Biotin uptake by mouse and human pancreatic beta cells/islets: a regulated, lipopolysaccharide-sensitive carrier-mediated process

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Ghosal A, Sekar TV, Said HM. Biotin uptake by mouse and human pancreatic beta cells/islets: a regulated, lipopolysaccharide-sensitive carrier-mediated process. Am J Physiol Gastrointest Liver Physiol 307: G365–G373, 2014. First published June 5, 2014; doi:10.1152/ajpgi.00157.2014.—Biotin is essential for the normal function of pancreatic beta cells. These cells obtain biotin from their surroundings via transport across their cell membrane. Little is known about the uptake mechanism involved, how it is regulated, and how it is affected by internal and external factors. We addressed these issues using the mouse-derived pancreatic beta-TC-6 cells and freshly isolated mouse and human primary pancreatic beta cells as models. The results showed biotin uptake by pancreatic beta-TC-6 cells occurs via a Na+-dependent, carrier-mediated process, that is sensitive to des-thiobiotin, as well as to pantothenic acid and lipoate; the process is also saturable as a function of concentration (apparent $K_m = 22.24 \pm 5.5 \mu M$). These cells express the sodium-dependent multivitamin transporter (SMVT), whose knockdown (with doxycycline-inducible shRNA) led to a severe inhibition in biotin uptake. Similarly, uptake of biotin by mouse and human primary pancreatic islets is Na+-dependent and carrier-mediated, and both cell types express SMVT. Biotin uptake by pancreatic beta-TC-6 cells is also adaptively regulated (via transcriptional mechanism) by extracellular substrate level. Chronic treatment of pancreatic beta-TC-6 cells with bacterial lipopolysaccharides (LPS) leads to inhibition in biotin uptake. This inhibition is mediated via a Toll-Like receptor 4-mediated process and involves a decrease in membrane expression of SMVT. These findings show, for the first time, that pancreatic beta cells/islets take up biotin via a specific and regulated carrier-mediated process, and that the process is sensitive to the effect of LPS.

bion; pancreatic beta cells; biotin uptake mechanism; transport regulation

THE WATER-SOLUBLE VITAMIN BIOTIN, also known as vitamin B7 or vitamin H, is required for normal cellular functions, growth, and development. Biotin acts as a cofactor (as a carboxyl carrier) for five carboxylases that catalyze indispensable steps in intermediate metabolism including gluconeogenesis and fatty acid metabolism (reviewed in Refs. 34, 35). Emerging evidences also point to a role for biotin in normal immune function and in the regulation of gene expression (reviewed in Refs. 24, 29). In reference to the latter, biotin status has been shown to influence the expression of more than 2,000 human genes, at both the transcriptional and post-transcriptional levels (3, 30, 44). The affected genes include those that are critical for maintaining the differentiated phenotype of pancreatic beta cells, preservation of their mass (i.e., their proportion), and for insulin secretion (3, 30, 38, 44). In reference to the latter, the vitamin has been shown to increases the expression of pancre-atic and duodenal homeobox 1 (Pdx-1) (44), a critical transcription factor for the expression of insulin, and several genes involved in its synthesis and secretion by pancreatic beta cells (2). In pancreatic beta cells, biotin appears to increase the expression of insulin receptor (7) and glucokinase (3, 30, 39), a rate-limiting enzyme in glucose-stimulated insulin secretion (20). It also decreases the expression of several gluconeogenic genes (6, 36). Finally, biotin supplementation appears to have the ability to reduce hyperglycemia and improve glucose tolerance in humans (5, 15, 20), as well as in animal models of diabetes (26, 46).

Despite the importance of biotin for the health and function of pancreatic beta cells, and its apparent influence on insulin and glucose physiology, little is known about the mechanism involved in biotin uptake by these cells, how the process is regulated, and how factors that affect the health/function of pancreatic cells (like bacterial lipopolysaccharides, LPS) affect biotin uptake. Like all other mammalian cells, pancreatic beta cells cannot synthesize biotin endogenously, and thus must obtain it from their surroundings (circulation) via transport across cell membrane. The aims of this study were to delineate the mechanism and regulation of biotin uptake by pancreatic beta cells and to examine the effect of chronic exposure to LPS on the uptake process. We used the mouse-derived culture pancreatic beta-TC-6 cells as well as freshly isolated primary mouse and human pancreatic islets. The results showed biotin uptake by pancreatic beta cells/islets is via a specific Na+-dependent carrier-mediated process that involves the sodium-dependent multivitamin transporter (SMVT) system. This process is adaptively regulated by the substrate level in the extracellular compartment and is sensitive to LPS.

