

SLC35G1: A highly chloride-sensitive transporter responsible for the basolateral membrane transport in intestinal citrate absorption

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Abstract

The intestinal absorption of essential nutrients, especially those not readily biosynthesized, is a critical physiological process for maintaining homeostasis. Numerous studies have indicated that intestinal absorption is mediated by various membrane transporters. Citrate, a crucial bioactive compound produced as an intermediate in the Krebs cycle, is absorbed in the small intestine through carrier-mediated systems because of its high hydrophilicity. While the luminal absorption of citrate is mediated by Na⁺-dicarboxylate cotransporter 1 (NaDC1), the mechanism governing the release of the transported citrate into the bloodstream remains unknown. Here, we explored the transporters responsible for intestinal citrate absorption at the basolateral membrane, focusing on highly expressed orphan transporters in the small intestine as candidates. Consequently, SLC35G1, originally identified as a partner of stromal interaction molecule 1, a cell surface transmembrane glycoprotein, was found to play a role in the intestinal absorption of citrate at the basolateral membrane. Furthermore, our results revealed that SLC35G1-mediated citrate transport was diminished by chloride ions at extracellular concentrations. This suggests that SLC35G1, to our best knowledge, is the first transporter identified to be extremely sensitive to chloride ions among those functioning on the basolateral membrane of intestinal epithelial cells. This study provides valuable insights into the intestinal absorption of citrate and significantly contributes to elucidating the poorly understood molecular basis of the intestinal absorption system.

eLife assessment

This work identifies the molecular function of an orphan human transporter, SLC35G1, providing **convincing** but somewhat **incomplete** evidence that this protein is involved in intestinal citrate absorption. This work provides **important** insight into transporter function and human physiology.

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Introduction

Citrate plays a crucial role as a tricarboxylic acid (TCA) cycle intermediate, contributing to the generation of metabolizable energy. Since citrate is obtained not only through biosynthesis but also from the diet, the existence of intestinal absorption system has long been acknowledged (*Browne et al., 1978* [↗](#)). Luminal absorption is predominantly mediated by Na⁺-dependent dicarboxylate transporter 1 (NaDC1/SLC13A2) (*Pajor, 2006* [↗](#)); however, the transporter responsible for the release of citrate and its metabolites across the basolateral membrane remain unidentified (*Pajor, 2014* [↗](#)). To elucidate the molecular mechanism underlying citrate absorption at the basolateral membrane, we explored the transporters implicated in the process. Our study provides novel insights into basolateral membrane transporters, addressing a previously poorly understood aspect in intestinal epithelial cells.

Results and discussion

Our investigation revealed that SLC35G1, a member of the solute carrier (SLC) 35 family and originally identified as a partner of stromal interaction molecule 1 (*Krapivinsky et al., 2011* [↗](#)), is capable of transporting citrate. While the functions of nucleoside-sugar transporters on the endoplasmic reticulum membrane have been identified for certain SLC35 family members, including SLC35A, SLC35B, SLC35C, and SLC35D (*Ishida and Kawakita, 2004* [↗](#)), the roles of SLC35E, SLC35F, and SLC35G have not yet been fully elucidated, as shown in **Figure 1A** [↗](#). For the functional analysis, we first established Madin-Darby canine kidney (MDCKII) cells stably expressing SLC35G1. Using these cells, we observed a linear increase in SLC35G1-mediated citrate uptake with time, specifically during the first 10 min in Hanks' solution mimicking the cytosolic ion content by eliminating Cl⁻ (**Figure 1B** [↗](#)). The acidic condition (pH 5.5) was used to gain sufficient uptake for functional analysis. Therefore, the uptake at 10 min was evaluated in subsequent studies. A kinetic analysis revealed that the SLC35G1-specific uptake of citrate exhibited saturation kinetics, with a $V_{\max}$ of 1.10 nmol/min/mg protein and a K_m of 519 μ M (**Figure 1C** [↗](#)). Notably, the specific uptake of citrate by SLC35G1 was extensively inhibited by extracellular Cl⁻ (**Figure 1D** [↗](#)), with an IC_{50} value of 6.7 mM (**Figure 1E** [↗](#)). As previously reported (*Melkikh and Sutormina, 2008* [↗](#)), the Cl⁻ concentration is lower in the cytosol (5 mM) than in the extracellular conditions (120 mM), suggesting that SLC35G1 is a potential citrate exporter. Additionally, we examined the effect of various compounds, including other TCA cycle intermediates and typical inhibitors of organic anion/cation transporters at a concentration of 200 μ M, to explore the potential role of SLC35G1 in their transport (**Figure 1F** [↗](#)). Among the tested compounds, certain anionic compounds significantly inhibited SLC35G1-specific citrate uptake, indicating that they are also recognized by SLC35G1. SLC35G1-specific citrate uptake showed pH dependence (**Figure 1G** [↗](#)). To investigate whether SLC35G1 utilizes an H⁺ gradient as a driving force for citrate transport, we examined the effect of the protonophore nigericin in the uptake solution at pH 5.5 to dissipate the H⁺ gradient across the plasma membrane. However, treatment with nigericin did not

