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Identification of Minimal Promoter and Genetic Variants of Kruppel-like Factor 11 Gene and Association Analysis with Type 2 Diabetes in Japanese

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Abstract. Genetic analysis of the KLF11 gene revealed two rare variants, A347S and T220M, segregating in families with early-onset type 2 diabetes, and one frequent polymorphic Q62R variant significantly associated with type 2 diabetes in Northern Europeans. Furthermore, it has been reported that over-expression of KLF11 has a deleterious effect on insulin promoter activity. Thus, an altered expression level of KLF11 may contribute to the occurrence of type 2 diabetes. To investigate the contribution of KLF11 to type 2 diabetes in Japanese, we surveyed the 5' flanking region of *KLF11* by reporter assay and identified the minimal promoter region of the gene. The promoter region from –250 to +162 bp including five Sp1 binding sites showed basal promoter activity both in MIN6-m9 and HepG2 cells. We also examined the entire region of *KLF11* to detect genetic variants. A total of 19 polymorphisms, six of which are novel, were identified, but none of them showed association with the occurrence of type 2 diabetes. Two of the identified polymorphisms, R29Q and S124F, are novel coding variants. Functional analyses of these variants were performed, and similarly reduced effects on transcriptional activities of insulin, catalase1, and the Smad7 gene were found. We conclude that variants of *KLF11* are not a major factor in the occurrence of type 2 diabetes in Japanese. The promoter region of *KLF11* identified in the present study should be useful in further elucidation of the transcriptional regulation mechanism of the gene and genetic analyses of type 2 diabetes.

Key words: KLF11, SNP, association study, promoter, type 2 diabetes

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KRUPPEL-LIKE transcription factor (KLF)11 (also known as TIEG2) is a member of the Sp1-like transcription factor family, which is defined by the presence of three conserved DNA-binding C-terminal zinc finger domains and variant N-terminal domains [1–4]. In contrast with Sp1, one of the best–characterized transcriptional activators, KLF11 behaves as a potent transcriptional repressor. KLF/Sp1-like transcription regulation may participate in many aspects of cellular function, including cell proliferation, apoptosis, differentiation, and neoplastic transformation [5–8].

The KLF11 gene is located at chromosome 2p25 [9], and is ubiquitously expressed in human tissues with an abundance in pancreas and muscle [4]. KLF11 has elicited significant attention due to its role as a negative regulator of exocrine cell growth by decreasing growth and increasing apoptosis via a mechanism that involves down-regulation of the oxidative stress genes SOD2 and catalase1 [10], which also are expressed in pancreatic islets, and an increased susceptibility to oxidative insult [11]. The Smad-regulated transcriptional pathway plays a central role in TGF-β

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induced cell growth inhibition [12]. Smad signaling activity is potentiated by KLF11 in normal epithelial cell lines through termination of the negative feedback loop imposed by Smad7, which requires binding to GC-rich promoter boxes of the Smad7 promoter [13], and the TGF-β signaling pathway is a major regulator of endocrine cell fate [14–16].

The role of KLF11 within the endocrine pancreas remains to be elucidated. Recently, Neve *et al.* reported that KLF11 binds to the insulin promoter and up-regulates its activity in beta-TC3 cells. Genetic analysis of *KLF11* revealed two rare variants (Ala347Ser and Thr220Met) that segregate with diabetes in families with early-onset type 2 diabetes (T2DM) and significantly impair its transcriptional activity [17]. On the other hand, Niu *et al.* reported that over-expression of hKLF11 inhibits the activity of human insulin promoter in INS-1E and beta-TC3 cells in a dose-dependent and glucose-independent manner [18]. Furthermore, it has been reported that a *KLF11* promoter variant has a deleterious effect on insulin sensitivity via STAT3-mediated up-regulation of *KLF11* [19]. Thus, an altered expression level of KLF11 may contribute to the occurrence of type 2 diabetes.

In this study, we surveyed the 5' flanking region of *KLF11* and identified the minimal promoter region of the gene, which should be useful in further genetic and functional analyses of type 2 diabetes. We also examined all of the regions of *KLF11* in twelve Japanese subjects to detect genetic variants, evaluated the pattern of linkage disequilibrium to infer haplotypes in the gene, and performed association studies with type 2 diabetes patients.

Material and Methods

Subjects

A total of 182 Japanese subjects with clinical diagnosis of early-onset type 2 diabetes (70 males and 112 females; onset age 11.9 ± 3.1 yr, BMI, 23.9 ± 6.2 kg/m^2; onset HbA1c 8.8 ± 3.1%, HbA1c 7.1 ± 2.3%) were screened for mutations by direct sequencing of PCR products. Patients with glutamic acid decarboxylase (GAD) antibodies and other types of diabetes were excluded on the basis of clinical data.

A total of 553 Japanese patients with late-onset T2DM [310 males and 243 females; age at testing, 61.1 ± 10.6 yr; BMI, 23.9 ± 4.1 kg/m^2; glycosylate hemoglobin (HbA1c), 7.7 ± 3.5%] and 563 control (224 males and 339 females; age at testing 67.4 ± 6. yr; BMI, 22.9 ± 2.9 kg/m^2; HbA1c, 5.0 ± 0.4%) wer examined for association study. The diagnosis c T2DM was based on medical records or 75 g ora glucose tolerance test according to the criteria of th Japan diabetes Society [20]. Informed consent wa obtained from all of the diabetic subjects and voluntee controls. The study was approved by the ethics com mittee of Gifu University.

SNP identification in KLF11

Genomic DNA was extracted from samples c whole blood using QIAamp DNA blood kit (QIAGEN Hilden, Germany) according to the manufacturer instructions. Twelve of the random control sample (24 alleles) were used to detect SNPs in *KLF11*. Prin ers for PCR experiments were designed by Primer (available from http://www.genome.wi.mit.edu/cg bin/primer/preimer3 www.cgi) on the basis of the g nomic contig sequence (GenBank ID: NT_005334.1 nt 5016199–5029771 bp) of the *KLF11* region. Th mixture for PCR was 20 μl in 10 ng template DNA 0.5 mM of each dNTP, 2.5 pmol of each forward an reverse primer, 0.5 U ExTaq polymerase (Takar Kyoto, Japan), and 2 μl of 10 × PCR buffer or 0.4 KOD FX (TOYOBO, OSAKA, JAPAN) and 10 μl 2 × PCR buffer for KOD FX. The reaction conditio with Ex Taq polymerase were an initial denaturatio step of 94°C for 1 min and a subsequent 35 cycles reaction at 94°C for 30 sec, 60°C for 30 sec, and 72° for 1 min; the reaction conditions with KOD FX we an initial denaturation step of 94°C for 2 min and subsequent 35 cycles of reaction at 98°C for 10 se 60°C for 30 sec, and 68°C for 1 min. After purific tion, each PCR product was subjected to cycle s quencing with BigDye Terminator cycle sequencin FS (Applied Biosystems, Foster City, CA) using ea forward and reverse primer. Reaction products we purified by ethanol precipitation and sequenced b ABI PRISM 3130 sequencer (Applied Biosystems).

Estimation of haplotype frequencies and evaluation o pattern of LD in KLF11

Haplotypes comprising tag SNPs and haplogen types were inferred by the expectation-maximizati

method by Haploview (http://www.broad.mit.edu/personal/jcbarret/haploview) and PHASE 2.1.1 (http://www.stat.washington.edu/stephens/software.html), respectively.

Mutation screening and genotyping of frequent polymorphisms in KLF11

We examined all of the coding regions and the putative promoter region of *KLF11* in 182 early-onset T2DM, 96 of the 553 late-onset T2DM patients (56 males and 40 females; age 63.2 ± 11.0 yr, BMI, 24.5 ± 5.4 kg/m^2; HbA1c 7.9 ± 1.6%) and 96 of 563 control subjects (35 males and 61 females; age 67.6 ± 5.8 age yr; BMI, 22.8 ± 2.8 kg/m^2; HbA1c 4.9 ± 0.3%). We performed an additional screening for R29Q and S124F mutations in all late-onset T2DM patients and controls.

Association study was performed for tag SNPs (SNP2, -3, -5, -6) in the promoter region with 96 subjects each from 552 late-onset T2DM and 563 controls by direct sequencing. As it was extremely difficult to amplify the promoter region due to its high GC content, only 96 subjects from each group were examined. Association study for tag SNP 13 (rs6432053) was performed in the 552 late-onset T2DM patients and 563 controls by TaqMan assay (Applied Biosystems) on an ABI PRISM 7900HT sequence detector (AppliedBiosystems). Thermal cycling conditions followed the manufacturer's instructions.

Cell lines

MIN6-m9 cells were maintained in DMEM containing 25 mM glucose, 10% heat-inactivated FBS, 50 mM 2-mercaptoethanol, 100 mg/l streptomycin sulfate, and 60.5 mg/l penicillin G under a humidified condition of 5% CO2-95% air at 37°C [21]. HepG2 cells were maintained in DMEM supplemented with 10% heat-inactivated FBS, 100 mg/l streptomycin sulfate, and 60.5 mg/l penicillin G under a humidified condition of 5% CO2-95% air at 37°C.

Identification of the minimal promoter region of human KLF11

To establish the promoter activity of the 5' flanking region of *KLF11*, we designed luciferase expression vectors including a series of 5' deletion fragments. Three different length fragments, from −1389 to +162 bp, −896 to +162 bp and −250 to +162 bp relative to the transcription start site, were prepared by PCR and inserted into the firefly luciferase reporter vector, pGL4.12-Basic (Promega, Madison, WI). The MIN6-m9 cells or HepG2 cells were seeded in 6-well culture plates. The confluency was 50–70% at the time of transfection. The reporter constructs (500 ng) were transfected to cells by using a ExGEN 500 *in vitro* Transfection Reagent (Fermentas, St. Leon-Rot, Germany). Transcriptional activity was normalized with a co-transfected control thymidine kinase (TK)-regulated Renilla luciferase vector, pRL-TK 17 ng (Promega). Transactivation activity was measured using Dual-Luciferase Reporter Assay system (Promega).

Subcloning of human KLF11 and variants

A cDNA identical to *KLF11* was retrieved from a human islet cDNA library and subcloned in pENTR/D-TOPO (Invitrogen, Carlsbad, CA) after amplification with Pfu (Stratagene, La Jolla, CA) and transferred for expression to pcDNA6.2-DEST (Invitrogen). The R29Q and S124F mutations were introduced by site-directed mutagenesis (Stratagene, La Jolla, CA) with pENTR/d-TOPO wild-type *KLF11* as template and confirmed by sequencing.

