FFAR2 and FFAR3 bind to short-chain fatty acids. To determine their roles in podocyte macropinocytosis, we used siRNA or shRNA to knock down the expression of these receptors (Figure 5A and Supplemental Figure 1A; supplemental material available online with this article; doi:10.1172/JCI79641DS1). Lipid-induced macropinocytosis was decreased when any one of the FFAR isoforms was reduced (Figure 5B). Simultaneous knockdown of all 3 isoforms led to a further reduction (Figure 5B).

Triggering of GPCRs stimulates the disassembly and activation of heterotrimeric G proteins composed of the Ga, Gb, and Gγ subunits. Stimulation of podocytes with lipids induced elevation of cAMP levels, a second messenger known to be regulated by GPCRs through Ga signaling (Supplemental Figure 2, A and B). However, treatment of podocytes with forskolin (an activator of adenylate cyclase) or cAMP analogs had no effect on dextran uptake (Supplemental Figure 2C). Furthermore, macropinocytosis was not induced when constitutively active Gaq (Q227L) was overexpressed (Supplemental Figure 2D). These results indicated that cAMP does not mediate the stimulation of macropinocytosis.
In addition to triggering the Go subunit, GPCR signaling induces the release of the Gβγ complex, which activates its own downstream effectors, including PI3K and RAC1 (35). To determine whether the Gβγ complex mediates lipid-induced macropinocytosis, we incubated podocytes with gallein, an inhibitor of Gβ. Fluorescein, a compound similar in structure to gallein that does not inhibit Gβ, was used as a control. Gallein reduced basal and lipid-induced dextran uptake in podocytes (Figure 6A). High concentrations of gallein almost completely blocked the stimulation of macropinocytosis by lipids.

These results were confirmed using shRNA to inhibit expression of Gβ. Expression analysis showed that 2 of the 4 Gβ isoforms, Gβ1 and Gβ2, are expressed in cultured podocytes (data not shown). Immunoblotting with isoform-specific Abs showed a significant reduction of specific Gβ isoforms in Gnb1 and Gnb2 single-knockdown podocytes (Figure 6B and Supplemental Figure 3A). Knockdown of either Gnb1 or Gnb2 impaired macropinocytosis induced by lipid (Figure 6C and Supplemental Figure 3B). Knockdown was less efficient in the Gnb1/Gnb2 double-knockdown cells, consistent with the idea that the complete absence of Gβ is toxic to the cells (Figure 6B and Supplemental Figure 4). Nonetheless, knockdown of both Gβ isoforms further reduced lipid-induced macropinocytosis (Figure 6C). This confirms that the response to lipids is mediated by Gβγ subunits.

Albumin-associated FFAs induce changes in actin structures and activate RAC1 and CDC42. Macropinosomes are formed at sites of membrane ruffling. To analyze the changes in the actin cytoskeleton induced by albumin-bound FFAs, we stained podocytes with phalloidin and analyzed them by confocal microscopy. Addition of lipids extracted from BSA led to dramatic changes in cell morphology, with formation of filopodial structures (Supplemental Figure 5A). We noted similar changes after ETA treatment (Supplemental Figure 5A).

The Rho GTPases RAC1 and CDC42 are critical regulators of the actin cytoskeleton and are key regulators of macropinocytosis. To determine whether albumin-associated lipids activate RAC1 and CDC42, podocytes were transfected with fluorescence resonance energy transfer (FRET) biosensors and analyzed using live cell imaging. Albumin-associated lipids rapidly induced activation of both RAC1 and CDC42 (Supplemental Figure 5, B and C). Confirming the role of RAC1, the addition of a RAC inhibitor attenuated macropinocytosis (Supplemental Figure 5D).

Nonetheless, knockdown of both Gβ isoforms further reduced lipid-induced macropinocytosis (Figure 6C). This confirms that the response to lipids is mediated by Gβγ subunits.