affect the specific uptake of citrate (**Figure 1H**), excluding this possibility. Given that one carboxylate can be protonated with a pK_a of 5.4 (Contreras-Trigo *et al.*, 2018) (**Figure 1I**), SLC35G1 may preferably transport dianionic citrate, like NaDC1 (Pajor and Sun, 1996). Finally, we determined the role of SLC35G1 in the transcellular transport of citrate at the basolateral membranes using SLC35G1-transfected polarized MDCKII cells on Transwell permeable membrane filters. As shown in **Figure 1J**, SLC35G1 predominantly localized to the basolateral membrane of polarized MDCKII cells. Transport studies were performed under pH gradient conditions (apical pH 5.5 and basal pH 7.4) in the presence of Cl^- to mimic intestinal physiological conditions. SLC35G1-transfected cells showed no significant change in intracellular citrate accumulation from the apical side, compared to mock cells (**Figure 1K**). However, apical-to-basolateral transcellular transport was significantly higher in SLC35G1-transfected cells (**Figure 1L**). On the other hand, SLC35G1 overexpression affected neither intracellular accumulation nor transcellular transport from the basolateral side. This is reasonable since the basolaterally localized SLC35G1 operates for efflux but not for uptake in the presence of Cl^- in the extracellular environment. These results suggest that SLC35G1 plays a role in the intestinal absorption of citrate at the basolateral membrane as an exporter under physiological conditions.

To further investigate the physiological role of SLC35G1, we examined its expression in human tissues (**Figure 2A**). Quantitative real-time PCR analysis revealed that SLC35G1 is highly expressed in the digestive tract, especially in the upper part of the small intestine, including the duodenum and jejunum, followed by the testis and pancreas. Additionally, immunohistochemical staining of the human jejunum clearly showed that SLC35G1 is localized on the basolateral membrane, as indicated by the co-localization of ATP1A1, a marker protein on the basolateral membrane (**Figure 2B**). To investigate the physiological impact of SLC35G1 on intestinal citrate absorption, we examined the effect of SLC35G1 knockdown on citrate uptake in human colorectal adenocarcinoma Caco-2 cells, a commonly used model for studying intestinal absorbency (Yee, 1997) (**Figure 2C**), in the absence of Cl^- . As shown in **Figure 2C**, citrate uptake was significantly reduced following RNA interference with siRNAs targeting SLC35G1 mRNA, providing evidence of the involvement of SLC35G1 in intestinal citrate absorption. The reduction in citrate uptake was not indicative of off-target effects, as multiple siRNAs with distinct nucleic acid sequences yielded similar reductions. Moreover, the expression of SLC35G1 mRNA was reduced by these siRNAs, confirming successful silencing of SLC35G1 (**Figure 2D**). The correlation between the decrease in citrate uptake and mRNA levels suggests that SLC35G1 is primarily involved in citrate uptake. Immunohistochemical staining revealed that endogenous SLC35G1 in polarized Caco-2 cells cultured on Transwell membranes was also localized on the basolateral membranes (**Figure 2E**). Taken together, these results indicate that intestinal citrate transport at the basolateral membrane is primarily mediated by SLC35G1. Additionally, it acts cooperatively with NaDC1, which is reported to be highly expressed in the jejunum (Pajor, 1995), for citrate absorption on the apical membrane, as illustrated in **Figure 2F**.

Our findings suggest that SLC35G1 is localized on the basolateral side of intestinal epithelial cells and, to our knowledge, is the first transporter identified with chloride-sensitivity, which is a unique characteristic to render with the directional transport function for an SLC transporter. These findings pave the way for several follow-up directions related to the molecular basis of the intestinal absorption of various compounds, including nutrients and drugs.