Functional analysis of KLF11 mutant proteins

The reporter constructs for insulin, catalase1, or Smad7 promoter-pGL3 were prepared by cloning the human insulin (−365 ~ +40 bp) [18], catalase1 (−734 ~ +11 bp) [10], or Smad7 (−836 ~ +74 bp) [11] gene promoter into the pGL3-Basic vector (Promega, Madison, WI). The MIN6-m9 cells (1×10^5 cells/well) were seeded in 6-well culture plates. The confluency was 50–70% at the time of transfection. Constructed plasmids, pcDNA6.2 wild-type hKLF11, or pcDNA6.2 mutant-type hKLF11 and each reporter construct were transfected to MIN6-m9 cells using ExGEN 500 *in vitro* Transfection Reagent (Fermentas, St. Leon-Rot, Germany). Transcriptional activity was normalized with a co-transfected control thymidine kinase (TK)-regulated Renilla luciferase vector, pRL-TK (Promega). Transactivation activity was measured using Dual-Luciferase Reporter Assay system (Promega).

Statistical analyses

Statistical difference in allele frequencies between late-onset T2DM and control subjects was assessed by χ^2 test or logistic regression analysis adjusted for relevant covariates, and other categorical clinical variables were compared using *t* test. Statistical analysis was performed with StatView 5.0 software (SAS Institute, Inc., Cary, NC). Comparison of estimated haplotype frequencies was performed by conducting separate one-degree of freedom tests for a series of 2 × 2 contingency tables testing the frequency of each specific haplotype vs all others between cases and controls, and omnibus testing of differences in haplotype frequency profiles between the cases and controls (statistical significance assessed empirically via permutation testing with PHASE 2.1.1 software). The present study had about 33–50% power to detect an OR of 1.20 when the frequency of a risk allele was 10–20% and *P*-value was less than 0.05 under a multiplicative model with 553 patients and 563 controls, while it had only 10–13% power to detect an OR of 1.20 when the frequency of a risk allele was 10–20% and *P*-value was less than 0.05 under a multiplicative model with 96 each of patients and controls.

Results

Identification of polymorphisms in KLF11

Twelve of the random controls were examined to detect genetic variations in the entire region of *KLF11* including all 4 exons. A total of 17 polymorphisms, four of which are novel, were found as shown in Table 1; the locations of these polymorphisms are shown in Fig. 1 in relation to the genomic structure of *KLF11*. The additional two variants, R29Q and S124F were found by screening a large number of type 2 diabetic patients. Two coding variants, R29Q and S124F, are novel. In the 1552 bp (from −1389 to +162 bp) region of the *KLF11* promoter, a total of seven polymorphisms including four novel ones were identified.

Table 1. Polymorphisms identified in *KLF11* region in this study

SNP No.	Position genome	db SNP ID	Variation	Location	Frequencies of minor allele
1	−1348	rs4669520	G>A	5' flanking	0.134
2	−1025	rs35035311	ins G	5' flanking	0.132
3	−530	novel	(CCG)*	5' flanking	4: 0.744 2: 0.139 5: 0.117
4	−499	novel	del (CCCCGCCG)	5' flanking	0.114
5	−446	novel	del/ins (CCCCCTCCG)	5' flanking	0.276
6	−278	novel	del/ins (GGCCGGGCACG)	5' flanking	0.138
7	−86		del/ins (GCC)	5' UTR	0.128
8	1467	rs6717092	C>G	Intron 1	0.136
9	2477	novel	G>A (R29Q)	Exon2	n.d
10	3992	novel	C>A (S124F)	Exon3	n.d
11	4806	rs11687357	T>A (V395V)	Exon3	0.133
12	5856	rs6432052	C>T	Intron 3	0.129
13	5992	rs6432053	T>C	Intron 3	0.268
14	6272	rs6721191	G>A	Intron 3	0.128
15	6741	rs4614909	T>A	Intron 3	0.263
16	8199	rs2487	T>C	Intron 3	0.135
17	10349	rs4669522	C>T	3' UTR	0.145
18	10644	rs7632	C>T	3' UTR	0.274
19	11224	rs6432055	C>T	3' flanking	0.259

*Triallelic variant with 2, 4, 5 CCG repeats. The nucleotide indicates the location of the SNP relative to the A of ATG of the initiator Met of KLF11 (GenBank No. NT_005334.15). The frequencies of minor alleles in this table are observed in 96 random control samples except SNP 9, and 10. n.d; not detected.

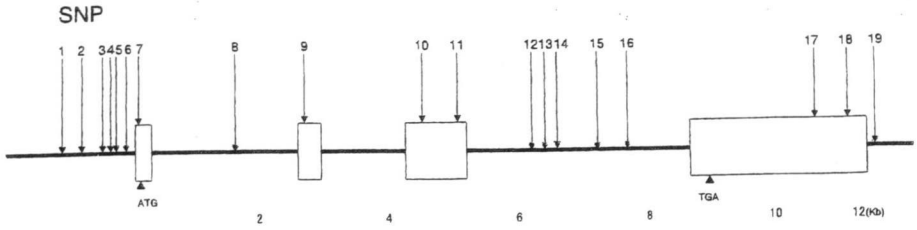

Fig. 1. Polymorphisms of *KLF11* identified in this study. The locations of the polymorphisms described in the text are shown. Nucleotide indicates the location of the SNP relative to the A of ATG of the initiator Met of KLF11.

Table 2. Frequencies of coding SNPs in *KLF11* in controls and in patients with T2DM

SNP No.	Position genome	db SNP ID	Nucleotide change	Exon	minor allele number		
					Controls (n = 563)	Late-onset T2DM (n = 553)	Early-onset T2DM (n = 182)
9	2477	novel	G>A (R29Q)	2	1	3	2
10	3922	novel	C>A (S124F)	3	0	0	1
11	4806	rs11687357	T>A (V395V)	3	26 (n = 96)	21 (n=96)	56

The nucleotide indicates the location of the SNP relative to the A of ATG of initiator Met of KLF11

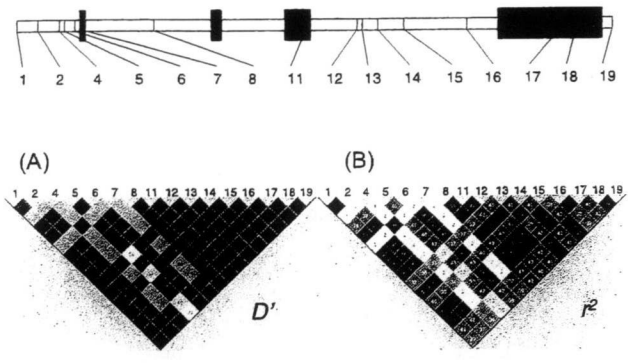

Fig. 2. Pairwise LD of *KLF11* evaluated by D' and r^2. The panel shows a Haploview representation of LD (D' and r^2) based on genotyping data with 16 polymorphisms from control subjects (n = 96) (A) Pairwise combination with LD of $D' = 1$ and LOD≥2, $D' = 1$ and LOD<2, $D'<1$ and LOD≥2, $D'<1$ and LOD<2 is shown with red, blue, pink and white. (B) Pairwise combination with LD of $r^2 = 1$, $0<r^2<1$, $r^2=0$ is shown in black, gray and white.

Evaluation of the pattern of LD in KLF11

Sixteen polymorphisms with frequencies of more than 10% were used to define haplotypes and to evaluate the pattern of LD. As shown in Fig. 2, the single, large LD block appears in this region. Haplotype combinations were estimated with 96 control subjects. Four major haplotypes comprising tag SNPs (SNP-2, -3, -5, -6, -and -13) were inferred in the entire *KLF11* region.

Mutation screening of KLF11 and association study in T2DM patients

All exons and the putative promoter region (–1389 to +162 bp) of *KLF11* were examined in 182 early-onset T2DM patients, 96 late-onset T2DM patients, and 96 control subjects. A total of 3 cSNPs (R29Q, S124F and V395V), two of which, R29Q and S124F, are novel, were found (Table 2). R29Q mutation was found in five T2DM (3 from late-onset and 2 from early-onset) patients and in one control (Fisher's P-value = 0.245). S124F mutation was found in one early-onset T2DM patient and was not found in controls. An association study using tag SNPs in T2DM patients was performed, but no association of *KLF11* variants with T2DM was found (Table 3A & B). No haplotypes were found to be susceptible to T2DM by χ^2 test. Using permutation testing (100 permutations), no significant differences in haplotype frequencies between control and T2DM were found (Table 4).

Functional analysis of KLF11 mutant proteins

The results of alignment by CLUSTALW show that R29 of KLF11 is conserved among human, mouse, and rat, while S124 is not conserved (Fig. 3). The transcriptional activity of the R29Q and S124F mutants of KLF11 were therefore compared with that of wild type

Table 3A. Association study using tag SNPs in *KLF11* in patients with late-onset T2DM and controls

SNP		Frequencies of genotype			Frequencies of alleles		allele		genotype		dominant		recessive	
		Control	T2DM		Control	T2DM	χ^2	*P*	χ^2	*P*	χ^2	*P*	χ^2	*P*
2	W/W	0.747	0.773	W	0.868	0.882	0.159	0.689	0.237	0.888	0.208	0.647	0.006	0.936
	W/M	0.242	0.214	M	0.132	0.117								
	M/M	0.01	0.011											
5	W/W	0.564	0.492	W	0.724	0.725	0.0003	0.984	4.81	0.09	0.755	0.384	2.684	0.101
	W/M	0.320	0.464	M	0.276	0.274								
	M/M	0.115	0.042											
6	W/W	0.734	0.732	W	0.861	0.854	0.036	0.848	0.451	0.797	0.0005	0.982	0.436	0.508
	W/M	0.255	0.244	M	0.138	0.145								
	M/M	0.01	0.023											
13	W/W	0.486	0.505	W	0.707	0.698	0.224	0.636	0.517	0.772	0.042	0.839	0.517	0.472
	W/M	0.418	0.415	M	0.293	0.302								
	M/M	0.094	0.078											

Association study was performed for the SNPs (SNP2, 5, and 6) in the promoter region with 96 subjects each from 553 T2DM and 563 controls by direct sequencing, and for SNP (SNP13) in the 553 T2DM patients and 563 controls by TaqMan assay. M, Mutant; W, wild type.

