Characterization of the human SLC30A8 promoter and intronic enhancer

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Abstract

Genome-wide association studies have shown that a polymorphic variant in SLC30A8, which encodes zinc transporter-8, is associated with altered susceptibility to type 2 diabetes (T2D). This association is consistent with the observation that glucose-stimulated insulin secretion is decreased in islets isolated from Slc30a8 knockout mice. In this study, immunohistochemical staining was first used to show that SLC30A8 is expressed specifically in pancreatic islets. Fusion gene studies were then used to examine the molecular basis for the islet-specific expression of SLC30A8. The analysis of SLC30A8-luciferase expression in βTC-3 cells revealed that the proximal promoter region, located between −6154 and −1, relative to the translation start site, was only active in stable but not transient transfections. VISTA analyses identified three regions in the SLC30A8 promoter and a region in SLC30A8 intron 2 that are conserved in the mouse Slc30a8 gene. Additional fusion gene experiments demonstrated that none of these Slc30a8 promoter regions exhibited enhancer activity when ligated to a heterologous promoter whereas the conserved region in SLC30A8 intron 2 conferred elevated reporter gene expression selectively in βTC-3 but not in αTC-6 cells. Finally, the functional effects of a single nucleotide polymorphism (SNP), rs62510556, in this conserved intron 2 enhancer were investigated. Gel retardation studies showed that rs62510556 affects the binding of an unknown transcription factor and fusion gene analyses showed that it modulates enhancer activity. However, genetic analyses suggest that this SNP is not a causal variant that contributes to the association between SLC30A8 and T2D, at least in Europeans.

Journal of Molecular Endocrinology (2011) 47, 251–259

Introduction

Zinc transporter-8 (ZnT-8) belongs to a family of zinc transporters that, along with metallothioneins, are involved in intracellular zinc homeostasis and signaling through compartmentation of the ion and regulation of its concentration (Wijesekara et al. 2009). The mouse Slc30a8 gene, which encodes ZnT-8, is mainly expressed in pancreatic β and α cells (Gyulkhandanyan et al. 2008, Pound et al. 2009), with much lower levels of expression in testis and submaxillary glands (Murgia et al. 2009). ZnT-8 is localized to insulin secretory granules within β cells (Chimienti et al. 2006) where it is thought to be required for providing zinc to allow for proper maturation, storage, and secretion of insulin (Wijesekara et al. 2009).

In keeping with an important role for ZnT-8 in the β cell, recent genome-wide association (GWA) studies linked a non-synonymous single nucleotide polymorphism (SNP), rs13266634, which changes amino acid 325 of human ZnT-8 from tryptophan to arginine, to increased susceptibility to type 2 diabetes (T2D; Saxena et al. 2007, Scott et al. 2007, Sladek et al. 2007, Zeggini et al. 2007), impaired proinsulin to insulin conversion (Stancakova et al. 2009), and reduced first-phase insulin secretion (Stancakova et al. 2009). This same variant is also associated with autoantibody epitope specificity changes in human type 1 diabetes (Wenzlau et al. 2008).

The rs13266634 variant has the potential to be causative, rather than just being in strong linkage disequilibrium with the actual causative variant, since it has been reported to affect zinc transport by ZnT-8 in cultured cell studies (Nicolson et al. 2009). However, a key question that remains to be addressed is whether this SNP is the only variant in the SLC30A8 gene altering susceptibility to T2D. This seems unlikely because the variants identified to date can only explain a small fraction of the calculated genetic contribution to the risk of developing T2D (Manolio et al. 2009).
While various explanations have been proposed for this missing heritability (Manolio et al. 2009), one possibility is that rare SNPs, which are not analyzed in GWA studies, exist in genes such as SLC30A8 that markedly affect their expression or the function of the encoded protein. The studies described here were initiated with the goal of characterizing key regions of the SLC30A8 gene so as to establish a framework for the future analysis of rare SNPs that have the potential to modulate SLC30A8 gene transcription. We show that the proximal human SLC30A8 promoter, located between −6154 and −1, relative to the translation start site, is only active in stable and not transient transfections. In addition, we identify a conserved islet β cell-specific enhancer in intron 2 of the SLC30A8 gene. Finally, a SNP, rs62510556, in this conserved intron 2 enhancer is shown to affect the binding of an unknown transcription factor and thereby modulate enhancer activity. This SNP therefore had the potential to be a second causal variant that contributed to the association between SLC30A8 and T2D. However, genetic analyses suggest that, in Europeans, this SNP is not associated with the risk for T2D.