Materials and Methods

Materials

[^{14}C]citrate (116.4 mCi/mmol) was obtained from PerkinElmer Life and Analytical Sciences (Boston, MA, USA). Unlabeled citrate and Dulbecco's modified Eagle's medium (DMEM) were sourced from Wako Pure Chemical Industries (Osaka, Japan), and fetal bovine serum (FBS) was

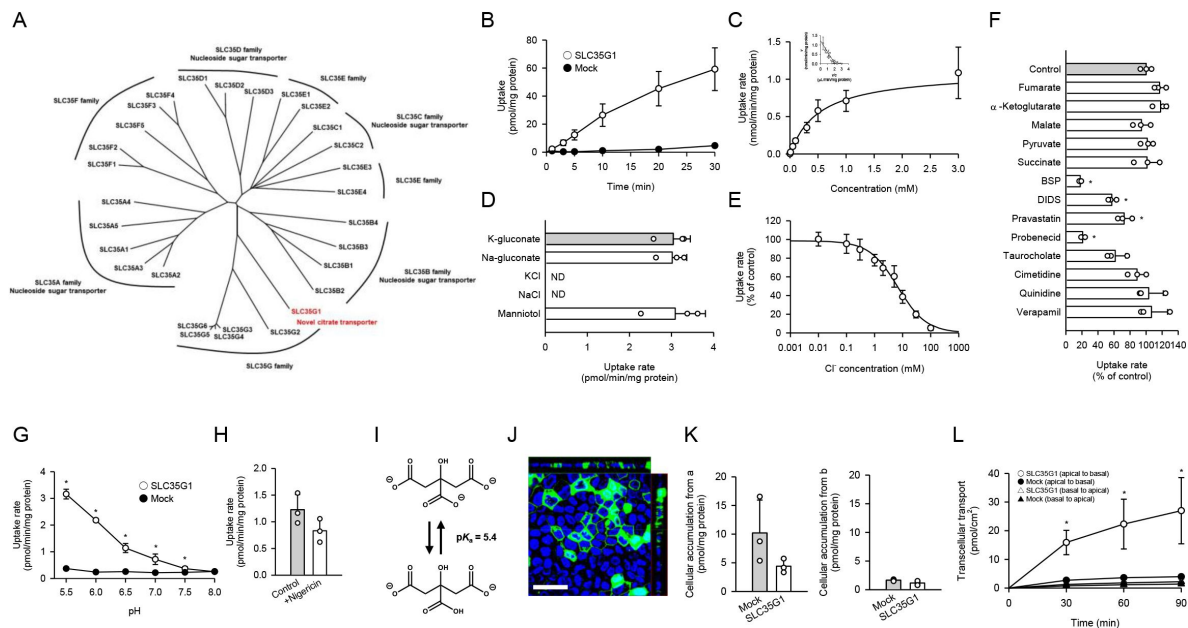


Figure 1.

Functional characteristics of SLC35G1 stably expressed in MDCKII cells. (A) Phylogenetic tree of the SLC35 members and identified functions. (B) Time course of [^{14}C]citrate (1 μM) uptake in SLC35G1-transfected MDCKII cells (open circles) and mock cells (closed circles), evaluated at pH 5.5 and 37°C. (C) Concentration-dependent [^{14}C]citrate uptake by SLC35G1, evaluated at various concentrations for 10 min at pH 5.5 and 37°C. The estimated values of V_{max} and K_{m} were 1.11 ± 0.16 nmol/min/mg protein and 519 ± 86 μM , respectively. (D) Effect of ionic conditions on [^{14}C]citrate (1 μM) uptake by SLC35G1, evaluated for 10 min at pH 5.5 and 37°C. K-gluconate in the control uptake solution was replaced as indicated. (E) Concentration-dependent chloride inhibition of [^{14}C]citrate (1 μM) uptake by SLC35G1, evaluated at various chloride concentrations for 10 min at pH 5.5 and 37°C. The estimated value of IC_{50} was 6.7 ± 1.4 mM. (F) Effect of various compounds on [^{14}C]citrate (1 μM) uptake by SLC35G1, evaluated for 10 min at pH 5.5 and 37°C in the presence (200 μM) or absence (control) of a test compound. BSP, bromosulphophthalein; DIDS, 4,4'-diisothiocyano-2,2'-stilbenedisulfonic acid. (G) Effect of pH on [^{14}C]citrate (1 μM) uptake in SLC35G1-transfected MDCKII cells (open circles) and mock cells (closed circles), evaluated for 10 min at 37°C, using the uptake solutions supplemented with 10 mM MES (pH 6.5 and below) or 10 mM HEPES (pH 7.0 and above). (H) Effect of the protonophore nigericin on [^{14}C]citrate (1 μM) uptake by SLC35G1, evaluated for 10 min at pH 5.5 and 37°C in the presence (10 μM) or absence (control) of nigericin after pretreatment for 5 min with or without nigericin under the same conditions. (I) Structural formula illustrating the chemical equilibrium of citrate. (J) Cellular localization of SLC35G1 stably expressed in polarized MDCKII cells. The confocal laser-scanning microscopic image shows SLC35G1 (green) and nuclei stained with 4',6-diamidino-2-phenylindole (DAPI; blue). Scale bar, 50 μm . (K) Intracellular accumulation of citrate in polarized MDCKII cells stably expressing SLC35G1. Intracellular accumulation of [^{14}C]citrate (1 μM) was evaluated for 90 min at pH 5.5 on the apical side (a) and pH 7.4 on the basolateral side (b) of intestinal epithelial cells. (L) Time course of transcellular [^{14}C]citrate (1 μM) transport in polarized MDCKII cells stably expressing SLC35G1 and mock cells, evaluated at pH 5.5 in the apical and pH 7.4 in the basolateral chamber. Data represent the mean $\pm$ SD of three biological replicates (B-H, K, L). Statistical differences were assessed using analysis of variance (ANOVA) followed by Dunnett's test (D, F, L) or using Student's t-test (G, H, K). *, $p < 0.05$ compared with the control (F), or compared with the mock at each pH (G) or time point (L).