Table 3B. Association study using tag SNPs in *KLF11* in patients with late-onset T2DM and controls

SNP3	Frequencies of genotype						*P**1
	1 1	1 2	1 3	2 2	2 3	3 3	
Control	0.515	0.252	0.178	0.021	0.021	0.010	0.297
T2DM	0.559	0.178	0.166	0	0.071	0.023	

SNP3	Frequencies of allele			*P**2
	1	2	3	
Control	0.731	0.157	0.110	0.491
T2DM	0.732	0.125	0.142	

SNP3	Frequencies of genotype		*P**3	Frequencies of genotype		*P**4
	2 2	non 2 2		3 3	non 3 3	
Control	0.021	0.978	0.181	0.010	0.989	0.489
T2DM	0	1		0.023	0.976	

SNP3	Frequencies of genotype		*P**5	Frequencies of genotype		*P**6
	2 2+1 2+2 3	1 1+1 3+3 3		3 3+1 3+2 3	1 1+1 2+2 2	
Control	0.294	0.705	0.502	0.210	0.789	0.418
T2DM	0.250	0.750		0.261	0.738	

Association study was performed for SNP3.

Allele 1 indicates 4 CCG repeats. Allele 2 indicates 2 CCG repeats. Allele 3 indicates 5 CCG repeats.

*1 Triallelic varient was analyzed in a 2 × 6 contingency table with genotype frequencies.

*2 Triallelic varient was analyzed in a 2 × 3 contingency table with allele frequencies.

*3 Analyses in the recessive model of 22 genotype vs. others.

*4 Analyses in the recessive model of 33 genotype vs. others.

*5 Analyses in the dominat model of 22 + 12 + 23 genotypes vs. 11 + 13 + 33 genotypes.

*6 Analyses in the dominat model of 33 + 13 + 23 genotypes vs. 11 + 12 + 22 genotypes.

Table 4. Major haplotypes and its combinations in *KLF11* and risk of late-onset T2DM

SNP	Haplotype frequencies		*P*-value
2 3 5 6 13	Control	T2DM	
1 1 1 1 1	0.59	0.57	0.463
1 1 2 1 1	0.127	0.125	0.504
1 3 1 1 2	0.113	0.129	0.985
2 2 2 2 2	0.119	0.113	0.640
Haplotype combination	**Risk (O.R.)**	**95% C.I.**	
1 1 1 1 1/1 1 1 1 1	1.29	0.71–2.35	
1 1 1 1 1/1 1 2 1 1	1.43	0.55–3.75	
1 1 1 1 1/1 3 1 1 2	0.60	0.26–1.36	
1 1 1 1 1/2 2 2 2 2	0.75	0.32–1.77	
1 1 2 1 1/1 1 2 1 1	0.32	0.03–3.19	
1 1 2 1 1/1 3 1 1 2	2.02	0.18–22.75	
1 1 2 1 1/2 2 2 2 2	0.19	0.02–1.67	
1 3 1 1 2/1 3 1 1 2	1.00	0.06–16.3	
1 3 1 1 2/2 2 2 2 2	6.38	0.75–54.13	

The haplotype frequencies were estimated from the genotype of 96 controls and 96 T2DM subjects. The O.R and 95% C.I. of each haplotype combination relative to the other haplotype combinations as a group are shown. The numbers 1 and 2 indicate major allele and minor allele (SNP 2, SNP 5, SNP 6, SNP 13). SNP 3; allele 1 indicates 4 CCG repeats, allele 2 indicates 2 CCG repeats, and allele 3 indicates 5 CCG repeats.

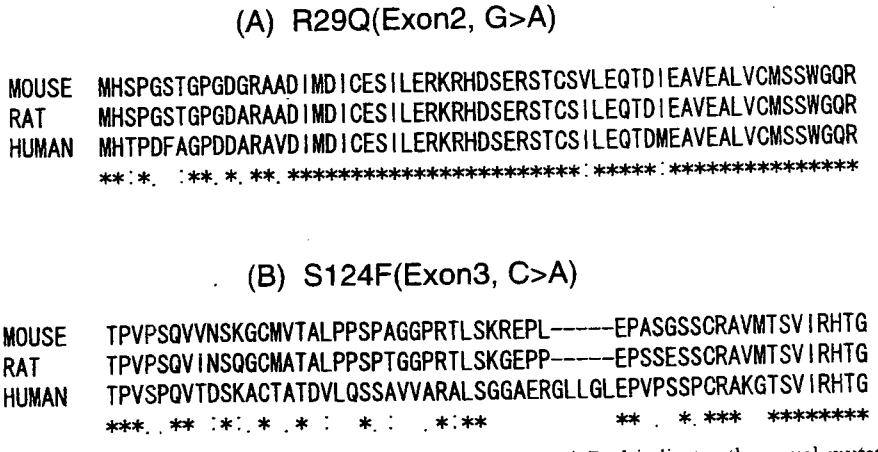

Fig. 3. The results of alignment of KLF11 among human, rat and mouse. A) Red indicates the novel mutation, R29Q, and blue indicates the region of SID. B) Red indicates the novel mutation, S124F, and blue indicates the region of R2. SID: mSin3A interaction domain; R2: transcriptional repression domain * completely conserved,: highly conserved,. moderately conserved.

KLF11. KLF11, catalase1, or Smad7 expression in MIN6-m9 cells was first confirmed, and all of these genes were endogenously expressed in both MIN6-m9 cells (data not shown). Wild-type KLF11 reduced all of these promoter activities to approximately 0.5-fold. Significantly reduced activity of R29Q mutant repression was found in catalase1 promoter, and reduced S124F mutant repression activity was found both in insulin and catalase1 promoter. However, the differences in activity between wild-type and these mutants of KLF11 were very small (Fig. 4).

Identification of the minimal promoter region of human KLF11

To identify the region essential for basal promoter activity of *KLF11*, the relative luciferase activity of the three sizes of 5' deletion reporter constructs was evalu-

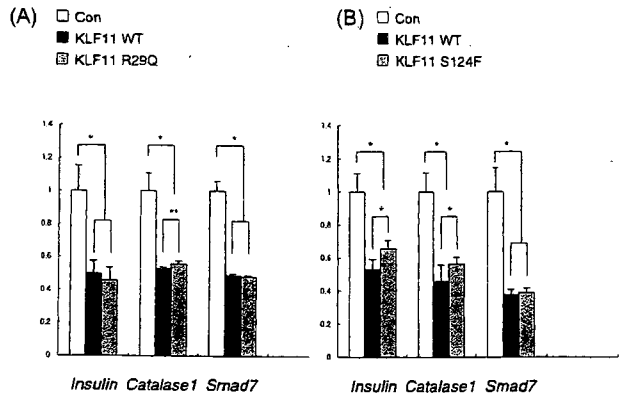

Fig. 4. Transactivation activity of mutant KLF11. Transcription activity with empty vector, wild type, and mutant KLF11 (500 ng) was analyzed by co-transfection assay using reporter vector of Insulin, Catalase-1 and Smad7 promoter-PGL3 (500 ng) and a Renilla luciferase (17 ng) as internal control. (A) The results of R29Q mutant (n = 6) (B) The results of S124F mutant (n = 6) Data are expressed as means ± SD.
*P<0.005, **P<0.05

ated. As shown in Fig. 5, the shortest promoter c struct comprising each of the four major haploty had basal activity both in MIN6-m9 cells and Hej cells, suggesting that the basal promoter is involve the region between −250 and +162 bp. The sec longest and longest promoter constructs had stror activity in HepG2 cells, suggesting that the esser enhancer element for promoter activity of *KLF1* incorporated in the region between −896 and −250 while the second longest and longest promoter c structs had similar activity in MIN6-m9 cells. On the promoter polymorphisms, SNP-4, is located at sixth Sp1 binding site from the transcription start and is not incorporated in one of the major haploty 1-3-1-1 (Table 4, Fig. 6). A significant differenc promoter activity between this haplotype and the o three major haplotypes was not detected in the moter assay in MIN6-m9 cells. One of the m haplotypes, 2-2-2-2, showed the highest transcripti activity with the longest and the second longest c structs (1.43 ± 0.046 fold, P = 0.0064; 1.28 ± 0 fold, P = 0.0069) (Fig. 5).

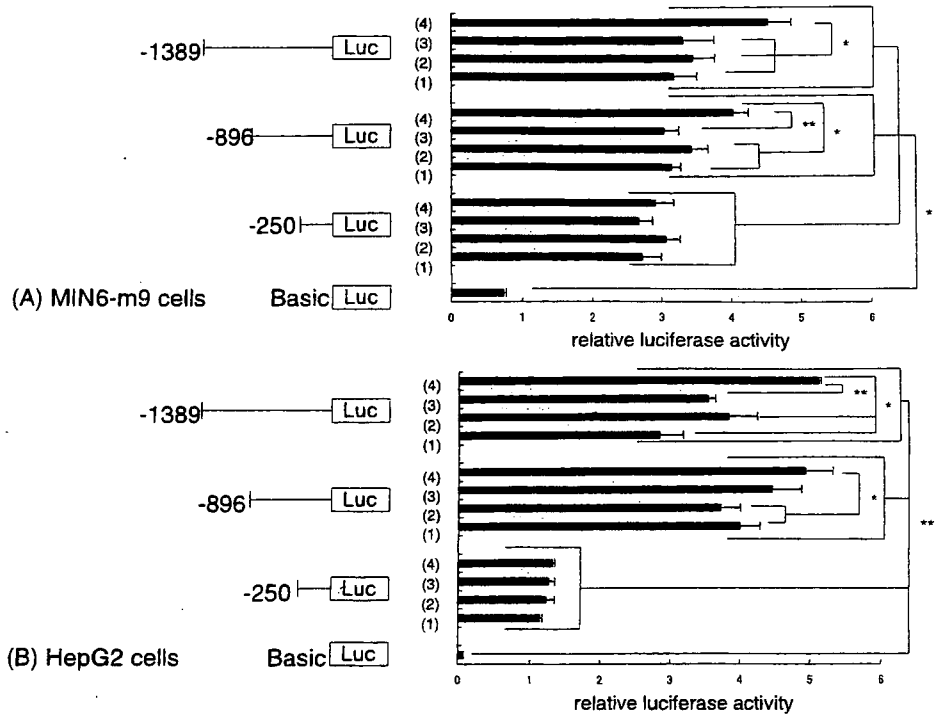

Fig. 5. Identification of *KLF11* promoter region using relative luciferase assays. The four haplotypes of the promoter regic indicated by (1) 1-1-1-1 (2) 1-1-2-1 (3) 1-3-1-1 (4) 2-2-2-2. The numerals 1 and 2 indicate major allele and minor allele 2, SNP 3, SNP 5, SNP 6). SNP 3, allele 1 indicates 4 CCG repeats, allele 2 indicates 2 CCG repeats, allele 3 indicates 5 repeats. (A) The result in MIN6-m9 cells (n = 3) (B) The result in HepG2 cells (n = 3). Results are expressed as means of a representative of experiments performed in triplicate. *P<0.05, **P<0.005