MATERIALS AND METHODS

Materials. Radioactive $^3$H-biotin and $^3$H-pantothenic acid (specific activity: 60 Ci/mmol and 50 Ci/mmol, respectively; radiolabeled purity for both $>97\%$) were purchased from American Radiolabeled Chemicals (ARC) (St. Louis, MO). Other reagents/chemicals used in these studies were purchased from commercial vendors, and all were of either analytical or molecular biology grades. Specific primers used for PCR amplifications were from Sigma Genosys (Woodlands, TX).

Cell culture and uptake studies. The mouse-derived beta-TC-6 cells (ATCC, Rockville, MD) were maintained under standard condition (5% CO$_2$ and 37°C) in DMEM growth medium supplemented with 15% FBS and antibiotics. To make a biotin-deficient medium, we used a custom-made vitamin deficient medium (DMEM from GibCO-BRL, Grand Island, NY) supplemented with 2.5% of dialyzed FBS (treated with avidin-agarose) (28). For knocking down SMVT using the inducible shRNA approach, cells were maintained in DMEM supplemented with 10% of Clontech’s Tet system approved FBS (Clontech Laboratories, Mountain View, CA). TLR4 gene inactivation was done by commercially available dominant negative mutant (pZERO-mTLR4; Invitrogen, CA). Uptake of $^3$H-biotin was...
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measured in cells incubated in Krebs-Ringer buffer (pH 7.4 unless otherwise stated) at 37°C as described before (23); uptake was linear as a function of time for 8 min (data not shown). Uptake was expressed in term of milligram cellular protein per unit time (i.e., femtomoles per milligram protein per minute). Protein concentrations were determined using a Bio-Rad DC protein assay kit (Hercules, CA).

Preparation of mouse and human primary pancreatic islets for uptake studies. Mouse primary pancreatic islets were isolated by enzymatic digestion followed by Ficoll gradient centrifugation method as reported by us before (23). Briefly, mice (8–10 wk old) were euthanized using ketamine and xylazine (Intraperitoneal injection of 100 and 10 mg/kg, respectively). The pancreas was isolated, minced, and digested with collagenase IV (1 mg/ml) containing DNase I (0.1 mg/ml) for 30 min with occasional shaking at 37°C. After digestion, pancreatic tissues were filtered through nylon mesh and the filtrate was subjected to discontinuous Ficoll gradient (25, 23, 20, and 11%, respectively) for isolation of islets. Islets were collected from the interface of 20 and 11% of Ficoll, subsequently washed three times, and used for uptake studies as described before (23). Cell viability was assessed using Trypan blue, with the result showing 85–90% viability.

Primary human pancreatic islets were obtained from healthy adult organ donors (National Disease Research Interchange, Philadelphia, PA). After removing the islets, samples were centrifuged (1,500 rpm for 8 min), washed, and resuspended in KR buffer, then used for uptake/molecular investigations. Islets viability was checked by Trypan blue and found to be around 70%.

Quantitative real-time PCR. Total RNA samples were isolated using TRIsol (Invitrogen, Carlsbad, CA) method as described in the manufacturer’s protocol. The isolated RNA samples were subjected to DNase I treatment to remove DNA contamination, and first strand c-DNAs were synthesized using iScript reverse transcriptase kit (Bio-Rad). Relative gene expression was measured by quantitative real-time PCR using gene-specific primers, and levels were normalized relative to mouse or human β-actin (for mSMVT, forward 5'-GGATCTGTTGGACGTGTA-3' and reverse 5'-CACATCTGTCAGACTGA-3'; for β-actin, forward 5'-ATCCCTCTCTCCCTTGGA-3' and reverse 5'-TTCATGAGTCCAGACAGGA-3'; for SMVT, forward 5'-TGTACCTCCTCCAGTCA-3' and reverse 5'-TAGAGCCACCTAGCACATATGGC-3'; for β-actin, forward 5'-GTGCGGTCATCGG-3'; for actin, forward 5'-CTCATATGGC-3'; for β-actin, forward 5'-GACTGAG-3').