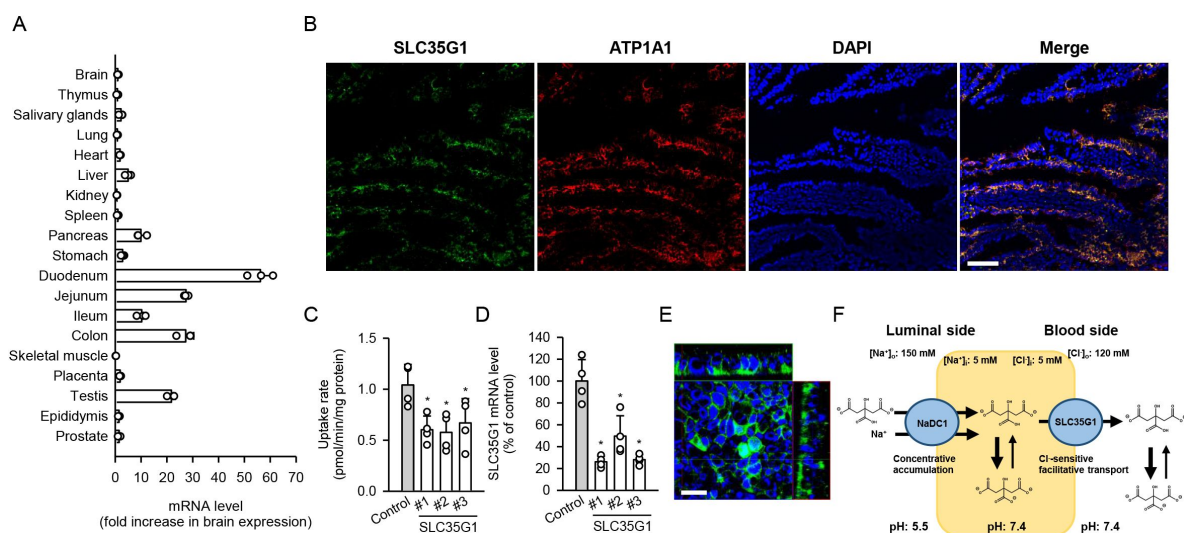


Figure 2.

(A) Analysis of SLC35G1 mRNA expression in various human tissues using quantitative real-time PCR. (B) The immunofluorescent images show the subcellular localization of SLC35G1 (green), breast cancer resistance protein (BCRP; red), and 4',6-diamidino-2-phenylindole (DAPI; blue) in the human jejunum. Scale bar, 100 μ m. (C-D) Effect of SLC35G1 silencing on citrate uptake and on SLC35G1 mRNA expression in Caco-2 cells. (C) The uptake rate of [¹⁴C]citrate (1 μ M) was evaluated for 10 min at pH 5.5 and 37°C in Caco-2 cells transfected with three different siRNAs specific to SLC35G1 mRNA or control siRNA. (D) SLC35G1 mRNA levels were assessed using quantitative real-time PCR analysis. (E) Cellular localization of endogenous SLC35G1 in polarized Caco-2 cells. The confocal laser-scanning microscopic image shows SLC35G1 (green) and nuclei stained with DAPI (blue). Scale bar, 50 μ m. (F) Schematic model showing intestinal citrate absorption mediated by NaDC1 and SLC35G1. Data represent the mean $\pm$ SD of three technical repeats (A) or biological repeats (C-D). Statistical differences were assessed using analysis of variance (ANOVA) followed by Dunnett's test (C-D).