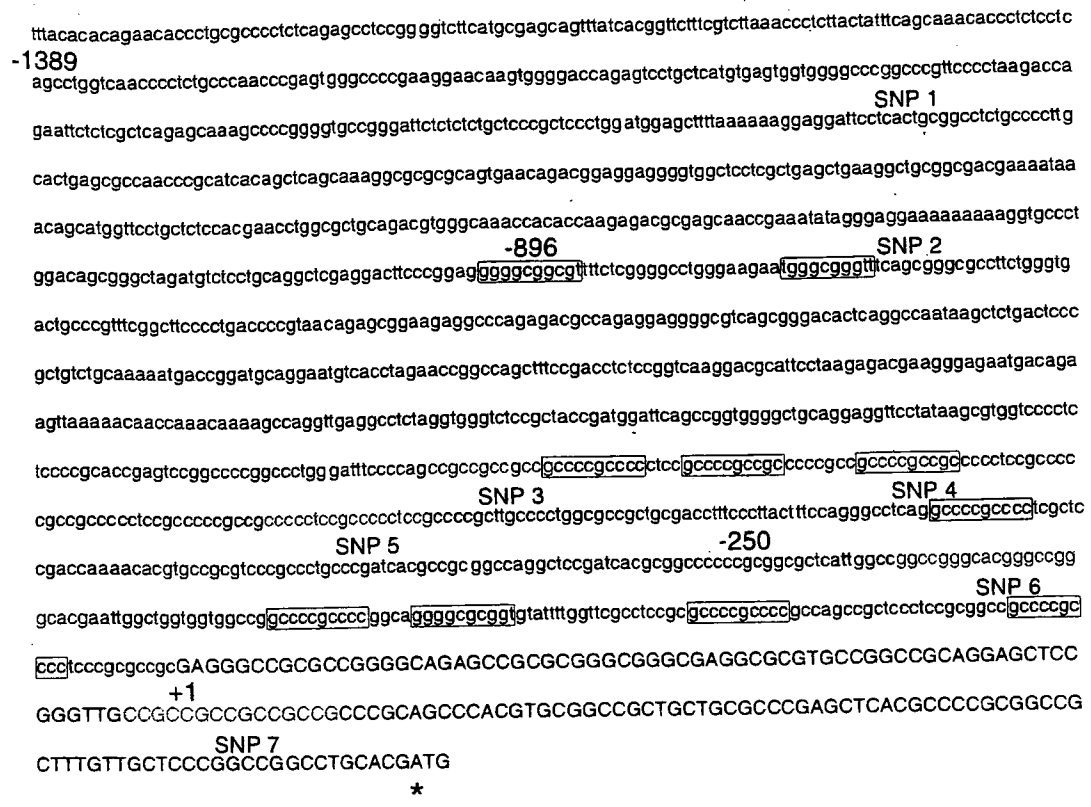

Fig. 6. Nucleotide sequence of the promoter region of *KLF11* from transcription start site to −1389 bp of 5' flanking region. Consensus sequences for Sp1 are boxed. Red color indicates the sites of polymorphisms. Large characters indicate 5' UTR region of *KLF11* and +1 denotes a transcription start site. Asterisk indicates the A of ATG of the initiator Met of KLF11.

Discussion

Genetic analysis of *KLF11* reveals two rare variants, A347S and T220M, which segregate in families with early-onset type 2 diabetes. In addition, analysis of 1,696 type 2 diabetic patients and 1,776 controls found one frequent polymorphic Q62R variant that significantly associates with late-onset type 2 diabetes in North European populations [17]. Florez *et al.* reported that KLF11 Q62R polymorphism is not associated with late-onset type 2 diabetes in 8,676 subjects of northern-European ancestry, and both A347S and T220M rare variants also are not found [22]. Recently, Ma *et al.* reported that neither Q62R nor any other common variant in *KLF11* was associated with late-onset type 2 diabetes in the Pima population [23]. Normoglycemic R62 carriers showed a significantly decreased plasma insulin level at 60 and 120 min after oral glucose load, leanness, and increased insulin sensitivity [17]. These characteristics clearly differ from those of Caucasian patients with T2DM, which are often caused by impaired insulin action mainly due to obesity. Obesity and insulin resistance are closely associated with type 2 diabetes in Caucasians, while type 2 diabetes in Japanese is characterized primarily by pancreatic beta-cell dysfunction [24, 25]. Thus, *KLF11* is a candidate diabetogenic gene in Japanese. Tanahashi *et al.* reported identification of eight variants, but were unable to find any missense mutation or association of common *KLF11* variants in late-onset Type2 diabetes in 1818 Japanese subjects [26].

In the present study, the minimal promoter region identified in this study, 5'UTR, coding region, 3'UTR, and flanking introns were screened for mutations in unrelated Japanese subjects with 182 early-onset and 96 late-onset T2DM patients. Our analysis revealed a novel missense mutation, R29Q (G>A), in exon 2 in two early-onset type 2 diabetes patients and three late-onset T2DM patients in the heterozygous state and S124F in exon 3 in one early-onset type 2 diabetes patient, but none of the A347S, T220M, Q62R, and promoter variant −1659G>C mutations previously

identified in Northern Europeans in *KLF11*.

We examined about 13 kb covering the entire coding region of *KLF11* and identified a total of 19 genetic variations including 6 novel variants. We defined haplotypes based on the LD pattern estimated using the 16 most frequent SNPs, the frequencies of which were more than 10%, and performed an association study with T2DM. No association of *KLF11* variants with T2DM was found and no haplotypes were found to show susceptibility to T2DM. We examined one variant, rs4073397, located 21 kb upstream from the coding region and outside of the LD block of the *KLF11* region, that shows a marginal association with T2DM in Japanese [26], but we could not replicate the association in this study with power similar to that of the former report ($P = 0.268$ and 0.576 for allele and genotype analysis, respectively; OR 1.2; RAF 0.5; $\alpha = 0.05$; $1-\beta = 63.9\%$).

We searched for consensus sequences of transcription factor binding sites in the promoter region by using TFSEARCH. As shown in Fig. 6, no TATA-box and ten Sp1 binding sites were found, but there were no differences in haplotype frequencies of the *KLF11* promoter region between T2DM patients and controls. It is of interest that one of the promoter polymorphisms, SNP-4, is located at the sixth Sp1 binding site from the transcription start site and that this binding site is not incorporated in one of the major haplotypes, but significantly reduced promoter activity of this haplotype was not detected by promoter assay in MIN6-m9 cells. One of the major haplotypes comprising all of the minor alleles showed the highest transcriptional activity with the longest and the second longest constructs. No association of the haplotype with occurrence of T2DM was found, but the findings are inconclusive due to the low statistical power of this study. In any case, the effect of the KLF11 expression level itself on the onset of type 2 diabetes should be slight, if any at all.

RT-PCR demonstrated endogenous KLF11 mRNA expression in whole rat pancreas, human pancreas, and mouse MIN6-m9 cells (data not shown). We therefore examined whether the KLF11 mutant affects transcriptional regulation of the human insulin gene. We found, contrary to Neve's report [17], that wild-type KLF11 inhibited insulin promoter activity as Niu *et al.* reported [18], but no difference in activity between wild and KLF11 mutants was found. Inhibition by wild-type KLF11 was similar in the three beta cell lines, INS-1E, beta-TC3 in the previous study, and MIN6-m9 in this study, indicating stable performance of KLF11 inhibition of insulin promoter activity in rodent beta cells.

KLF11 is involved in the TGF-β pathway, which plays a critical role in the development and homeostasis of exocrine and endocrine pancreas via Smad signaling [16, 27]. KLF11 may affect pancreatic beta cell function by modulating the expression of free radical scavengers such as superoxide dismutase (SOD) 2 and catalase1, recently identified as KLF11 target genes [10]. Oxidative stress is generally believed to be involved in the progression of pancreatic beta cell dysfunction found in T2DM [28, 29]. Since a decreased expression level of these antioxidant enzyme genes might contribute to the occurrence of type 2 diabetes, we examined the effects of the KLF11 R29Q and S124F variants on the expression levels of these target genes.

We then examined whether or not KLF11 mutants affect transcriptional regulation of the catalase1 and Smad7 genes. A significant but small difference in promoter activity between wild-type and R29Q mutant was found in catalase1 only. R29Q mutation is located 12 amino acids upstream of SID (mSin3A interaction domain)/R1 domain, which determines repression activity of KLF11 [10, 30–33]. This mutant of KLF11, although showing somewhat different activities in the catalase1 promoter, showed similar transcriptional activity compared with wild-type KLF11. Although it is inconclusive whether or not R29Q mutation contributes to the development of type 2 diabetes because of the small sample number in this study (Fisher's *P*-value = 0.245), our results suggest that the mutation does not contribute to the development of type 2 diabetes through alteration of the expression level of these target genes. No unusual clinical characteristics were found in subjects with R29Q mutation.

S124F mutation is located between the SID/R1 and R2 domain, and is not conserved among rat, mouse, and human, *i.e.*, proline for rat and mouse and serine for human. Similar data were obtained from S124F mutant of KLF11, which showed somewhat different activities in insulin and catalase1 promoters and similar transcriptional activity compared with wild-type KLF11, suggesting little biological effect. No useful clinical information was available for the patient with S124F mutant.

In this study, we focused on the effects of KLF11 on

beta cell function. In addition, the caveolin-1 gene, which is highly expressed in adipose tissue, is repressed by KLF11 in a cholesterol-dependent manner [34]. The findings that caveolin-1 binding to the insulin receptor stimulates both kinase activity and recruitment of the insulin receptor to lipid rafts at the plasma membrane, and that insulin receptor mutations impairing calveolin binding result in T2DM [35] indicate that caveolin-1 is essential for insulin signaling and suggest that KLF11 might affect insulin sensitivity as well.

In conclusion, we identified two novel missense variants of *KLF11* and the minimal promoter region of *KLF11*, but neither of the variants nor the haplotypes identified in this study was associated with the occurrence of type 2 diabetes in Japanese, although the findings are inconclusive due to the low statistical power of the study. Further investigation with a larger sample number is required to determine the magnitude of the contribution of the R29Q and S124F mutations to the development of diabetes and the role of KLF11 in normal pancreatic β-cell function. Identification of the minimal promoter region of *KLF11* should be useful in further elucidation of its transcriptional regulation mechanism.