Figure 4. Podocyte macropinocytosis is stimulated by albumin-associated FFAs. (A) Podocytes were incubated with 7.5% BSA or FFA-free BSA in the presence of FITC-dextran for 30 minutes and analyzed by flow cytometry. (B) Podocytes were incubated with 7.5% BSA, BSA lipid extract, or HSA lipid extract in the presence of FITC-dextran for 30 minutes and analyzed by flow cytometry. (C) Podocytes were incubated with increasing concentrations (1 or 10 μM) of FFAs in the presence of FITC-dextran for 30 minutes and analyzed by flow cytometry. (D) Podocytes were incubated with individual FFAs (2 μM) or a mixture of the FFAs (2 μM each) in the presence of FITC-dextran for 30 minutes and analyzed by flow cytometry. All results are shown as the fold change in mean fluorescence intensity. Data represent the mean ± SD of 3 independent experiments analyzed by ANOVA, followed by Bonferroni’s post-hoc analysis. *P ≤ 0.05; **P ≤ 0.01.
to develop severe proteinuria (Figure 7B, day 24) compared with none of the control mice. These results suggest that high FFA levels can aggravate podocyte injury and exacerbate proteinuria.

Discussion

Large vesicles within podocytes are often seen by electron microscopy in proteinuric kidney diseases (7). There has been much speculation about the origin of these vesicles (36–39), but their functional significance has remained unresolved. Recent studies have demonstrated that impairment of the endocytic machinery in podocytes leads to proteinuria, indicating that endocytosis may play a crucial role in podocyte function (19, 40, 41). Our results reveal that podocytes induce significant levels of macropinocytosis in response to FFAs. FFAs stimulate macropinocytosis through a pathway distinct from that in other cell types, one that involves FFARs, GJ/Gy, and RAC1.

Our results indicate that podocytes are capable of internalizing large amounts of extracellular fluid and molecules by macropinocytosis. Demonstrating whether fluid-phase uptake occurs by macropinocytosis is not a straightforward task because of the nonspecific nature of its cargo and the lack of signature marker proteins. The uptake of large molecules is considered the most reliable measure of macropinocytosis. Tracer molecules larger than 70 kDa are internalized predominantly by macropinocytosis, since the small size of micropinosomes or endosomes restricts both the size and numbers of high molecular weight molecules (42). We showed that podocytes were able to efficiently internalize 70 kDa dextran in vivo (Figure 1, A–C) and even larger dextrans (up to 2,000 kDa) in vitro (Figure 3A), consistent with macropinocytosis. Suppression of uptake by inhibitors of PI3K, aquaporin, and actin polymerization further lends support for macropinocytosis as the phenomenon we measured (Figure 3B).

The role of macropinocytosis varies depending on cell type. Immature DCs use macropinocytosis as a means of surveying the surrounding environment for foreign pathogens (23). In Dictyostelium and Ras-transformed cells, macropinocytosis serves as a major pathway for nutrient supply (43, 44). In some conditions, macropinocytosis is transiently induced by certain stimuli such as phorbol esters or growth factors such as EGF or CSF-1 (25, 32, 45).

Our work suggests that macropinocytosis may be involved in the removal of plasma proteins that enter and cross the GBM. Because the filter is not completely effective, it has been argued that an active clearance mechanism must exist to prevent the filter from clogging. The high expression of receptors for albumin, IgG, and complement on podocytes support the idea that podocytes play a specialized role in the uptake and removal of plasma proteins that cross the GBM.

Macropinocytosis may also be a route of nutrient uptake in podocytes, similar to Ras-transformed cells (43, 44). Podocytes are unique in that they are located wholly in the urinary space and are separated from the blood supply by the GBM. This might restrict their exposure to nutrients, partially explaining why podocytes exhibit constitutive autophagy and why impairing autophagy is detrimental to podocytes (46, 47). We observed trafficking of the macropinosomes to the lysosomes in podocytes (data not shown), and it is therefore plausible to speculate that proteins internalized via macropinocytosis can be degraded and used as a source of energy and anabolic substrates.

It is interesting that FFAs can induce macropinocytosis. FFAs have been implicated in a feedback loop that mediates the hypertriglyceridemia that accompanies nephrotic syndrome (26). Significant urinary loss of albumin decreases the plasma lipid–buffering capacity, leading to elevated levels of unbound FFAs (26). It was recently shown that this elevation of FFAs increases circulating ANGPTL4, which inhibits lipoprotein lipase, and thereby leads to elevated plasma triglycerides (26). Notably, ANGPTL4 produced from podocytes induces proteinuria in rats through mechanisms that are yet to be elucidated (26, 48). We found that FFAs induced ANGPTL4 expression in podocytes (Supplemental Figure 6), indicating that FFAs could induce proteinuria through ANGPTL4 induction.