obtained from Sigma Aldrich (St. Louis, MO, USA). All other reagents were of analytical grade and commercially acquired.

Cell culture

Madin-Darby canine kidney II (MDCKII) cells and Caco-2 cells were cultured at 37°C and 5% CO₂ in DMEM supplemented with 10% FBS, 100 U/mL penicillin, and 100 µg/mL streptomycin, as previously described ([Mimura et al., 2017](#)).

Preparation of plasmids

The cDNA for human SLC35G1 was cloned using a reverse transcription (RT)-PCR-based method, as previously described ([Mimura et al., 2017](#)). Briefly, an RT reaction was performed to obtain a cDNA mixture, using 1 µg of the human intestine total RNA (BioChain Institute, Newark, CA), an oligo(dT) primer, and the highly efficient reverse transcriptase ReverTra Ace (Toyobo, Osaka, Japan). The SLC35G1 cDNA was then amplified by PCR, using KOD plus polymerase (Toyobo) and the following primers: forward primer, 5'-GAGATGCGGCCTCAGGACAG-3', and reverse primer, 5'-TAGCCTCCCCACCATATCCC-3'. These primers were designed based on the GenBank sequences for SCL35G1 (accession number: NM_001134658.2). The second PCR was performed using the initial PCR product as a template, with a forward primer containing an EcoRI restriction site (underlined), 5'-AGAATTCCGAGATGCGGCCTCAGGAC-3', and a reverse primer containing an XbaI restriction site (underlined), 5'-GTTCTAGATGTGTGCGTATGCTG-3'. The resulting cDNA product was inserted into the pCI-neo vector (Promega, Madison, WI, USA) between the EcoRI and XbaI sites, and the sequence of the final product was determined using an automated sequencer.

Uptake study

First, we established MDCKII cells stably expressing SLC35G1 as previously described ([Yamamoto et al., 2010](#)). Briefly, MDCKII cells were transfected with the plasmid carrying the SLC35G1 cDNA, using Lipofectamine 2000 as a transfection reagent. The cells were then cultured in DMEM supplemented with 10% FBS and 800 µg/mL G418 for 2–3 weeks. Subsequently, G418-resistant clones were selected and assessed for the transport of [¹⁴C]citrate. MDCKII cells stably expressing SLC35G1 with high citrate transport activity were used in subsequent studies.

MDCKII cells stably expressing SLC35G1 (1.5×10^5 cells/mL, 1 mL/well) were grown in 24-well plates for 48 h until they reached confluence. For standard transport assays, cells were preincubated in substrate-free uptake buffer, which was Hanks' solution modified to reflect cytosolic conditions (142.06 mmol/L K-gluconate, 0.812 mmol/L MgSO₄, 0.379 mM K₂HPO₄, 0.441 mM KH₂PO₄, 0.952 mM Ca-gluconate, 25 mM D-glucose) and supplemented with 10 mM 2-(N-morpholino)-ethanesulfonic acid (MES; pH 5.5), for 5 min. Subsequently, uptake assays were initiated by replacing the substrate-free uptake buffer with an uptake buffer containing a [¹⁴C]citrate (0.25 mL). For initial uptake analysis experiments, the uptake period was set to 10 min in the initial phase, in which uptake was in proportion to time. Other experiments were conducted in a time-dependent manner, as specified. When examining the effects of various compounds on citrate uptake, the test compounds were added to the buffer only during the uptake period. All procedures were performed at 37°C. Assays were stopped by adding 2 mL of ice-cold substrate-free uptake buffer, followed by two washes with an additional 2 mL of the same buffer. The cells were solubilized in 0.5 mL of 0.2 mol/L NaOH solution containing 0.5% sodium dodecyl sulfate (SDS), and the associated radioactivity was measured by liquid scintillation counting for uptake evaluation. The cellular protein content was determined by the bicinchoninic acid (BCA) method, using bovine serum albumin as the standard (3). In experiments to examine the effect of ionic conditions, K-gluconate in the control uptake solution was replaced as indicated. Uptake solutions were supplemented with 10 mM MES (pH 6.5 and below) or 10 mM HEPES (pH 7.0 and above) in experiments to examine the effect of pH. In experiments to examine the effect of nigericin as an agent for intracellular acidification, a mannitol-based buffer (250 mM mannitol, 1.2 mM MgSO₄, 2