Acknowledgments

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Hepatic overexpression of dominant negative Mlx improves metabolic profile in diabetes-prone C57BL/6J mice

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ABSTRACT

Mlx and ChREBP form a heterodimer to regulate glucose-mediated gene expression in the liver. This study was performed to determine if the metabolic syndrome might be improved using dominant negative Mlx (dnMlx). An adenovirus bearing dnMlx was constructed and used to test the inhibitory effect of dnMlx on lipogenesis both *in vitro* and *in vivo*. Adenoviral overexpression of dnMlx in rat hepatocytes inhibited expression of glucose-regulated genes, including *Chrebp* and *Transketolase*, which constitute a positive feedback loop in the regulation of *Chrebp* gene expression. Adenoviral overexpression of dnMlx in 25-week-old male C57BL/6J mice reduced hepatic triglyceride contents and improved glucose intolerance by inhibiting expression of *Glucose-6-phosphatase* and *Elovl6* mRNA in addition to lipogenic enzymes. In conclusion, overexpression of dnMlx improves glucose intolerance by inhibiting expression not only of lipogenic enzymes but also other important genes such as *Glucose-6-phosphatase* and *Elovl6*.

Nonalcoholic fatty liver disease is associated with metabolic syndrome and poses increased risk of cardiovascular disease. Development of non-alcoholic fatty liver disease is caused by decreased fatty acid oxidation and/or increased triglyceride synthesis. In the fed state, excess glucose uptake is converted to liver triglyceride storage. Hepatic *de novo* lipogenesis is regulated by insulin and glucose. Insulin and glucose induces glycolytic and lipogenic gene expression by sterol regulatory element binding protein (SREBP1c) and carbohydrate response element binding protein (ChREBP), respectively, [1,2]. Experiments in knockout mice indicate that SREBP1c and ChREBP exhibit *de novo* lipogenesis of 50% and 60%, respectively, [1]. Inhibition of these transcription factors reverses hepatic steatosis in obesity [1]. Thus, SREBP1c and ChREBP coordinately regulate hepatic lipogenesis. ChREBP heterodimerizes with Mlx to bind to the carbohydrate response elements (ChoRE) in the promoter of glycolytic and lipogenic genes [1].

We previously reported that gene deletion of ChREBP in ob/ob mice improved metabolic syndrome compared with ob/ob mice [3]. Consistent with our previous study, adenoviral delivery of ChREBP short hairpin RNA (shRNA) into the liver improved hepatic steatosis and insulin resistance by inhibiting hepatic lipogenesis [4]. In contrast, liver-specific inhibition of SREBP1c was found to improve hepatic steatosis but not glucose intolerance [1]. Liver-specific inhibition of PPARγ also improved hepatic steatosis, but increased glucose intolerance [1]. Clarification of the differences between ChREBP and SREBP1c or PPARγ in the development of the metabolic syndrome thus might facilitate development of clinical treatment options for the condition [1].

In this study, we investigate the mechanism of the improvement by liver-specific inhibition of ChREBP transactivity of glucose intolerance. An adenovirus bearing dominant negative Mlx (dnMlx) was constructed to test the transactivity of ChREBP *in vitro* and *in vivo*. Our findings in Ad-dnMlX-injected mice suggest that drugs disrupting the association between ChREBP and Mlx might be useful in preventing metabolic syndrome.

Materials and methods

Animals, isolation of rat primary hepatocytes, and cell culture. The protocols for all animal experiments were approved by the Institutional Animal Care and Use Committee of Gunma University Medical School (code no. 08-025). Six-week-old male Wistar rats were purchased from Japan SLC (Hamamatsu, Shizuoka, Japan) and male C57BL/6J mice were purchased from Charles River Japan (Yokohama, Kanagawa, Japan). Rat hepatocytes were isolated from 6-week-old male Wistar rats by the collagenase perfusion method. Isolated hepatocytes were suspended in DMEM supplemented with 10% fetal calf serum (FCS), 100 nM insulin, 100 nM dex, 10 nM T_3, and 100 μg/ml pen/strep [5]. Cells were seeded in 6-well plates or 10-cm dishes and grown in a humidified atmosphere of

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5% CO_2/95% air at 37 °C. After incubation for 4 h, the medium was replaced with DMEM containing 10 nM T_3.

Construction of plasmid and adenovirus vectors. PCR to construct pENTR vectors was performed using PrimeSTAR DNA polymerase (Takara) and primers (Sigma–Aldrich). A series of Mlx deletion mutants with an N-terminal Flag tag were amplified from mouse liver cDNA (Fig. 1A). PCR fragments (2–245aa, 67–245aa, and 88–245aa) were cloned into the pENTR vector (Invitrogen), yielding pENTR-Mlx1-1, -Mlx2-1, or -Mlx4-1, respectively. Adenovirus vectors bearing Mlx4-1 were constructed by recombining pENTR-Mlx4-1 vectors into pAd/CMV/V5-DEST using LR Clonase II Master Mix (Invitrogen) according to the manufacturer's protocol. The pcDNA6.2 vectors bearing Mlx1-1, Mlx2-1, or Mlx4-1 (pcDNA-Mlx1-1, pcDNA-Mlx2-1, or pcDNA-Mlx4-1, respectively) were constructed in the same manner as the adenovirus. pGL3-Lpk and Ad-daChREBP were the same vector and adenovirus used previously [5]. pGL4-TK-RLuc vector was purchased from Promega.

Treatment with recombinant adenovirus in rat hepatocytes. Rat isolated hepatocytes were cultured in 6-well plates in 2 ml of DMEM. Hepatocytes were infected with adenovirus bearing GFP, Mlx4-1, or dominant active ChREBP (daChREBP) at m.o.i. of 2, 10, or 50 for 2 h, media were removed, and infected cells were incubated in media with 2.5 or 25 mM glucose for 18 h. The cells were then collected and used for RT-PCR analysis.

RNA extraction and quantitative real-time PCR. Total RNA was extracted from hepatocytes or liver samples using an RNeasy Mini Plus kit (Qiagen) according to the manufacturer's protocol [5]. Taqman PCR probes for semi-quantitative RT-PCR were purchased from Applied Biosystems.

Mammalian transfection and reporter assay. Primary hepatocytes were cultured in 6-well plates in 2 ml of DMEM without antibiotics. The cells were transfected with Lipofectamine 2000 (10 μl), pGL3-Lpk (3.6 μg), or the series of pcDNA-Mlx vectors (empty, Mlx1-1, Mlx2-1, or Mlx4-1) (0.4 μg) and the pGL4-TK-Renilla luciferase vector (0.4 μg) [5]. After 24 h of incubation with 2.5 or 25 mM glucose, the cells were collected and used to measure luciferase activity (Dual Luciferase Assay System; Promega) according to the manufacturer's protocol.

Establishment of Ad dominant negative Mlx4-1-infected mice. Twenty-five-week-old male C57BL/6J mice were anesthetized with pentobarbital and injected *via* the tail vein with 3×10^{13} particle/kg body weight (BW) of Ad-GFP or Ad-Mlx4-1 in a final volume of 300 μl of phosphate buffered saline. After 5 days, the mice were sacrificed and the liver was used for extraction of total RNA and liver metabolites.

Measurement of plasma profile and liver metabolites and oral glucose tolerance test. Plasma concentrations of glucose, insulin, and triglyceride were measured as described previously [3]. Total cholesterol, alanine aminotransferase (ALT), and aspartate aminotransferase (AST) were measured using Cholesterol and Transaminase Wako test kits (Wako). Liver glycogen, triglyceride, and cholesterol contents were measured as described previously [3]. Oral glucose tolerance tests at 3 days were performed by oral injection of glucose at a dose of 1 g glucose/kg BW after 18-h fast. Blood glucose levels were measured at the designated times using a FreeStyle Kissei Meter (Kissei, Tokyo, Japan).

Data presentation and statistical methods. All data are expressed as means ± SD. The listed *n* values represent the number of single experiments performed (each experiment was duplicated). Comparisons between two groups were performed by Student's *t*-test, and $P < 0.05$ was considered significant.

Results

Mlx4-1 acts as dominant negative Mlx to inhibit glucose-induced Lpk and Fas mRNA expression

As our and other groups reported previously, inhibition of ChREBP transactivity was found to be beneficial for treating metabolic disorders in ob/ob mice [3,4]. A series of pcDNA6.2-Mlx mutants was constructed as shown in Fig. 1A and screened for dnMlx by analyzing Lpk promoter activity. Consistent with Fig. 1A, Mlx4-1 inhibited glucose-induced Lpk promoter activity by 60% (Fig. 1B). In contrast, Mlx2-1 increased Lpk promoter activity by 60% (Fig. 1B). As with the localization of Mlx mutants, Mlx2-1 was mainly localized in the nucleus, while Mlx4-1 and Mlx1-1 were localized in both the cytosol and nucleus (see Supplementary Fig. S1).

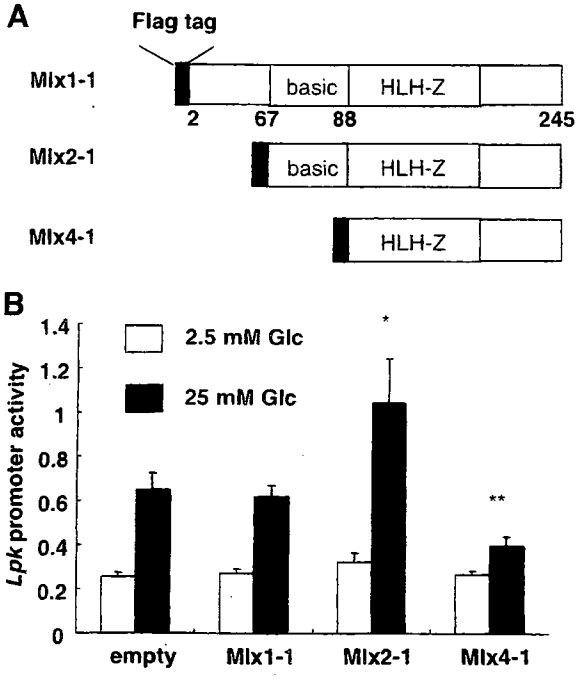

Fig. 1. (A) Schematic representation of wild-type Mlx (Mlx1-1), dominant active Mlx (Mlx2-1), and dominant negative Mlx (Mlx4-1). (B) Effects of Mlx1-1, Mlx2-1, or Mlx4-1 on Lpk promoter activity. Isolated hepatocytes were transfected with 3.6 μg of pGL3-Lpk, 0.4 μg of pGL4-TK-RLuc, and 0.4 μg of pcDNA6.2 empty, Mlx1-1, Mlx2-1, or Mlx4-1 vector using Lipofectamine 2000. Transfected cells were cultured for 24 h and used for analysis of luciferase activity. Data are means ± S.D. ($n = 6$ per group). *, **, $p < 0.05$ *vs.* pcDNA6.2 empty.