SMVT knockdown by inducible shRNA in beta-TC-6 cells. Three SMVT gene-specific shRNA target sequences (5'-AATGGGCTGTCCTCCTTGTTAG-3' and 5'-CACAGGGAAGACAGCCCAT-3') were designed for cloning into the pSingle-tTS-shRNA vector following manufacturer's protocol (Clontech Laboratories, Mountain View, CA). Briefly, the complementary strands were annealed to each other, and the double stranded DNA was ligated to the pSingle-tTS-shRNA vector (which was linearized with XhoI and HindIII). The construct was transformed into XL1 blue Escherichia coli, and the isolated plasmid was sequenced to verify the insert.

The recombinant pSingle-tTS-shRNA plasmids were then transfected into cultured pancreatic beta-TC-6 cells; 48 h after transfection, cells were maintained in G418 (500 μg/ml) for selection. Gene knockdown was induced by treating the cells with doxycycline (800 ng/ml) for 72 h. Cell populations treated in identical manner, but without doxycycline, were used as controls.

Western blot analysis. Total protein was isolated using RIPA buffer (Sigma) in presence of a protease inhibitors cocktail (Roche, Nutley, NJ). Total isolated protein was loaded onto NuPAGE 4–12% Bis-Tris gradient minigels (Invitrogen) and subjected to Western blot analysis. The blot was incubated with anti-mSMVT antibody (raised in rabbit) and monoclonal anti-β-actin antibody followed by incubation with anti-rabbit IR 800 dye and anti-mouse IR 680 dye (LI-COR, Lincoln, Nebraska) secondary antibodies (1:25,000) at room temperature for 1 h. The expressions of respective proteins were quantified by using Odyssey application software (version 3.0) in Odyssey Infrared imaging system (LI-COR).

Cell surface biotinylation assay. The effect of LPS on the expression of the SMVT protein at the cell membrane of pancreatic beta-TC-6 was examined by a biotinylation assay using a cell surface biotinylation kit (Pierce Biotechnology, Rockford, IL). Briefly, cells were maintained under serum starved condition overnight and treated with LPS (1 μg/ml) for 24 h (42). Cell surface biotinylation was performed by treating cells with sulfo-NHS-SS-biotin followed by isolation of surface proteins by incubating the cell lysate with streptavidine-agarose beads following manufacturer’s protocol. Relative surface expression of SMVT was determined with respect to total cellular SMVT by mean of Western blotting.

Statistical analysis. Data shown here are means ± SE of at least 3 separate experiments and were analyzed for significance using the Student’s t-test. Uptake data were expressed as femtomoles per milligram protein per unit time or as percentage relative to simultaneously performed controls. To determine transport kinetic parameters of the carrier-mediated process, uptake by the latter component was determined by subtracting uptake by diffusion from total uptake at each concentration examined. The apparent \( K_L \) and \( V_{max} \) of the carrier-mediated process were determined using Michaelis-Menten equation in Graph Pad Prism software (Version 5.03).

Results

Physiological Characterization of the Biotin Uptake Process of Pancreatic Beta Cells/Islets

General characteristics. Isosmotic removal of Na+ in the incubation buffer with another monovalent cation (K+) led to a significant (\( P < 0.01 \)) inhibition in the initial rate of biotin (5 nM) uptake by pancreatic beta-TC-6 cells (155 ± 13 and 20 ± 6 fmol·mg protein⁻¹·min⁻¹ in the presence and absence of Na+, respectively). The initial rate of biotin uptake by pancreatic beta-TC-6 cells was also pH dependent with a significantly (\( P < 0.01 \)) higher uptake at pH 7.4 than at pH 6.5 and 5.5 (as percentage to uptake at pH 7.4: 100 ± 0.88, 65.16 ± 3.19, 48.32 ± 4.46, respectively). We examined the effect of unlabeled biotin, its structural analog desthiobiotin, and that of lipoate and pantothenic acid (all at 500 μM) on the initial rate of 3H-biotin (5 nM) uptake, and observed a significant (\( P < 0.01 \) for all) inhibition in 3H-biotin uptake in the presence of all these compounds (as percentage: 100 ± 3.84, 13.57 ± 2.44, 13.72 ± 4.61, 12.67 ± 3.71, and 11.57 ± 3.13 for control and in the presence of unlabeled biotin, desthiobiotin, lipoate, and pantothenic acid, respectively).