Materials and methods

Materials

The BAC plasmids from which mouse Slc30a8 and human SLC30A8 genomic regions were isolated (see below) were purchased from BACPAC Resources (Children’s Hospital Oakland Research Institute, Oakland, CA, USA).

Immunohistochemistry

Human pancreata were fixed in 4% paraformaldehyde in PBS (Invitrogen Corporation) for 12 h and were paraffin embedded. Immunostainings were performed on 6 μm sections that were de-paraffinized three times with HistoClear (National Diagnostics, Atlanta, GA, USA) for 5 min, then hydrated serially in 100% (twice), 95%, and 70% ethanol and water for 2 min. Antigen retrieval was performed on sections by incubating in 0.01 M citrate buffer, pH 6.0, for 5 min in a microwave using medium power settings. Sections were incubated for 1 h at room temperature with blocking buffer (TSA system; Invitrogen Corporation) and then at room temperature overnight in a humid chamber with three primary antibodies: mouse anti-human ZnT-8 (1:20; John Hutton, UC Denver; please see Supplementary Data, see section on supplementary data given at the end of this article, for details on antibody generation), Guinea pig anti-insulin (1:50; Sigma), and rabbit anti-glucagon (1:50; Dako North America, Inc., Carpinteria, CA, USA) in TNB antibody dilution buffer (Invitrogen Corporation). The slides were then drained and washed three times for 5 min in PBS before secondary antibodies (1:250) conjugated to aminomethylcoumarin acetate, Cyanine 2, or Cyanine 5 fluorophores (Jackson Immunoresearch Laboratories, West Grove, PA, USA) were applied and incubated at room temperature for 60 min. The slides were then washed in PBS and mounted with a glycerol-based media.

Images were acquired with Intelligent Imaging System software using an Olympus IX81-inverted-motorized microscope equipped with Olympus DSU spinning disk confocal optics and a Hamamatsu ORCA IIER monochromatic CCD camera. The images were later pseudo colored for illustration: red (ZnT-8), blue (glucagon), and green (insulin).

Fusion gene plasmid construction

Please see Supplementary Data, see section on supplementary data given at the end of this article.

Cell culture, transfection, and luciferase assays

Mouse islet β cell-derived βTC-3 cells and α cell-derived zTC-6 cells were grown in DMEM containing 10% (vol/vol) fetal bovine serum. For transient transfections, cells were transfected with 0.5 μg of an expression vector encoding SV40-Renilla luciferase (Promega) and 2 μg of a firefly luciferase pGL3 or pGL4 fusion gene plasmid using the lipofectamine reagent (GibcoBRL) as described previously (Bischof et al. 2001). Following overnight incubation in serum-containing medium, cells were harvested by trypsin digestion and then solubilized in passive lysis buffer (Promega). After two cycles of freeze/thawing, firefly and Renilla luciferase activity were assayed using the Promega Dual-Luciferase Reporter Assay System according to the manufacturer’s instructions. To correct for variations in transfection efficiency, the results are expressed as the ratio of firefly:Renilla luciferase activity. In addition, three independent preparations of each fusion gene plasmid construct were analyzed in triplicate.

For stable transfections, cells were transfected with 2 μg of a firefly luciferase pGL4 fusion gene plasmid using the lipofectamine reagent as described previously (Bischof et al. 2001). Three independent preparations of each fusion gene plasmid construct were analyzed in triplicate. Following overnight culture at 37 °C, cells were incubated with serum-containing medium supplemented with hygromycin (Sigma–Aldrich) at a final concentration of 500 μg/mL. Every 2–3 days, hygromycin-containing medium was replaced. After 3–4 weeks, or until individual colonies could be visualized, colonies were pooled using trypsinization, transferred...
to 10 cm dishes, and hygromycin treatment was discontinued. Once the cells had reached confluence, luciferase activity in the pooled cultures was then assessed and the Pierce BCA protein assay used to correct for variations in protein content.