Mechanism by which Mlx4-1 inhibits ChREBP-mediated Lpk and Fasn gene expression

In the present study, a deletion mutant, Mlx4-1, was established that inhibits glucose-induced *Lpk* and *Fasn* gene expression. The effects of this mutant on *Lpk* and *Fasn* mRNA gene expression were evaluated. Consistent with Fig. 1B, Mlx4-1 dose-dendently inhibited glucose-induced *Lpk* and *Fasn* mRNA expression (Fig. 2A). When the Mlx4-1 mRNA level was increased 1680-fold, induction of these genes by glucose was completely blocked. The pGL3-3X*Lpk* and 3X*Fasn*-ChoRE vector were then used to clarify whether these inhibitory effects are due to binding of ChREBP/Mlx4-1 to ChoRE. Mlx4-1 completely inhibited ChREBP-regulated *Lpk* and *Fasn* reporter activity in rat hepatocytes (see Supplementary Fig. S2A). The inhibitory effects of Mlx4-1 on glucose-induced expression of *Chrebp* and *Transketolase* (*Tkt*) in rat primary hepatocytes were then examined. *Tkt* is an enzyme that forms xylulose-5-phosphate (Xu-5-P) from two glycolytic intermediates, glyceraldehyde 3-P (GAP) and fructose-6-P (Fru 6-P) (GAP + Fru 6-P ↔ Xu 5-P + erythrose 4-P) in the pentose phosphate pathway [1]. Xu-5-P activates

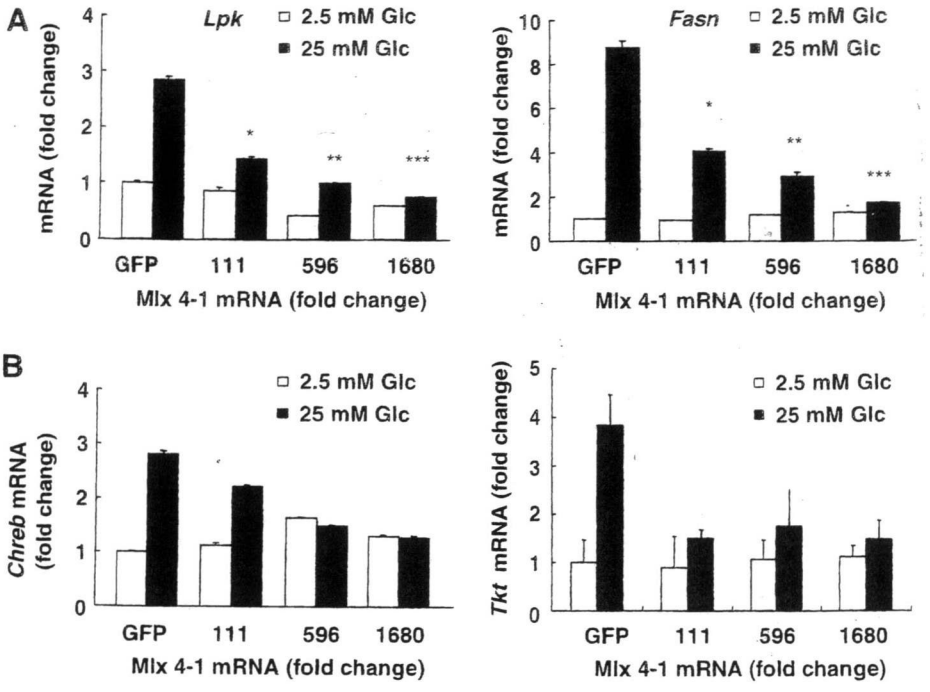

Fig. 2. (A) Overexpression of Mlx4-1 in rat hepatocytes inhibited glucose-induced *Lpk* and *Fasn* mRNA expression in a dose-dependent manner. *, **, *** $p < 0.05$ *vs.* GFP. (B Mlx4-1 inhibited glucose-mediated *Chrebp* and *Tkt* mRNA induction in rat hepatocytes.

protein phosphatase 2A (PP2A), which in turn activates ChREBP by dephosphorylation [1]. Glucose stimulation was found to increase *Chrebp* and *Tkt* mRNA expression (see Supplementary Fig. S2B). Consistent with these data, a 1680-fold increase in Mlx4-1 completely inhibited glucose-induced *Chrebp* and *Tkt* mRNA expression in rat hepatocytes (Fig. 2B). These findings suggest that ChREBP and Tkt constitute a positive feedback loop involved in the regulation of glucose-mediated gene expression such as *Lpk* and *Fasn*.

Overexpression of Mlx4-1 improves glucose and lipid metabolism in diabetes-prone C57BL/6J mice

C57BL/6J mice develop metabolic syndrome with obesity and diabetes in response to a diet high in carbohydrate and/or fat [6]. Moreover, C57BL/6J mice develop glucose intolerance with age [6]. In this study, 25-week-old male C57BL/6J mice were used as a model diabetes-prone mouse to determine whether overexpression of Mlx4-1 improves glucose intolerance and other metabolic parameters in middle-aged C57BL/6J mice. Mice infected with Ad-GFP were used as controls. To minimize the side effects of adenovirus infection in the liver, all experiments were terminated after 5 days. Ad-Mlx4-1-injected mice appeared normal without hepatomegaly (Table 1). As shown in Table 1, body and tissue weights in Ad-Mlx4-1-infected mice were similar to those in controls. Ad-Mlx 4-1 overexpression did not affect food intake, as shown by stomach weight and food intake (Table 1). As shown in Table 2, AST and ALT concentrations were only slightly changed as compared with previously reported observations [4]. The delivery of 3×10^{13} particles/kg BW of Ad-Mlx4-1 or Ad-GFP adenovirus into C57BL/6J mice was liver-specific (data not shown). Increases of about 170-fold in endogenous Mlx mRNA levels were observed in livers infected with Ad-Mlx4-1 as compared with Ad-GFP (Fig. 3A). In liver overexpressing Ad-Mlx4-1, expression levels of the ChREBP target genes *Lpk* and *Fasn* were decreased by 84% and 65%, respectively, (Fig. 3A), suggesting that Mlx4-1 also functions as a dominant negative form of Mlx *in vivo*.

Liver triglyceride contents in Ad-Mlx4-1-injected mice were decreased by 40% due to decreased hepatic lipogenesis, but liver cholesterol contents were unchanged (Fig. 3B). Plasma lipid profile of Ad-Mlx4-1 mice was similar to that of controls (Table 2). Liver glycogen contents of Ad-Mlx4-1 mice were similar to controls (Fig. 3B). Plasma glucose concentration in Ad-Mlx4-1-injected mice was significantly decreased in both fasted and fed states (Table 2). In contrast, plasma insulin, triglyceride, and total cholesterol

Table 1
Phenotypic characteristics of 5-day-treated Ad-Mlx4-1 C57BL/6J mice.

	Ad-GFP	Ad-Mlx4-1
BW (g)	30.6 ± 2.1	30.4 ± 1.9
Food intake (g)	3.68 ± 0.26	3.60 ± 0.28
Stomach (%)	2.24 ± 0.26	2.04 ± 0.54
Liver (%)	5.8 ± 0.24	6.6 ± 0.73
White adipose tissue (%)	2.4 ± 1.4	1.6 ± 0.6
Kidney (%)	1.36 ± 0.14	1.45 ± 0.03

Data are means ± S.D. ($n = 5$ per group).

Table 2
Metabolic characteristics of 5-day-treated Ad-Mlx4-1 C57BL/6J mice.

	Ad-GFP	Ad-Mlx4-1	*P*-value
5-h fast			
Plasma glucose (mg/dl)	115 ± 6.2	81.4 ± 10.8*	$P = 0.014$
Plasma TG (mg/dl)	97.8 ± 22.1	89.6 ± 16.3	
Plasma T.Chol (mg/dl)	78.7 ± 10.1	81.5 ± 14.0	
18-h fast			
Plasma glucose (mg/dl)	86.2 ± 11	67.8 ± 6.6*	$P = 0.010$
Plasma insulin (ng/ml)	0.63 ± 0.21	0.43 ± 0.07	
Ad. lib. Fed			
Plasma glucose (mg/dl)	178 ± 34	111 ± 7.9*	$P = 0.019$
Plasma insulin (ng/ml)	0.83 ± 0.26	0.80 ± 0.26	
ALT (Units/l)	47.5 ± 16.6	93.9 ± 20.0*	$P = 0.010$
AST (Units/l)	32.3 ± 7.9	87.2 ± 14.2*	$P = 0.005$

Data are means ± S.D. ($n = 5$ per group). *$p < 0.05$ vs GFP. Abbreviations: ALT, alanine aminotransferase; AST, aspartate aminotransferase.