Similar findings were obtained with freshly isolated primary mouse pancreatic islets in that the initial rate of biotin uptake was significantly (\( P < 0.05 \)) higher at physiological pH 7.4 compared with pH 6.5 and 5.5 (11.1 ± 0.42, 8.73 ± 0.46, and 3.61 ± 0.65 fmol·mg protein⁻¹·min⁻¹, respectively; \( P < 0.05 \)), and that Na⁺ replacement with K⁺ led to a significant (\( P < 0.05 \)) inhibition in uptake (as percentage: 100 ± 19.12 and 13.3 ± 5.8 in the presence and absence of Na⁺, respectively). Moreover, unlabeled biotin (1 mM) caused a significant (\( P < 0.01 \)) inhibition in the initial rate of uptake of 3H-biotin (5 nM) (as percentage: 100 ± 10 and 35.7 ± 7 in the absence and presence of unlabeled biotin, respectively). In other studies, we extended the investigations to the human situation and examined the effect of Na⁺ removal (replacement with Li⁺) and that of unlabeled biotin (1 mM) in the incubation medium on the initial rate of 3H-biotin (5 nM) uptake by primary human pancreatic islets. The results showed a significant inhibition in...
Collectively, the above described results suggest that biotin uptake by mouse and human pancreatic beta cells/islets is mediated via a Na$^+$-dependent carrier-mediated mechanism. 

Kinetic parameter of biotin uptake by pancreatic beta cells. 

Kinetic parameters of the biotin uptake process of pancreatic beta-TC-6 cells were determined by examining the initial rate of biotin uptake as a function of substrate concentration. The results showed that uptake includes a saturable component over the micromolar range (Fig. 1A) with a $V_{max}$ and an apparent $K_m$ of 55.1 ± 5.9 fmol-mg protein$^{-1}$·min$^{-1}$ and 22.24 ± 5.5 μM, respectively (Fig. 1A). Since studies by others (13, 45) have suggested the possible existence of another biotin uptake system that functions at the nanomolar range, we tested the possible existence of such a system by examining uptake as a function of that concentration range. No evidence for the existence of such a system was observed, as biotin uptake was linear over this range (Fig. 1B).

Molecular identity of the biotin uptake system of pancreatic beta cells/islets. The SMVT system is expressed in a variety of tissues (41). Here we examined whether mouse and human pancreatic beta cells/islets express the SMVT system at the mRNA levels. The levels showed that SMVT is indeed expressed, albeit at different levels, in pancreatic beta-TC-6 cells and in mouse and human primary pancreatic islets. Human pancreatic islets showed more expression of SMVT than cultured and primary mouse pancreatic beta-TC-6 cells, respectively. 

To examine the relative contribution of the SMVT system toward carrier-mediated biotin uptake by pancreatic beta-TC-6 cells, we used the approach of gene silencing with shRNA. We stably transfected the cells with doxycycline-inducible shRNA targeted to mouse SMVT. Gene knockdown was induced by incubating the transfected cells with doxycycline. The effectiveness of the gene silencing was verified by demonstrating a significant reduction (around 70%; $P < 0.01$ for both) in expression of SMVT at the mRNA and protein levels in the shRNA transfected and induced cells compared with non-induced cells (Fig. 2, A and B). The consequence of knocking down the SMVT system on carrier-mediated biotin uptake was determined with the results showing ~60% ($P < 0.01$) inhibition in carrier-mediated biotin uptake in induced cells expressing shRNA compared with noninduced cells (Fig. 2C). These findings suggest that the SMVT system is the major biotin uptake carrier by pancreatic beta-TC-6 cells. Since SMVT also transports pantothenic acid, we tested if knocking down SMVT (with the same shRNA approach) also inhibits uptake of this substrate. The results indeed showed a significant decrease in $^3$H-pantothenic acid uptake ($P < 0.05$) in induced cells expressing shRNA compared with noninduced cells (Fig. 2D).