**Statistical analyses**

The transfection data were analyzed for differences from the control values, as specified in the figure legends. Statistical comparisons were calculated using an unpaired Student's *t*-test. The level of significance was *P* < 0.05 (two-sided test).

**Results**

**The human SLC30A8 gene is expressed in both pancreatic islet α and β cells**

Chimienti *et al.* (2004) had suggested that in pancreatic islets, expression of the mouse *Slc30a8* gene, which encodes the zinc transporter ZnT-8, is restricted to insulin-secreting β cells, but recent data suggest that it is also expressed in glucagon-secreting α cells (Gyulkhandanyan *et al.* 2008, Pound *et al.* 2009). To assess the expression pattern of human SLC30A8, immunohistochemical staining was performed on human pancreas sections. Figure 1 shows that ZnT-8 was absent from exocrine tissue but was detected in both α and β cells in human pancreatic islets, consistent with observations made in mice (Gyulkhandanyan *et al.* 2008, Pound *et al.* 2009).

**Highly conserved putative human SLC30A8 and mouse Slc30a8 promoter regions are unable to drive reporter gene expression in transient transfection experiments**

To identify candidate regions of the human SLC30A8 and mouse *Slc30a8* genes that may serve as promoters, a sequence alignment using the VISTA program (Frazer *et al.* 2004) was performed with human and mouse gene sequence 10 kbp 5′ of the translation start site (Chimienti *et al.* 2004). This analysis identified several highly conserved regions in the mouse and human genes in the area located ~8000 and 6000 bp, respectively, 5′ of the translation start site (Fig. 2). Figure 2 also shows that, while the conserved regions are the same, the spacing between conserved regions is reduced in the human promoter. An analysis of SLC30A8-expressed sequence tags in the NCBI nucleotide database suggests that SLC30A8 gene transcription initiates at multiple start sites in a ~500 bp region located immediately 5′ of the translation initiation codon, consistent with the absence of a consensus TATA box sequence in this location (Smale 1997). To investigate whether this region represents the SLC30A8 promoter, a SLC30A8-luciferase fusion gene was constructed, containing putative promoter sequence between −6154 and −1, relative to the translation start site, and transiently transfected into βTC-3 cells, an islet β cell-derived cell line (Efrat *et al.* 1988). Basal luciferase expression directed by this fusion gene was below the level obtained with the promoterless luciferase expression vector (Fig. 3A). Identical results were obtained in transient transfection experiments in HIT

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**Figure 1** Immunohistochemical detection of ZnT-8 in human pancreas. Paraffin-embedded sections of adult human pancreata were immunostained for the presence of insulin (green) and glucagon (blue) and ZnT-8 (red) as described in the Materials and methods section. A representative section is shown. Scale bar: 10 μm. Full colour version of this figure available via http://dx.doi.org/10.1530/JME-11-0055.
Identification of human SLC30A8 and mouse Slc30a8 promoter regions that drive reporter gene expression in stable transfection experiments