Our findings, however, also suggest that FFAs could affect proteinuria by directly altering podocyte function and viability. We and others have previously shown that RAC1 activation in podocytes leads to podocyte foot process effacement and proteinuria in mice (49, 50). In addition, excessive macropinocytosis and accumulation of albumin in podocytes has been shown to induce lysosomal dysfunction, podocyte loss, and subsequent glomerulo-
sclerosis (15, 16, 51–55). Consistent with this, we found that mice with elevated FFA levels were more susceptible to Adriamycin and exhibited significantly higher levels of albuminuria (Figure 7). The effects of a HFD on the kidney are complex, and there may be additional factors that are affecting proteinuria, but the results are consistent with a role for FFAs.

It is intriguing to consider the possibility that an interplay between FFAs and ANGPTL4 plays a critical role in the transition from proteinuria to full-blown nephrotic syndrome. Podocyte injury would lead to proteinuria, but the transition to nephrotic syndrome might involve the elevation of both plasma FFAs and ANGPTL4. The combined effect of albuminuria and hyperlipidemia (caused by elevated ANGPTL4) would lead to an increase in the FFA/albumin ratio. Once the level of FFAs exceeds the buffering capacity of albumin, the FFAs could play a key role in a vicious cycle of persistence leading from albuminuria and podocyte damage that converts proteinuria into nephrotic syndrome. In support of this idea, lipoprotein apheresis treatment in some patients with nephrotic syndrome (56) has been described previously (27–29). For HFD experiments, age- and weight-matched male 129/SvJ mice were randomly grouped and given a normal chow diet (13 kcal% fat; LabDiet) or a HFD (60 kcal% fat; D12492; Research Diets Inc.). After 8 weeks on the diet, mice were injected i.v. with Adriamycin (10 mg/kg body weight) or an equal volume of saline as a control.

Taken together, we have identified a pathway of inducible macropinocytosis in podocytes that may play a role in maintenance of the glomerular filtration barrier. Persistent activation of this pathway during proteinuria, however, may have maladaptive consequences and lead to nephrotic syndrome. FFAs and FFARs are new potential targets for the treatment of nephrotic syndrome.

Methods

Reagents. FITC-Ficoll (70 kDa), FITC-dextran (10, 70, 150, 500, 2,000 kDa), Adriamycin, BSA, mouse serum IgG, mannann, p-chloromercuribenzoate (pCMB), wortmannin, cytochalasin D, recombinant EGF, ovalbumin, 8-Br-cAMP, 8-pCPT-2′-O-Me-cAMP, forskolin, 3-isobutyl-1-methylxanthine (IBMX), isoproterenol, fluorescein, anti-podocin Ab (catalog P0372), and anti–β-actin Ab (clone AC-15) were obtained from Sigma-Aldrich. FFA-free BSA was purchased from SeraCare Life Sciences. HSA was purchased from Williams Medical Company. Hoechst 33342 and recombinant PDGF was purchased from Life Technologies. Anti–phospho-ERK Ab (clone 197G2) was obtained from Cell Signaling Technology. Rhodamine B–dextran (70 kDa) was purchased from Nanocs. Oleic acid, eicosatetraenoic acid, eicosapentaenoic acid, and docosahexaenoic acid were obtained from Nu-Chek Prep. Gallein and EHT1864 was purchased from Tocris Bioscience. Anti–Gβ1 (catalog sc-379) and anti–Gβ2 (catalog sc-380) antibodies were purchased from Santa Cruz Biotechnology Inc. Anti–laminin α5 (57) and anti–CD2AP (58) Abs have been previously described.

Mice. All mice were housed in a specific pathogen–free facility at Washington University School of Medicine. C57BL/6j, 129/SvJ, and BALB/cj mice were obtained from The Jackson Laboratory. Laminin β2–knockout (Lamb2−/−) mice with a muscle–specific rescue transgene have been described previously (27–29). For HFD experiments, age-and weight-matched male 129/SvJ mice were randomly grouped and given a normal chow diet (13 kcal% fat; LabDiet) or a HFD (60 kcal% fat, D12492; Research Diets Inc.). After 8 weeks on the diet, mice were injected i.v. with Adriamycin (10 mg/kg body weight) or an equal volume of saline as a control.