The human SLC5A6 (the gene that encodes SMVT) has two promoters (promoter 1 and 2; P1 and P2) with activity of P1 being higher than that of P2 in a number of tissues, as we reported before (8, 27). Thus we determined the relative activity of these two promoters in pancreatic beta-TC-6 cells [the human SLC5A6 5’-promoters are active in mice in vivo (27)]. The results showed a significantly ($P < 0.01$) higher P1 activity than P2 (Fig. 3), suggesting these cells utilize the former promoter to a greater extent than the latter in driving the transcription of this gene in pancreatic beta cells.

Regulation of the Biotin Uptake by Pancreatic Beta Cells

Adaptive regulation by extracellular substrate level. We examined whether the biotin uptake process of pancreatic beta cells is adaptively regulated by the prevailing vitamin level. We examined the initial rate of biotin uptake by pancreatic beta-TC-6 cells maintained in biotin-deficient medium and in biotin oversupplemented (100 μM) medium (see MATERIALS AND METHODS). The results showed a significantly ($P < 0.01$) higher $^3$H-biotin (5 nM) uptake in cells maintained in biotin-deficient medium compared with those maintained in biotin oversupplemented medium (Fig. 4A). Expression of the SMVT protein and mRNA were both found to be significantly ($P < 0.01$ for both) higher in the cells that were maintained in the biotin-deficient medium compared with those in the over-

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Fig. 1. Uptake of biotin by pancreatic beta-TC-6 cells as a function of substrate concentration. Confluent monolayers were incubated at 37°C in Krebs-Ringer buffer, pH 7.4, in the presence of micromolar (1–50 μM) (A) and nanomolar (5–50 nM) (B) concentrations of biotin. Uptake by the carrier-mediated system was calculated as described in MATERIALS AND METHODS. Values are means ± SE of at least 3 separate uptake determinations. When not visible, error bars are smaller than the displayed symbol.
supplemented medium (Fig. 4, B and C). We further examined if the adaptive regulation in biotin uptake is mediated by induction of the SMVT promoters. For this we used the full-length human SMVT promoters P1 and P2 fused to the firefly luciferase reporter gene (27, 28). Promoter constructs were transfected into pancreatic beta-TC-6 cells and maintained for 96 h in biotin-deficient and oversupplemented medium. The result showed a significantly (\( P < 0.01 \) for both) higher promoter activity in cells maintained in the biotin-deficient medium compared with those in the oversupplemented medium (Fig. 4D, i and ii).

Possible regulation of biotin uptake in pancreatic beta cells by intracellular signaling pathways and by high glucose levels. We examined whether the process of biotin uptake by mouse pancreatic beta cells is regulated by intracellular signaling pathways, focusing on those pathways that regulate the uptake of other nutrients in a variety of other cellular systems [e.g., protein kinase A (PKA), Ca^{2+}/calmodulin, protein tyrosine kinase (PTK), and protein kinase C (PKC)] (11; reviewed in Ref. 32). Using specific modulators of these regulatory pathways, the results showed that modulators of PKA (dibutyryl cAMP and forskolin), Ca^{2+}/calmodulin (calmidazolium chloride), and PTK (genistein)-mediated pathways have no effect on biotin uptake by pancreatic beta-TC-6 cells (data not shown), the classic PKC activator phorbol 12-myristate 13-acetate (PMA), but not its negative control (4α-PMA), caused a significant (\( P < 0.05 \)) inhibition (as percentage: 100 \( \pm \) 6, 75.7 \( \pm \) 3.5, and 106.1 \( \pm \) 6.7 for control, PMA-treated, and 4α-PMA-treated cells, respectively).

Since biotin plays a role in normal pancreatic beta cells homeostasis and function (38), and high glucose levels affect
pancreatic physiology (9, 17, 18, 37), we also investigated the effect of prolonged exposure (96 h) of pancreatic beta-TC6 cells to a high glucose (26 mM) level on biotin uptake. The results, however, showed no effect of such a treatment on biotin uptake (as percentage: 100/11006 11.3 and 114/11006 8.8 in the presence of 5.5 and 26 mM glucose, respectively), suggesting that biotin uptake is not affected by hyperglycemia.