Another possible explanation for the lack of fusion gene expression in transient transfection experiments was the known differences in chromatin structure between that on endogenous promoters and that on transiently transfected plasmid templates (Smith & Hager 1997). Thus, previous studies have demonstrated the potential for major differences in expression levels when fusion genes are compared using transient and stable transfection (Smith & Hager 1997). Some promoters/enhancers are only active, or are much more active, when analyzed in stable transfections (Smith & Hager 1997). To assess whether chromatin structure was essential for human SLC30A8 and mouse Slc30a8 promoter function, luciferase fusion genes containing either the human SLC30A8 sequence from −6154 to −1 or the mouse Slc30a8 sequence from −1803 to −1 were analyzed in the context of the pGL4 vector. This vector contains a hygromycin resistance gene, which allows for negative selection. BTC-3 cells were stably transfected with these human or mouse promoter-luciferase fusion genes and treated with hygromycin until individual colonies were visualized. The individual colonies were then pooled and luciferase activity assayed. Under these conditions, the human SLC30A8 (Fig. 3C) and mouse Slc30a8 (Fig. 3D) genomic regions analyzed both drove fusion gene expression at much higher levels than the promoterless pGL4 vector, indicating the presence of functional promoters. A difference in activity was observed between the human and mouse promoters, but presumably this is mainly because the human promoter fragment used (Fig. 3C) was much longer than the mouse (Fig. 3D) and is likely to contain additional enhancer regions (Fig. 2). Although zinc has been reported to regulate Slc30a8 gene expression in INS-1E cells (Smidt et al. 2009), no effect of zinc on human SLC30A8 promoter activity was observed in the stable cell lines (Supplementary Figure 1, see section on supplementary data given at the end of this article), suggesting that the effect of zinc is mediated through other genomic regions or post-transcriptionally.

The VISTA analysis identified three conserved regions in the mouse Slc30a8 promoter, located between approximately (−7751 and −7250), (−5498 and −4730) and (−3163 and −2698) (Fig. 2B). These regions are found in similar locations in the human SLC30A8 gene (Fig. 2A). We hypothesized that these regions might represent transcriptional enhancers important for islet-specific expression of the Slc30a8 gene. To address this hypothesis, these regions, designated as promoter enhancers 1, 2, and 3 (Fig. 2B), were isolated and ligated 5′ of a heterologous

Figure 2 The putative human SLC30A8 and mouse Slc30a8 promoters are highly conserved. The figure shows a VISTA browser plot (Frazer et al. 2004) comparing 10 kbp of human SLC30A8 versus mouse Slc30a8 (A) and mouse Slc30a8 versus human SLC30A8 (B) gene sequence. The translation start site is at bp 10 000 and the level of conservation is indicated on the vertical axis. Conserved regions above 70%/100 bp are highlighted in gray and three putative promoter enhancer regions in the mouse Slc30a8 promoter are designated 1, 2, and 3. It is shown that, while the conserved regions are the same, the spacing between conserved regions is reduced in the human promoter.

cells, an alternate islet β cell-derived cell line, and with SLC30A8/luciferase fusion genes in both the pGL3 and the pGL4 luciferase vectors (data not shown). A Slc30a8/luciferase fusion gene containing putative mouse Slc30a8 promoter sequence between −1803 and −1 was also constructed and analyzed by transient transfection in both cell lines and in both luciferase vectors. As with the putative human promoter, the putative mouse promoter was also incapable of driving reporter gene expression (Fig. 3B and data not shown).

The results of stable transfection experiments (see below) suggest that these human and mouse DNA fragments are not acting as repressors. Rather the reductions in reporter gene expression below the level obtained with the promoterless luciferase expression vector (Fig. 3A and B) are more likely due to the presence of SLC30A8 and Slc30a8 genomic DNA further reducing low non-specific read-through transcription.

A possible explanation for the lack of promoter activity was that a cryptic RNA secondary structure, forming between the luciferase coding sequence and the 5′-untranslated region located between the transcription start site and translation start site, was impairing mRNA translation (Kozak 1989). Fusion genes were therefore generated containing genomic sequence that terminated at known human (−6154/−235; NM_173851) and chimpanzee (−6154/−522; XM_519918) transcription start sites (Fig. 3A) or at a known mouse (−1805/−335; NM_172816) transcription start site (Fig. 3B). However, none of these fusion genes conferred reporter gene expression in transient transfection assays (Fig. 3A and B).