Cell culture. Conditionally immortalized podocytes were generated as described previously (59) and maintained at 33°C in RPMI1640 supplemented with 10% FBS, 1 mM sodium pyruvate, 10 mM HEPES, 100 U/ml penicillin, 100 μg/ml streptomycin, 0.1 mM β-mercaptoethanol, and 100 U/ml recombinant mouse IFN-γ (a gift of Robert Schreiber, Washington University, St. Louis, Missouri, USA).

BM-derived DCs were cultured as previously described (60). Briefly, BM cells were cultured in Iscove’s modified Dulbecco’s medium (IMDM) supplemented with 10% FBS (HyClone), 1 mM
sodium pyruvate, 10 mM HEPES, 100 U/ml penicillin, 100 μg/ml streptomycin, 0.1 mM β-mercaptoethanol, and 100 ng/ml recombinant granulocyte macrophage colony-stimulating factor (rGM-CSF) (R&D Systems) for 8 days.

Electron microscopy. Slices of kidney cortex or podocytes cultured on coverslips were fixed overnight in 4% paraformaldehyde (PFA) and 4% glutaraldehyde in 0.1 M sodium cacodylate buffer followed by subsequent washes, dehydrated in graded ethanol series, and embedded in resin according to standard protocols.

In vivo endocytosis. WT or Lamb2−/− mice were injected i.v. with a bolus of FITC-Ficoll (70 kDa) or FITC-dextran (10 kDa) in 0.9% NaCl at a dose of 250 mg/kg of body weight. BALB/c mice were injected i.v. with Adriamycin (10 mg/kg body weight) or an equal volume of saline as a control. Six days after the Adriamycin injection, the mice were injected i.v. with FITC-labeled albumin (250 mg/kg body weight). For BSA injection experiments, mice (C57BL/6J and 129/SvJ mixed background) were given a daily i.p. injection of endotoxin-free BSA (15 mg/g body weight in PBS) for 4 days. On day 4, the mice were injected i.v. with 70 kDa FITC-dextran (250 mg/kg body weight). Twenty-four hours after injection of FITC-labeled tracers, kidneys were harvested after several washes, the slides were imaged on an Olympus FV1000 confocal microscope.

For immunofluorescence assays, the kidney sections were fixed with 1% PFA in PBS for 5 minutes, followed by blocking and permeabilization with 2% FBS in PBS with 0.1% saponin. The slides were incubated with Abs against laminin α5 or podocin for 1 hour at room temperature, followed by extensive washing. Fluorescently conjugated secondary Abs were then applied for 1 hour at room temperature. After several washes, the slides were imaged on an Olympus confocal microscope.

In vitro macropermeability assays. Mouse podocytes in 6-well plates were serum starved with serum-free RPMI for 2 hours. The cells were then incubated in RPMI supplemented with 0.5 mg/ml FITC- or rhodamine B-dextran for 30 minutes on ice or at 37°C. The cells were subsequently washed 3 times with ice-cold PBS and fixed with 4%PFA for confocal microscopic analysis or trypsinized and resuspended in FACS buffer (2% FBS and 2 mM EDTA in 1× PBS) for flow cytometric analysis. FACS data were collected on FACS Cantor II or LSR II flow cytometers (BD Biosciences) and analyzed with FlowJo software.

Western blots. Podocytes were lysed in a modified radioimmunoprecipitation assay (RIPA) lysis buffer (50 mM Tris-HCl [pH 7.4], 150 mM NaCl, 1 mM EDTA, 1% NP-40, 0.25% sodium deoxycholate, 1 mM PMSF, 1 μg/ml aprotinin, 1 μg/ml leupeptin, 1 μg/ml pepstatin, 1 mM Na3VO4, 1 mM NaF) for 30 minutes on ice. The protein content of the lysates was quantified with a protein assay kit (Bio-Rad). Equivalent amounts of each sample were separated by SDS-PAGE, transferred to nitrocellulose membranes, and immunoblotted with phosphorylated ERK (p-ERK), CD2AP, Gβ1, Gβ2, or β-actin. The blots were visualized by ECL or infrared imaging on a LI-COR Odyssey system (LI-COR).