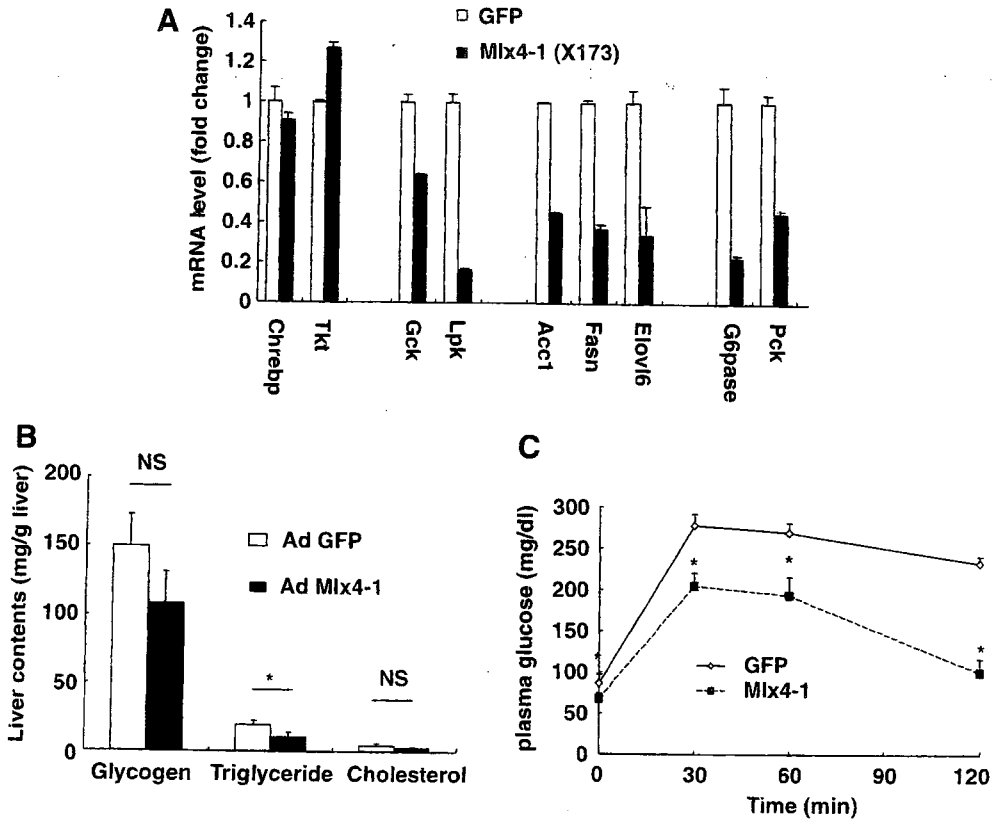

Fig. 3. (A) RT-PCR analysis of glycolytic, lipogenic, gluconeogenic, and lipolytic enzyme mRNA levels in liver of C57BL/6J mice infected with Ad-GFP or Ad-Mlx4-1. Results are means±SD ($n = 5$ per group). $p < 0.05$ vs. Ad-GFP injected C57BL/6J mice. (B) Determination of liver glycogen, triglyceride, and cholesterol contents in Ad-GFP or Ad-Mlx4-1 injected mice. Results are means±SD ($n = 5$ per group) $p < 0.05$ *vs.* Ad-GFP-injected mice. (C) Glucose tolerance tests (1 g/kg BW) were performed in C57BL/6J mice treated for 3 days with Ad-GFP or Ad-Mlx4-1 adenovirus. Animals were fasted for 18 h before OGTT ($n = 5$ per group). Data are means ± SD ($n = 5$ per group). $p < 0.05$ *vs.* Ad-GFP-injected C57BL/6J mice.

concentrations were similar to controls (Table 2). Consistent with these observations, oral glucose tolerance test showed that overexpression of Mlx4-1 improved glucose clearance from the body (Fig. 3C). In addition, glycolytic, lipogenic, and gluconeogenic gene mRNA expression levels were measured. As described above, glycolytic genes such as *Lpk* and lipogenic genes such as *Fasn*, *Acc1*, and ELOVL family member 6 (*Elovl6*) were suppressed by overexpression of Ad-Mlx4-1. In the gluconeogenesis pathway, glucose-6-phosphatase (*G-6-Pase*) and phosphoenolpyruvate carboxykinase (*Pepck*) mRNA levels were decreased by 80% and 50%, respectively, (Fig. 3C).

ChREBP induces G-6-Pase gene expression in rat hepatocytes

G-6-Pase gene expression is regulated by glucose signaling [7]. Moreover, Elovl6 is involved in lipid metabolism, and deletion of *Elovl6* improves glucose intolerance in ob/ob mice [8]. As shown in Fig. 3A, *G-6-pase* and *Elovl6* mRNA were down-regulated in the liver of Ad-Mlx4-1-injected mice. We therefore examined whether glucose and ChREBP can induce *G-6-Pase* and *Elovl6* mRNA in rat hepatocytes. Glucose increased hepatic *G-6-Pase* and *Elovl6* mRNA expression in a dose dependent manner (see Supplementary Fig. S4). Moreover, overexpression of dominant active ChREBP increased *G-6-Pase* and *Elovl6* mRNA expression in rat primary hepatocytes (Fig. 4A). Consistent with the findings shown in Fig. 4A, overexpression of dominant negative Mlx4-1 suppressed glucose-induced *G-6-Pase* and *Elovl6* mRNA expression (Fig. 4B). Thus, ChREBP regulates *G-6-Pase* and *Elovl6* gene expression in rat hepatocytes.

Discussion

This study was performed to determine whether hepatic inhibition of ChREBP transactivity can improve glucose intolerance in C57BL/6J mice. Overexpression of dnMlx/Mlx4-1 inhibited glucose-induced *Lpk*, *Fasn*, *Chrebp*, and *Tkt* gene expression in rat hepatocytes. Moreover, adenoviral delivery of dnMlx/Mlx4-1 into the liver improved glucose intolerance. Thus, blocking the association between ChREBP and Mlx is a promising therapeutic strategy to cure metabolic syndrome.

Mlx and ChREBP form the ChREBP-Mlx complex that binds ChoRE in glycolytic and lipogenic gene promoters such as *Lpk* and *Fasn*. Mlx4-1 is a dominant negative form of Mlx without the N-terminal and DNA-binding domains (Fig. 1A). Mlx4-1 is localized in both the cytosol and nucleus (see Supplementary Fig. S1). In contrast, Mlx2-1 is a dominant active form lacking only the N-terminal domain and is localized mainly in the nucleus. Consistent with our data, some groups have reported that the N-terminal domain of ChREBP has an important role in functions of ChREBP such as nuclear translocation and glucose sensitivity [9]. These observations suggest that the N-terminal domain of Mlx plays a role in determining glucose sensitivity and localization.

dnMlx/Mlx4-1 inhibits glucose-mediated *Lpk* and *Fasn* mRNA expression in rat hepatocytes. Towle et al. reported that Mlx plays an important role in glucose regulation of lipogenic enzymes, using their original Mlx mutant lacking only the DNA-binding domain, and obtained results compatible with ours [10]. Unlike their mutant, we constructed a mutant lacking both the N-terminal and the DNA-binding domains. Our observations suggest that the

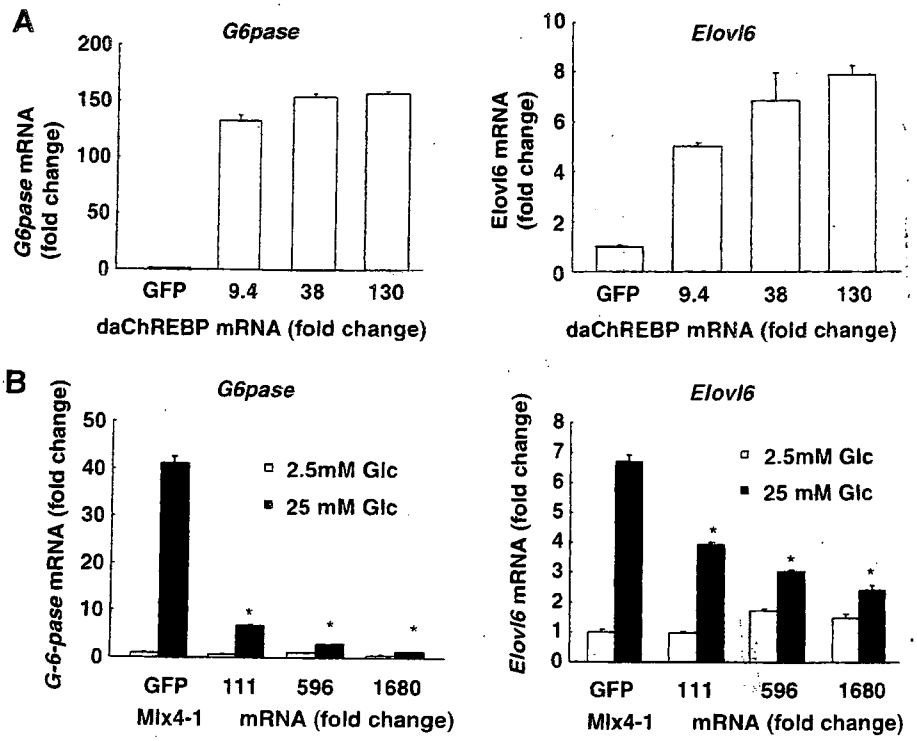

Fig. 4. (A) Adenoviral overexpression of dominant active ChREBP (daChREBP) induced *G-6-Pase* and *Elovl6* mRNA expression in rat hepatocytes. Adenovirus expressing eithe GFP or daChREBP was transduced into rat hepatocytes at m.o.i. of 2, 10, or 50. As control, a recombinant adenovirus expressing GFP was used at m.o.i. of 50. Two h afte infection, cells were kept in DMEM including 2.5 mM glucose for an additional 18 h. Total RNA was then extracted from hepatocytes and RT-PCR analysis was performe Values represent means±S.D. $p < 0.05$ *vs.* Ad-GFP. (B) Adenoviral overexpression of Mlx4-1 inhibited glucose-stimulated *G-6-Pase* and *Elovl6* mRNA expression in ra hepatocytes. Adenovirus overexpressing either GFP or Mlx4-1 was transduced into rat hepatocytes at m.o.i. of 2, 10, or 50. As control, a recombinant adenovirus expressin GFP was used at m.o.i. of 50. Two h after infection, cells were kept in DMEM including glucose concentrations of 2.5 or 25 mM for an additional 18 h. Total RNA was the extracted from hepatocytes and RT-PCR analysis was performed. Values represent means±S.D. $p < 0.05$ *vs.* Ad-GFP.

DNA-binding domain is critical in transactivity of Mlx. Moreover, dnMlx/Mlx4-1 inhibited activation of *Chrebp* and *Tkt* mRNA expression by glucose. In the pentose pathway, glucose is converted to Xu-5-P, an activator of ChREBP [1]. As Xu-5-P is produced by Tkt, ChREBP and Tkt constitutes a positive feedback loop by increasing *Tkt* and *ChREBP* mRNA in rat hepatocytes. It is surprising that glucose increases *Chrebp* mRNA expression in rat hepatocytes and the mechanism remains unknown. Using dnMlx-expressing adenovirus vector, ChREBP was found to directly regulate *Chrebp* gene expression. However, *Tkt* and *Chrebp* mRNA levels were not decreased in the livers of Ad-Mlx4-1-injected mice. In contrast, overexpression of daChREBP caused 40- and 14-fold increases in endogenous *Chrebp* and *Tkt* mRNA levels, respectively, (data not shown). Thus, while glucose regulates *Tkt* and *ChREBP* mRNA expression in rat hepatocytes, other factors may regulate their gene expression more potently *in vivo*.