Journal of Molecular Endocrinology (2011) 47, 251–259
thymidine kinase (TK)-luciferase fusion gene containing TK genomic sequence between −105 and +51, relative to the transcription start site (Vander Kooi et al. 2005). Luciferase expression directed by these fusion genes was then analyzed by transient transfection of βTC-3 cells. None of these Slc30a8 promoter regions enhanced reporter gene expression beyond that driven by the TK-luciferase fusion gene alone, regardless of orientation (Supplementary Figure 3, see section on supplementary data given at the end of this article). Similarly, when ligated 5’ of a heterologous G6PC2-luciferase fusion gene containing the proximal human G6PC2 promoter sequence between −150 and +3, again relative to the transcription start site, none of these Slc30a8 promoter regions enhanced reporter gene expression beyond that driven by the −150/+3 G6PC2-luciferase fusion gene alone, regardless of orientation (Supplementary Figure 3, see section on supplementary data given at the end of this article). These data suggest that none of these promoter regions are enhancers.

**A conserved islet β cell-specific enhancer is located in the second intron of the SLC30A8 gene**

Intronic enhancers have previously been identified in several genes whose expressions are enriched in islets including those encoding glucagon (Zhou et al. 2006), islet amyloid polypeptide (Ekawa et al. 1997), and G6pc2 (Wang et al. 2008). We also recently identified an intronic enhancer located between +20 125 and +20 745 in intron 2 in the mouse Slc30a8 gene (Pound et al. 2010). A sequence alignment using the VISTA program shows that this region is conserved and found at a location between +16 333 and +16 954 in intron 2 in the human SLC30A8 gene (Fig. 4).

**Figure 3** The putative human SLC30A8 and mouse Slc30a8 promoter regions are able to drive reporter gene expression in stable but not transient transfection experiments. (A and B) βTC-3 cells were transiently co-transfected, as described in the Materials and methods section, with the empty pGL3 vector or the indicated human SLC30A8 (A) or mouse Slc30a8 (B) promoter-firefly luciferase fusion genes (2 μg) and an expression vector encoding Renilla luciferase (0.5 μg). Following transfection, cells were incubated for 18–20 h in serum containing medium and then harvested and luciferase activity assayed. Results are presented as the ratio of firefly:Renilla luciferase activity, expressed relative to the ratio obtained with the empty pGL3 vector, and represent the mean ± S.E.M. of three experiments each using an independent preparation of all fusion gene plasmids with each plasmid assayed in triplicate. *P < 0.05. (C and D) βTC-3 cells were transfected with the empty pGL4 vector or the indicated human SLC30A8 (C) or mouse Slc30a8 (D) promoter-firefly luciferase fusion genes (2 μg). Following transfection, cells were incubated for 18–20 h in serum containing medium after which cells were incubated with media containing 500 μg/ml hygromycin. After 3–4 weeks, or until individual colonies could be visualized, colonies were pooled using trypsinization, transferred to 10 cm dishes, and hygromycin treatment was discontinued. Once the cells had reached confluence, luciferase activity in the pooled cultures was then assessed and the Pierce BCA protein assay used to correct for variations in protein content. Results are presented as the ratio of firefly activity to protein content in the cell lysate, expressed relative to the ratio obtained with the empty pGL4 vector, and represent the mean ± S.E.M. of three experiments each using an independent preparation of all fusion gene plasmids with each plasmid assayed in triplicate. *P < 0.05.
Cells (Fig. 1) are overlapping but distinct. These data demonstrate that this region is an islet-specific enhancer and suggest that the mechanisms controlling SLC30A8 expression in α and β cells (Fig. 1) are overlapping but distinct.

Discussion

In this study, we show that the human SLC30A8 gene, like the mouse Slc30a8 gene, is expressed in both pancreatic islet α and β cells (Fig. 1) and we identify a conserved SLC30A8 promoter region that drives fusion gene expression in stable, though not transient, transfections (Figs 2 and 3). Though it is uncommon for promoters/enhancers to require a precise chromatin context to function, several examples do exist (Smith & Hager 1997). In addition, we have identified a conserved islet β cell-specific enhancer in SLC30A8 intron 2 (Figs 4 and 5). A SNP, rs62510556, within this enhancer affects the binding of an unknown transcription factor and modulates enhancer activity (Supplementary Figure 4, see section on supplementary data given at the end of this article); however, genetic analyses suggest that, in Europeans, rs62510556 is not a causal variant that contributes to the association between SLC30A8 and T2D (Supplementary Table 1, see section on supplementary data given at the end of this article). Future studies will examine whether an association exists in other populations. Thus, the