Lipid extraction. Lipids were extracted from BSA or HSA using the Bligh-Dyer method with minor modifications. Three milliliters of 20% BSA in ddH2O was added to a mixture of 6 ml chloroform and 12 ml methanol in a glass tube and mixed on an orbital shaker for 15 minutes at room temperature. Chloroform (6 ml) was added to the mixture while vortexing at low speeds, followed by 6 ml of 1 M NaCl. The samples were centrifuged at 800 g for 5 minutes to separate the aqueous and organic phases. The lower organic phase was carefully collected, aliquoted into 1-ml tubes, evaporated under vacuum, and stored at ~80°C.

For endocytosis assays, the lipids were resuspended in 30 μl DMSO, and the cells were treated with 1 to 5 μl/ml lipid suspension. Assuming loss of 50% of the lipids during extraction, this is estimated to be equivalent to the amount of lipids bound to BSA in a 0.066% to 0.33% solution.

Gene knockdown and overexpression experiments. ON-TARGETplus siRNA targeting FFAR isoforms was purchased from Dharmacon (GE Healthcare). Podocytes were transfected with a pool of siRNAs containing 4 individual siRNAs targeting each isoform using the Nucleofector System (Lonza). Transfection efficiency was monitored using the siGLO Green Transfection Indicator (GE Healthcare).

Lentiviral constructs containing shRNAs targeting FFAR isoforms, Gαi isoforms, and firefly luciferase (control) were generated using the pFRLu-YFP lentiviral vector (61). The targeting sequences were: fLuc, CCAACCTATTTCTCCTTCT; FFAR1, ATCTTTGCCTTGGCCCAC- TTG; FFAR2, CGGTTTGTCATAGCCCTTGAAT; FFAR3, ACTGT- GAACCTGAGTAAAGAAT; GNB1, CATTATCCTGTGTTAT CACA; GNB2, CATCTGCTCCATCTATAG. PCR products containing the U6 promoter followed by the shRNA sequences were cloned into the pFRLu-YFP vector using the Xbal/Xhol site.

For lentivirus production, 293T cells were transfected with the lentiviral constructs along with packaging plasmids (pMDLg/pRRE and pRSV-Rev) and an envelope plasmid (pMD2.G). Proliferating podocytes were infected with supernatants containing lentivirus and 8 μg/ml protamine sulfate for 24 hours. Cells expressing high levels of YFP were sorted on a FACSAria II flow cytometer (BD Biosciences) 7 days after infection.

To generate podocytes stably expressing constitutively active Gaαs, cells were transfected with a pcDNA3.1 vector containing Gaαs (Q227L) (a gift of Kun-Liang Guan, UCSD, San Diego, California, USA). Sta-
bly transfected cells were selected by serial passage in 400 μg/ml G418 for 1 week.

**cAMP FRET assays.** A pcDNA3 plasmid containing the FRET-based cAMP biosensor ‘Epac1’ was a gift of Kees Jalink (The Netherlands Cancer Institute, Amsterdam, The Netherlands). Cultured podocytes were transfected with ‘Epac1’ using the Nucleofector System and seeded on glass-bottom dishes (MatTek Corp.). Images were obtained using an Olympus FV1000 confocal microscope in a temperature-controlled chamber (37°C). The cells were excited at 440 nm, and donor and acceptor emission was detected simultaneously using a 510 nm beamsplitter and 2 photomultipliers with optical filters: 465–495 nm (CFP) and 535 to 565 nm (YFP).

FRET measurements were quantified using ImageJ software (NIH) and the Ratio Plus plugin. After regions were drawn around individual cells, emission ratios were obtained by calculating FRET intensities divided by donor intensities. Time-course ratio measurements were normalized to baseline values before stimulation. The FRET value was set at 1 at the onset of the experiment.

**FFA, albumin, and creatinine assays.** Mouse serum and urine samples were collected at the indicated time points. FFA (BioVision), albumin (Bethyl Laboratories Inc.), and creatinine (BioAssay Systems) levels were quantified by ELISA according to the manufacturers’ instructions.

**Statistics.** Data are presented as the mean ± SD. We determined significance by ANOVA or a 2-tailed Student’s t test as indicated in the figure legends. ANOVA, followed by Bonferroni’s post-hoc analysis, was used to determine significant differences in experiments with 3 or more samples. A P value of 0.05 or less was considered statistically significant.

**Study approval.** Animal care and experiments were conducted in accordance with protocols approved by the Animal Studies Committee of Washington University (protocol number 20120013), in compliance with the Animal Welfare Act.

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