mM KH_2PO_4 , 5 mM D-glucose, 10 μM nigericin, and 20 mM MES) was used and uptake assays were conducted for 10 min at pH 5.5 and 37°C in the presence (10 μM) or absence (control) of nigericin after pretreatment for 5 min with or without nigericin under the same conditions. To estimate nonspecific uptake, uptake assays were conducted in mock cells transfected with an empty pCI-neo vector. The specific uptake of citrate by SLC35G1 was estimated by subtracting the uptake in mock cells from that in SLC35G1-transfected cells.

Transcellular transport study

MDCKII cells were seeded at a density of 2×10^5 cells on each polycarbonate membrane insert in a 12-well Transwell plate and cultured for 5 days. After removing the culture medium from both sides of the inserts, cells were preincubated for 5 min at 37°C in Hanks' solution (136.7 mM NaCl, 5.36 mM KCl, 0.952 mM CaCl_2 , 0.812 mM MgSO_4 , 0.441 mM KH_2PO_4 , 0.385 mM Na_2HPO_4 , and 25 mM D-glucose) supplemented with 10 mM MES (pH 5.5) in the apical chamber and 10 mM HEPES (pH 7.4) in the basolateral chamber. To initiate transcellular transport from the apical side to the basolateral side, 0.5 mL of the Hanks' solution (pH 5.5) containing [^{14}C]citrate was replaced in the apical chamber. For transport in the opposite direction (basolateral side to apical side), 1.5 mL of Hanks' solution (pH 7.4) containing [^{14}C]citrate was replaced in the basal chamber. To monitor transcellular transport, samples (100 μL from basal chamber and 50 μL from the apical chamber) were periodically collected, replenishing each collected volume with an equal volume of fresh buffer. At the end of the transport study, the assays were stopped by adding ice-cold Hanks' solution (1 mL for the apical chamber and 3 mL for the basolateral chamber), followed by washing the cells twice with the same buffer. The cells were then solubilized in 0.5 mL of 0.2 M NaOH solution containing 0.5% SDS at room temperature for 1 h. The radioactivity associated with the cells was measured by liquid scintillation counting for uptake evaluation.

Quantification of SLC35G1 mRNA by quantitative real-time PCR

Total RNA samples from various human tissues (BioChain Institute) and Caco-2 cells were used to prepare cDNA using the ReverTra Ace reverse transcriptase. A quantitative real-time PCR was performed using SsoFast EvaGreen Supermix with Low ROX (Bio-Rad Laboratories, Hercules, CA, USA) on a 7300 Fast Real-time PCR System (Applied Biosystems, Foster City, CA, USA) with the following primers: forward primer for SLC35G1, 5'-AGAGCCCACTGAGAAAAGGA-3'; reverse primer for SLC35G1, 5'-GTAGGTGCTGGCTCTGCCT-3'; forward primer for GAPDH, 5'-CGGAGTCAACGGATTTGGTCGTAT-3'; reverse primer for GAPDH, 5'-AGCCTTCTCCATGGTGGTGAAGAC-3'. GAPDH was employed as an internal control for normalization of the mRNA expression levels of SLC35G1.

Knockdown study

Caco-2 cells (5.0×10^4 cells/mL, 1 mL/well) were grown on 24-well-coated plates for 6 h, transfected with 5 pmol/well of the Silencer Selected siRNAs specific to the mRNA of SLC35G1 (Thermo Fisher Scientific, Waltham, MA), using 1.5 mL/well of Lipofectamine RNAi MAX (Thermo Fisher Scientific), and cultured for 5 days for silencing of the designated transporter by RNAi. The sequences of the siRNAs are following: sense sequence of #1 siRNA, GGAGUGAUCCUUAUCGUGATT; antisense sequence of #1 siRNA, UCACGAUAAGGAUCACUCCAG, sense sequence of #2 siRNA, CUUGC UUAUAUACAGAAATT; antisense sequence of #2 siRNA, UUUCUGUAUAUAAGCAAGGG, sense sequence of #3 siRNA, CAUUUGGUAUAUAUGUAGUATT; antisense sequence of #3 siRNA, UACUACAUAUAACCAAAUGCT. For control, negative control Silencer Selected siRNA (Thermo Fisher Scientific), was used. Citrate uptake assays were conducted as described above for SLC35G1-transfected MDCKII cells.