Figure 4 Identification of a highly conserved region within intron 2 of the human SLC30A8 and mouse Slc30a8 genes. A VISTA browser plot (Frazer et al. 2004) comparing the human SLC30A8 and mouse Slc30a8 gene sequences between exons 2 and 3 is shown. The level of conservation is indicated on the vertical axis. Conserved regions above 70%/100 bp are highlighted in gray. Exons 2 and 3 and the putative intron 2 enhancer (Enh) are boxed.

Fusion gene analyses showed that the mouse Slc30a8 enhancer in intron 2 was selectively active in BTC-3 but not in αTC-6 cells, indicating that this region is an islet β cell-specific enhancer (Pound et al. 2010). To determine whether the +16 579 and +16 954 region of intron 2 in the human SLC30A8 gene also represents a transcriptional enhancer, this region was isolated using PCR and ligated 5′ of the −150/+3 G6PC2-luciferase fusion gene described above. Luciferase expression directed by this fusion gene was then analyzed by transient transfection of βTC-3 and αTC-6 cells. Figure 5A shows that, in βTC-3 cells, this region elevated reporter gene expression beyond that driven by the −150/+3 G6PC2-luciferase fusion gene alone. This effect was dependent on orientation (Fig. 5A), which is not consistent with the strict definition of an enhancer (Blackwood & Kadonaga 1998). However, it is likely that, because of its close proximity to the G6PC2 promoter, this SLC30A8 enhancer is affecting transcription factor binding to the heterologous G6PC2 promoter in a manner that is different to the mechanism by which it affects SLC30A8 promoter activity from its native location in SLC30A8 intron 2. Strikingly, Fig. 5B shows that, in αTC-6 cells, this region did not elevate reporter gene expression beyond that driven by the −150/+3 G6PC2-luciferase fusion gene alone. These data demonstrate that this region is an islet β cell-specific enhancer and suggest that the mechanisms controlling SLC30A8 expression in α and β cells (Fig. 1) are overlapping but distinct.

Figure 5 Analysis of the transcriptional enhancer activity of the highly conserved region within intron 2 of the human SLC30A8 gene in the context of the G6PC2 promoter. βTC-3 (A) and αTC-6 (B) cells were transiently co-transfected, as described in the Materials and methods section, with the indicated firefly luciferase fusion genes (2 μg) and an expression vector encoding Renilla luciferase (0.5 μg). The fusion genes represent the enhancerless human G6PC2 promoter-luciferase vector (V) or the SLC30A8 intron 2 sequence between +16 579 and +16 954 ligated to the human G6PC2 promoter-luciferase vector in the correct (C) or inverted (I) orientation relative to the endogenous SLC30A8 gene. Following transfection, cells were incubated for 18–20 h in serum-containing medium and then harvested and luciferase activity assayed. Results are presented as the ratio of firefly:Renilla luciferase activity, expressed relative to the ratio obtained with the enhancerless G6PC2 heterologous vector, and represent the mean±S.E.M. of three experiments each using an independent preparation of all fusion gene plasmids with each plasmid assayed in triplicate. *P<0.05.
rs13266634 SLC30A8 variant, which changes amino acid 325 of human ZnT-8, is associated with T2D risk in Asians and Europeans, but not in Africans (Xu et al. 2011). Similarly, a variant, rs560887, in the G6PC2 gene has been associated with increased susceptibility to the development of T2D in some populations (Hu et al. 2009, 2010, Reiling et al. 2009) but not others (Dupuis et al. 2010). These observations emphasize the importance of assessing the potential causative involvement of SNPs and genes in multiple populations.