Effect of bacterial LPS on biotin uptake by pancreatic beta cells. Gut microbiota has recently been proposed as an environmental factor that increases the risk of metabolic disorders such as diabetes mellitus. Patients with Type 2 diabetes have altered gut microbial diversity and an increase in the level of circulating bacterial LPS, which is associated with a low-grade endotoximia (4, 16, 43). LPS has been shown to exert deleterious effects on the health/function of pancreatic beta cells, and it does so via Toll-Like receptor 4 (TLR4)–mediated mechanism (1). The effect of LPS on biotin uptake by pancreatic beta cells is not known and, therefore, was examined using pancreatic beta-TC-6 cells. The results showed that exposure (24 h) of the cells to clinically relevant LPS concentrations (1 µg/ml) (1, 42) lead to a significant and concentration-dependent inhibition in the initial rate of biotin uptake (Fig. 5A) (LPS did not affect cell viability as indicated by Trypan blue analysis where >95% of the treated cells were found to be viable). Since LPS exerts its effect via TLR4, we examined the effect of inhibiting the expression of this receptor by expressing a dominant negative mutant on the ability of LPS to inhibit biotin uptake by pancreatic beta-TC-6 cells (see MATERIALS AND METHODS). The results showed that such a treatment leads to significant (P < 0.01) protection against the inhibitory effect of LPS on biotin uptake by these cells (Fig. 5B).

To determine if the inhibitory effect of LPS is mediated via inhibition in the expression of SMVT protein and mRNA, we examined the effect of LPS treatment of pancreatic beta-TC6 cells by Western blotting and quantitative PCR, respectively. The results showed LPS treatment to have no effect on either of these parameters (Fig. 6, A and B). We also examined the effect of LPS on activity of the SLC5A6 promoters transfected into pancreatic beta-TC-6 cells and again observed no effect (Fig. 6C, i and ii). These findings suggest that the inhibitory

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**Fig. 4.** Adaptive regulation of SMVT as a function of extracellular biotin level. Pancreatic beta-TC-6 cells were maintained in biotin-deficient or biotin oversupplemented (100 µM) medium for 96 h followed by determination of initial rate of carrier-mediated uptake (A), level of SMVT protein (Western blotting) (B), level of SMVT mRNA (quantitative real-time PCR (C), and activity of the SLC5A6 promoter 1 (i) and promoter 2 (ii) (D). Results are means ± SE of at least 3 independent experiments. *P < 0.05.
effect of LPS on biotin uptake by pancreatic beta cell is not mediated via changes in protein and RNA levels, nor in the transcription rate of the SLC5A6 gene. This led us to speculate that the effect is probably mediated by alteration in the expression of the SMVT protein at the cell membrane. To test this possibility, we performed biotinylation assays (see METHODS) and indeed found a significant ($P < 0.05$) reduction in the level of expression of the SMVT protein at the cell membrane with no change in level of expression of total cellular SMVT protein in LPS-treated cells compared with control cells (Fig. 6D).

**DISCUSSION**

Previous in vitro and in vivo studies have shown that biotin is important for normal health/function of pancreatic beta cells. The vitamin plays a role in the expression of genes that are critical for maintaining the differentiated phenotype of pancreatic beta cells and in preserving their mass; it also plays a role in insulin secretion (3, 30, 39, 44) and in expression of glucokinase (30, 39) and Pdx1 (44), proteins that favor function and preservation of pancreatic beta cells (2, 21). Despite the importance of biotin for the normal homeostasis and function of the endocrine pancreas, little is known about how cells of this important organ take up biotin, how the process is regulated, and how internal and external factors affect the uptake process. Our objectives in the current investigations were to address these issues, and we used cultured mouse-derived pancreatic beta-TC-6 cells and complemented the findings with studies using freshly isolated mouse and human primary (native) pancreatic islets. The results showed the uptake of $^3$H-biotin by pancreatic beta-TC-6 cells to be Na$^+$-dependent and carrier-mediated as indicated by the inhibition caused by unlabeled biotin and its structural analog desthiobiotin, and by the saturation in biotin uptake as a function of concentration. Similarly, uptake of biotin by native freshly isolated primary mouse and human pancreatic islets was Na$^+$-dependent and carrier-mediated in nature. As seen with other cell types of the digestive system, biotin uptake by pancreatic beta cells was also inhibited by pantothenic acid and lipoate, thus pointing to possible involvement of the SMVT in the uptake process. Indeed, mouse and human pancreatic beta cells/islets were found, by Western blotting and qualitative PCR, to express the SMVT system. Studies on biotin uptake in certain other cellular systems have suggested possible involvement of another (non-SMVT) biotin uptake carrier that operates in the nanomolar range (13, 45), but no such evidence were found in the current studies. The latter was shown by the lack of saturation in the initial rate of biotin uptake over the nanomolar range, and by the SMVT shRNA knockdown approach which established a major role for the SMVT system in biotin uptake by pancreatic beta cells.