Immunofluorescence staining

To examine the localization of SLC35G1, MDCKII cells stably expressing SLC35G1 were seeded at a density of 2×10^5 cells/insert on a 12-well Transwell plate and cultured for 5 days, and Caco-2 cells were seeded at a density of 5×10^5 cells/insert on a 12-well Transwell plate and cultured for 21 days. The cells were washed thrice with ice-cold PBS and fixed in 5% paraformaldehyde for 15 min. After washing thrice with PBS, the cells were incubated for 1 h at room temperature with an anti-human SLC35G1 goat polyclonal antibody at a dilution of 1:100 in Can Get Signal Immunostain Immunoreaction Enhancer Solution A (Toyobo). The cells were washed with PBS, and the primary antibody was probed with anti-goat IgG Alexa Fluor 488 (Jackson ImmunoResearch Laboratories, West Grove, PA, USA) at a dilution of 1:400 in Can Get Signal Immunostain Immunoreaction Enhancer Solution B (Toyobo) for 1 h at room temperature. After three washes with PBS, the cells were mounted on a glass slide in 9:1 glycerol/PBS containing 1 μ M DAPI.

A specimen of normal human adult small intestine frozen tissue sections (US Biomax, Derwood, MD, USA) was blocked in G-Block (GenoStaff, Tokyo, Japan) for 1 h and then incubated for 1 h at room temperature with an anti-human SLC35G1 goat polyclonal antibody at a dilution of 1:100 in Can Get Signal Immunostain Immunoreaction Enhancer Solution A. After washing thrice with PBS, the primary antibody was probed with anti-goat IgG Alexa Fluor 488 by incubating for 1 h at room temperature. Additionally, we stained ATP1A1 with an anti-human ATP1A1 mouse monoclonal antibody (clone BXP-21, Abcam, Cambridge, UK) labeled with the Ab-10 Rapid Hilyte Fluor 647 labeling kit (Dojindo Laboratories, Kumamoto, Japan) according to the manufacturer's instructions. After washing thrice with PBS, the tissues were mounted in 9:1 glycerol/PBS containing 1 μ M DAPI.

The localization of immunofluorescently labeled proteins and nuclei was visualized using a confocal laser scanning microscope (LSM510; Zeiss, Jena, Germany).

Data Analysis

The saturable transport of citrate by SLC35G1 was analyzed by assuming Michaelis-Menten-type carrier-mediated transport, as represented by the following equation: $v = V_{\max} \times s / (K_m + s)$. The apparent parameters of the maximum transport rate ($V_{\max}$) and Michaelis constant (K_m) were estimated by fitting this equation to the experimental profile of the uptake rate (v) versus the concentration (s) of citrate as the substrate, using a nonlinear least-squares regression analysis program, WinNonlin (Pharsight, Mountain View, CA, USA), with v^{-2} as the weight.

When s is considerably smaller than K_m ($s < K_m$), v in the presence of an inhibitor can be expressed as $v = v_0 / (1 + (i/IC_{50})^n)$. The half-maximal inhibitory concentration (IC_{50}) was estimated, along with the Hill coefficient (n) and v in the absence of inhibitors (v_0), by fitting this equation to the experimental profile of v versus the inhibitor concentration (i).

Acknowledgements

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Reviewer #1 (Public Review):

Summary:

The current manuscript provides strong evidence that the molecular function of SLC35G1, an orphan human SLC transporter, is citrate export at the basolateral membrane of intestinal epithelial cells. Multiple lines of evidence, including radioactive transport experiments, immunohistochemical staining, gene expression analysis, and siRNA knockdown are combined to deduce a model of the physiological role of this transporter.

Strengths:

The experimental approaches are comprehensive, and together establish a strong model for the role of SLC35G1 in citrate uptake. The observation that chloride inhibits uptake suggests an interesting mechanism that exploits the difference in chloride concentration across the basolateral membrane.

Weaknesses:

Some aspects of the results would benefit from a more thorough discussion of the conclusions and/or model.