While genetic data have strongly linked the SLC30A8 gene to increased susceptibility to the development of T2D in several, though not all, human populations (Xu et al. 2011), the manner in which defects in ZnT-8 expression or function lead to islet dysfunction and hence diabetes is unclear. While the SLC30A8 rs13266634 variant has been reported to affect zinc transport by ZnT-8 in cultured cells (Nicolson et al. 2009), it does not affect glucose-stimulated insulin secretion from isolated human islets (Cauchi et al. 2010). However, this may simply relate to the small number of human islets examined (Cauchi et al. 2010) and the relatively small contribution of the SLC30A8 rs13266634 variant to diabetes risk (Saxena et al. 2007, Scott et al. 2007, Sladek et al. 2007, Zeggini et al. 2007). Surprisingly, though, studies in genetically modified mice, in which more significant changes in Slc30a8 expression can be achieved, have also failed to demonstrate a critical role for ZnT-8 in the control of glucose metabolism. Thus, mice in which the Slc30a8 gene was globally deleted have normal glucose tolerance (Lemaire et al. 2009, Nicolson et al. 2009, Pound et al. 2009) and mice with a β cell-specific Slc30a8 gene deletion have only mildly impaired glucose tolerance (Wijesekara et al. 2010). These observations suggest that either ZnT-8 is more important for the control of glucose metabolism in humans than mice or defects in glucose metabolism will only become apparent in older mice or mice harboring disease-associated variants in additional susceptibility genes. The latter possibilities appear more likely since the absence of ZnT-8 clearly affects β cell function, as apparent from the observed reduction in fasting plasma insulin in mice lacking ZnT-8 as well as glucose-stimulated insulin secretion and zinc content in islets isolated from those mice (Pound et al. 2009). Among these changes, the reduction in islet zinc content is quantitatively the most dramatic and also surprising, in relation to the mild metabolic phenotype observed, given the abundant literature supporting a key role of zinc in the proper maturation, storage, and secretion of insulin (Wijesekara et al. 2009). If future studies reveal that no association exists between rs62510556 and T2D, regardless of the population studied, this may indicate that the rs62510556 SNP does not change SLC30A8 expression sufficiently in vivo to have a biological effect or that the presence of a variant form of ZnT-8, as manifest by the rs13266634 SNP, increases T2D risk in some populations whereas changes in SLC30A8 expression do not. This last possibility is particularly intriguing given the very mild phenotype of Slc30a8 knockout mice since it would raise the interesting concept that perhaps it is the presence of a mutant form of ZnT-8 that causes problems with β cell function whereas the absence of ZnT-8, as manifest in Slc30a8 knockout mice, is less deleterious.

The mild phenotype observed in Slc30a8 knockout mice may also be partly explained by the existence of unknown compensatory changes that have occurred during development to offset the absence of ZnT-8. Indeed, using an shRNA-mediated approach to down-regulate Slc30a8 mRNA expression by >90% in the INS-1 pancreatic β cell line, Fu et al. (2009) demonstrated diminished uptake of exogenous zinc, reduced insulin content, and decreased glucose-stimulated insulin secretion. They also predicted that SNPs that affect SLC30A8 expression, such as the one reported here, would have the potential to affect insulin secretion and the glycemic response in vivo (Fu et al. 2009).

In summary, these experiments have shown that the human SLC30A8 genomic region located between −6154 and −1, relative to the translation start site, contains a promoter that is only active in stable and not transient transfections. In addition, the human SLC30A8 genomic region located between +16579 and +1954 in intron 2 contains a conserved islet β cell-specific enhancer. Given the critical role of ZnT-8 in islet zinc metabolism and the association between SLC30A8 and T2D risk, it is possible that SNPs that affect SLC30A8 expression, rather than ZnT-8 function, may also influence T2D risk. While we find that a SNP, rs62510556, in the conserved intron 2 enhancer, which modulates enhancer activity, is not associated with T2D risk, at least in Europeans, it is possible that future studies may uncover rare SNPs with a more pronounced effect on SLC30A8 expression that do influence T2D risk.

Supplementary data

This is linked to the online version of the paper at http://dx.doi.org/10.1530/JME-11-0055.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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References


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