Following delineation of the mechanism of biotin uptake by pancreatic beta cells/islets, we examined potential regulation of the uptake process by extracellular and intracellular factors. Biotin uptake by pancreatic beta-TC-6 cells was shown to be adaptively regulated by the prevailing biotin level in the extracellular environment, and was higher in cells maintained under a biotin-deficient condition compared with those maintained in the presence of a high level of biotin. This adaptive regulation in biotin uptake was associated with parallel changes in the level of expression of the SMVT protein and mRNA, as well as in the activity of the SLC5A6 promoters. These findings suggest possible involvement of a transcriptional mechanism(s) in mediating the observed adaptive response in pancreatic beta cells biotin uptake process. We also examined possible regulation of the pancreatic beta cells/biotin uptake process by specific intracellular regulatory pathways and found that specific modulators of the PKA, PTK, and Ca$^{2+}$/calmodulin-mediated pathways had no effect on biotin uptake. On the other hand, a role for the PKC-mediated pathway was suggested by the effect of the PKC modulator PMA (but not by its negative control 4α-PMA) on biotin uptake by pancreatic beta cells. It is interesting to mention here that biotin uptake by intestinal epithelial cells is also under the regulation of this intracellular regulatory pathway, suggesting that different cells may use the same regulatory mechanism to regulate their biotin uptake (32).
The intestinal microbiota appears to be an important environmental factor that influences the risk of metabolic disorders like diabetes mellitus (4). Studies have also shown that subjects with Type 2 diabetes have altered microbiota diversity and an enrichment in gram-negative bacteria (which express LPS) (16, 43). Indeed there is an increase in the level of LPS in the circulation of those subjects and a low-grade endotoxemia, which are believed to play a role in the onset of the metabolic disorders (1). Pancreatic beta cells express significant levels of TLR4 which make them sensitive to the effect of LPS (10, 14, 40). Circulating LPS binding to TLR4 leads to activation of the nuclear factor kappa-light-chain-enhancer of activated B-cells (NF-κB), p38 mitogen-activated protein kinases (p38 MAPK), activator protein 1 (AP-1), and interferon-inducible inflammatory gene expression (1, 14). We observed that chronic exposure of pancreatic beta-TC-6 cells to LPS lead to a significant inhibition in biotin uptake. This inhibition was not associated with changes in the level of expression of the total cellular SMVT protein, nor changes in level of its mRNA or activity of its gene promoters, but rather due to a decrease in the level of expression of the SMVT protein at the cell membrane as demonstrated by biotinylation assay. This is similar to what

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**Fig. 6.** Effect of exposure of pancreatic beta cells to LPS on molecular parameters of SMVT. Pancreatic beta-TC-6 cells were pre-exposed to LPS (1 µg/ml for 24 h) followed by determination of level of expression of SMVT protein (A) and mRNA (B) levels and activity of SLC5A6 promoter promoters 1 and 2 (C, i and ii). D shows the result of the biotinylation assay. Level of expression of biotinylated membranous SMVT was normalized relative to total SMVT in the cellular homogenate. *Inset*: a representative Western blot showing level of expression of SMVT at the cell membrane and in the total cellular homogenate. All methodologies are described in MATERIALS AND METHODS. Data are means ± SE of 3 independent experiments and expressed as % relative to simultaneously performed untreated controls. *P < 0.05.
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others have seen in studies on the inhibitory effects of LPS on the serotonin transporter in intestinal epithelial cells (22).

In summary, our studies show for the first time that biotin uptake by mouse and human pancreatic beta cells/islets is mediated via a regulated carrier-mediated mechanism that involves the SMVT system. This study also shows that the bacterial LPS inhibits biotin uptake by reducing the amount of the SMVT protein that is expressed at the cell membrane.

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DISCLOSURES
No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

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