For example, the authors find that SLC35G1 prefers the dianionic (singly protonated) form of citrate, and rationalize this finding by comparison with the substrate selectivity of the citrate importer NaDC1. However, this comparison has weaknesses when considering the physiological pH for SLC35G1 and NaDC1. NaDC1 binds citrate at a pH of ~5.4 (the pKa of citrate is 5.4, so there is a lot of dianionic citrate present under physiological circumstances). SLC35G1 binds citrate under pH conditions of ~7.5, where a very small amount of dianionic citrate is present. The data clearly show a pH dependence of transport, and the authors rule out proton coupling, but the discrepancy between the pH dependence and the physiological expectations should be addressed/commented on.

The rationale for the series of compounds tested in Figure 1F, which includes metabolites with carboxylate groups, a selection of drugs including anion channel inhibitors and statins, and bile acids, is not described. Moreover, the lessons drawn from this experiment are vague and should be expanded upon. It is not clear what, if anything, the compounds that reduce citrate uptake have in common.

The transporter is described as a facilitative transporter, but this is not established definitively. For example, another possibility could involve coupling citrate transport to another substrate, possibly even chloride ion.

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Reviewer #2 (Public Review):**Summary:**

The primary goal of this study was to identify the transport pathway that is responsible for the release of dietary citrate from enterocytes into blood across the basolateral membrane.

Strengths:

The transport pathway responsible for the entry of dietary citrate into enterocytes was already known, but the transporter responsible for the second step remained unidentified. The studies presented in this manuscript identify SLC35G1 as the most likely transporter that mediates the release of absorbed citrate from intestinal cells into the serosal side. This fills an important gap in our current knowledge of the transcellular absorption of dietary citrate. The exclusive localization of the transporter in the basolateral membrane of human intestinal cells and the human intestinal cell line Caco-2 and the inhibition of the transporter function by chloride support this conclusion.

Weaknesses:

- (i) The substrate specificity experiments have been done with relatively low concentrations of potential competing substrates, considering the relatively low affinity of the transporter for citrate. Given that NaDC1 brings in not only citrate as a divalent anion but also other divalent anions such as succinate, it is possible that SLC35G1 is responsible for the release of not only citrate but also other dicarboxylates. But the substrate specificity studies show that the dicarboxylates tested did not compete with citrate, meaning that SLC35G1 is selective for the citrate (2-), but this conclusion might be flawed because of the low concentration of the competing substrates used in the experiment.
- (ii) The authors have used MDCK cells for assessment of the transcellular transfer of citrate via SLC35G1, but it is not clear whether this cell line expresses NaDC1 in the apical membrane as the enterocytes do. Even though the authors expressed SLC35G1 ectopically in MDCK cells and showed that the transporter localizes to the basolateral membrane, the question as to how citrate actually enters the apical membrane for SLC35G1 in the other membrane to work remains unanswered.
- (iii) There is one other transporter that has already been identified for the efflux of citrate in some cell types in the literature (SLC62A1, PLoS Genetics; 10.1371/journal.pgen.1008884), but no mention of this transporter has been made in the current manuscript.

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Reviewer #3 (Public Review):**Summary:**

Mimura et al describe the discovery of the orphan transporter SLC35G1 as a citrate transporter in the small intestine. Using a combination of cellular transport assays, they show that SLC35G1 can mediate citrate transport in small intestinal cell lines. Furthermore, they investigate its expression and localization in both human tissue and cell lines. Limited evidence exists to date on both SLC35G1 and citrate uptake in the small intestine, therefore this study is an important contribution to both fields. However, the main claims by the authors are only partially supported by experimental evidence.

Strengths:

The authors convincingly show that SLC35G1 mediates uptake of citrate which is dependent on pH and chloride concentration. Putting their initial findings in a physiological context, they present human tissue expression data of SLC35G. Their Transwell assay indicates that SLC35G1 is a citrate exporter at the basolateral membrane.

Weaknesses:

Further confirmation and clarification are required to claim that the SLC indeed exports citrate at the basolateral membrane as concluded by the authors. Most experiments measure citrate uptake, but the authors state that SLC35G1 is an exporter, mostly based on the lack of uptake at physiological conditions faced at the basolateral side. The Transwell assay in Figure 1L is the only evidence that it indeed is an exporter. However, in this experiment, the applied chloride concentration was not according to the proposed model (120mM at the basolateral side). The Transwell assay, or a similar assay measuring export instead of import, should be carried out in knockdown cells to prove that the export indeed occurs through SLC35G1 and not through an indirect effect. Related to the mentioned chloride sensitivity, it is unclear how the proposed model works if the SLC faces high chloride conditions under physiological conditions though it is inhibited by chloride.

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