We and other groups have independently reported that gene deletion or shRNA of *Chrebp* improves metabolic disorders in ob/ob mice [3,4]. However, complete deletion of *Chrebp* causes massive hepatomegaly due to liver glycogen accumulation [3]. Moderate inhibition of ChREBP transactivity thus might improve the symptoms of metabolic syndrome without hepatomegaly. In rat hepatocytes, Mlx4-1 functions only at higher glucose concentrations. In contrast, *Chrebp* gene deletion or *Chrebp* shRNA works at both lower and higher glucose concentrations. Since this is a unique characteristic of dnMlx/Mlx4-1, we tested 25-week-old diabetes-prone C57BL/6J mice. The C57BL/6J mouse is a model of diet-induced obesity and diabetes [6]. As C57BL/6J mice develop glucose intolerance with age similarly to humans, middle-aged C57BL/6J mice were used to test the effects of dnMlx on improvement of glucose intolerance. Overexpression of dnMlx/Mlx4-1 improved glucose intolerance and liver lipid contents without hepatomegaly. These observations suggest that drugs disrupting the association between ChREBP and Mlx may be promising for preventing the development of metabolic syndrome.

dnMlx/Mlx4-1 inhibited expression of genes encoding the glycolytic enzyme *Lpk*, lipogenic enzymes *Acc1*, *Fasn*, and *Elovl6*, and gluconeogenic enzyme *G-6-Pase*, although the precise mechanism by which inhibition of ChREBP transactivity improves metabolic syndrome remains unknown. Elovl6 catalyzes conversion of palmitate to stearate [8]. Consistent with Fig. 4B, dnMlx inhibited glucose-induced *Elovl6* gene expression in primary hepatocytes [11]. Gene deletion of *Elovl6* in high-fat-loaded mice or ob/ob mice improved glucose intolerance by modifying hepatic fatty acid composition, but did not improve hepatic steatosis [8]. We did not analyze hepatic fat composition in Ad-Mlx4-1-injected mice, but fat composition in Chrebp$^{-/-}$ mice was similar to that in normal controls (unpublished data). Moreover, glucose clearance in *Elovl6* knockout mice was similar to that in control [8]. Thus, *Elovl6* mRNA may contribute to improvement of glucose intolerance, even though its effect in Ad-dnMlx/Mlx4-1 mice is limited.

DnMlx inhibited glucose induction of *G-6-pase* mRNA expression. Acute inhibition of the G-6-Pase system lowers the plasma glucose concentration in rats [12]. These observations suggest that G-6-Pase plays an important role in glucose homeostasis in rodents. Some groups have reported the possibility that ChREBP binds to ChoRE in the rat *G-6-Pase* promoter region [7]. Fig. 4A and B indicates that glucose and ChREBP strongly regulate *G-6-pase* gene expression in rat hepatocytes. As SREBP1c did not regulate *G-6-Pase* mRNA expression, and deletion of SREBP1c did not improve glucose intolerance, the difference in *G-6-pase* gene regulation be-

tween ChREBP and SREBP may underlie the improvement of glucose intolerance by ChREBP but not by SREBP [1].

In conclusion, experiments using dnMlx/Mlx4-1 indicate that ChREBP is regulated by *Chrebp* and *Tkt* gene expression, and forms a positive feedback loop in rat hepatocytes. Moreover, overexpression of dominant negative Mlx improves glucose intolerance in diabetes-prone C57BL/6J mice with metabolic syndrome. These observations suggest that drugs capable of dissociating the ChREBP-Mlx complex may be a promising approach to treatment of metabolic syndrome including glucose intolerance.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bbrc.2008.12.100.

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ORIGINAL ARTICLE

Construction of a prediction model for type 2 diabetes mellitus in the Japanese population based on 11 genes with strong evidence of the association

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Prediction of the disease status is one of the most important objectives of genetic studies. To select the genes with strong evidence of the association with type 2 diabetes mellitus, we validated the associations of the seven candidate loci extracted in our earlier study by genotyping the samples in two independent sample panels. However, except for *KCNQ1*, the association of none of the remaining seven loci was replicated. We then selected 11 genes, *KCNQ1*, *TCF7L2*, *CDKAL1*, *CDKN2A/B*, *IGF2BP2*, *SLC30A8*, *HHEX*, *GCKR*, *HNF1B*, *KCNJ11* and *PPARG*, whose associations with diabetes have already been reported and replicated either in the literature or in this study in the Japanese population. As no evidence of the gene–gene interaction for any pair of the 11 loci was shown, we constructed a prediction model for the disease using the logistic regression analysis by incorporating the number of the risk alleles for the 11 genes, as well as age, sex and body mass index as independent variables. Cumulative risk assessment showed that the addition of one risk allele resulted in an average increase in the odds for the disease of 1.29 (95% CI=1.25–1.33, $P=5.4\times10^{-53}$). The area under the receiver operating characteristic curve, an estimate of the power of the prediction model, was 0.72, thereby indicating that our prediction model for type 2 diabetes may not be so useful but has some value. Incorporation of data from additional risk loci is most likely to increase the predictive power.
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Keywords: gene–gene interaction; genome-wide association study; prediction model; single nucleotide polymorphism (SNP); type 2 diabetes mellitus

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INTRODUCTION

Genome-wide association studies (GWASs) have identified novel susceptibility genes for type 2 diabetes mellitus in Caucasians.[1–5] *TCF7L2*, *CDKAL1*, *CDKN2A/B*, *IGF2BP2*, *SLC30A8* and *HHEX* have been widely replicated as susceptibility genes for type 2 diabetes in Asian populations[6–12] as well as in populations of European ancestry.[13,14] We recently identified *KCNQ1* as a novel susceptibility gene, as well as seven other candidate susceptibility loci in a multistage GWAS for type 2 diabetes in the Japanese population, in which a total of 1612 cases and 1424 controls and 100 000 single nucleotide polymorphisms (SNPs) were included.[15] *KCNQ1* was found to confer risk of type 2 diabetes with a relatively large effect size in Asian populations (odds ratio (OR) for Japanese, Chinese and Korean individuals of 1.42),[15] which was similar to that demonstrated earlier for *TCF7L2* in the Japanese population.[6]

Follow-up of GWASs includes analysis of second-tier genes, meta-analysis for specific populations, as well as analysis of gene–gene or gene–environment interactions. A large-scale meta-analysis[16] and an analysis of gene–gene interaction for susceptibility genes[17] have been performed for type 2 diabetes in populations of European ancestry.

In this study, we attempted to confirm in independent subject panels of Japanese and Hong Kong Chinese individuals the associations of the seven candidate susceptibility loci that we identified in addition to *KCNQ1* in our GWAS of type 2 diabetes.[15] However, as described in this article, we failed to replicate the associations of the seven loci with diabetes. We then attempted to extract genes with strong evidence of the associations with diabetes, and selected 11 genes, including *KCNQ1*. As we did not detect any gene–gene interaction between the 11 genes, we then attempted to construct a prediction model for this disease by using the data from the 11 genes, as well as age, gender and body mass index (BMI) as independent variables to obtain a comprehensive understanding of the genetic background of diabetes in the Japanese population.

MATERIALS AND METHODS

Validation of the results from a multistage GWAS in the Japanese population

Study subjects. We assembled two independent subject panels for our replication study: replication-Japanese and replication-Chinese. The 1000 cases and 1000 controls for the replication-Japanese panel were recruited by the Study Group of the Millennium Genome Project for Diabetes Mellitus. The inclusion criteria for diabetic patients were (i) an age at disease onset of 30–60 years and (ii) the absence of antibodies to GAD. Types of diabetes other than type 2 were excluded on the basis of clinical data. The criteria for controls included (i) an age of >50 years, (ii) no past history of a diagnosis of diabetes and (iii) an HbA_{1c} content of $<5.8\%$.

For the replication-Chinese panel, subjects of southern Han Chinese ancestry, who resided in Hong Kong, were recruited. The cases consisted of 1416 individuals with type 2 diabetes selected from the Prince of Wales Hospital Diabetes Registry;[5,18] 626 of these subjects had early-onset diabetes (age at diagnosis of <40 years) and a positive family history, whereas the remaining 790 patients were randomly selected from the registry. Patients with classic type 1 diabetes with acute ketotic presentation or a continuous requirement for insulin within 1 year of diagnosis were excluded. The controls consisted of 1577 subjects with normal glucose tolerance (fasting plasma glucose concentration of $<6.1\ mmol\ l^{-1}$); 596 of these individuals were recruited either from the general population participating in a community-based screening program for cardiovascular risk or from hospital staff, whereas the remaining 981 subjects were recruited from a population-based screening program for cardiovascular risk in adolescents.[19] The clinical characteristics of the subjects in each panel are summarized in Supplementary Table 1A. The study protocol was approved by the local ethics committee of each institution. Written informed consent was obtained from each subject.

Study design and statistical analysis. For the validation of the results from our earlier multistage GWAS,[15] seven SNPs (rs2250402, rs2307027, rs3741872, rs574628, rs2233647, rs3785233 and rs2075931) were genotyped in the two panels either by sequence-specific primer–PCR analysis followed by fluorescence correlation spectroscopy[20] or by real-time PCR analysis with TaqMan probes (Applied Biosystems, Foster City, CA, USA). Differences in allele frequency between cases and controls for each SNP were evaluated by χ^2 with one degree of freedom. Meta-analysis was performed by the Mantel–Haenszel method (fixed-effects models) with the 'meta' package of the R-Project (http://www.r-project.org). A P-value of <0.05 was considered statistically significant.

Examination of gene–gene interaction and construction of a prediction model

Study subjects. In total, 2424 cases and 2424 controls of the Japanese population obtained by combining the second and third screening panels in our original study[15] and the replication-Japanese panel of this study were included in this analysis (analysis-panel). The criteria for the second and third screening panels were described in the earlier report.[15] The clinical characteristics of the subjects are summarized in Supplementary Table 1B.

Selection of the loci included in this study. Prediction of the phenotypes on the basis of genetic polymorphisms should include the genetic data from the loci with strong evidence of the association. Starting from 15 genes described in earlier reports, we selected 11 genes with strong evidence of the association on the basis of the data in the literature and on the results of the replication experiments in this study. Process of the selection of the 11 genes will be described in detail in Results.

Statistical methods. Multiplicative gene–gene interaction was evaluated for each pair of the 11 genes using an interaction term in addition to the terms for the pair of the genes in the logistic regression model. The genotypes for each locus were coded by 0, 1 and 2. Correction for multiple testing was performed by Bonferroni's method.

As there was no evidence for the presence of gene–gene interactions, we attempted to construct a phenotype prediction model by incorporating the number of risk alleles for the 11 loci as an independent variable in addition to age, gender and BMI. The Cochran–Armitage test was used to examine the trend of the increase in the odds by increasing the number of the risk alleles. To construct a prediction model, the log of odds was expressed by the linear combination of the independent variables. Coefficients for the variables were estimated by the logistic regression analysis after making disease (cases) or nondisease (controls) as the dependent variable. Using the coefficients estimated by the logistic regression analysis, we constructed a phenotype prediction model. To evaluate the prediction model, receiver operating characteristic (ROC) curves[21] for the sensitivity and specificity of the prediction model with or without adjustment for age, sex and BMI were generated, and the area under the curve (AUC) was calculated from the ROC curve.

RESULTS

Validation of the results from a multistage GWAS in the Japanese population

We identified earlier 10 loci associated with type 2 diabetes by three-staged GWAS starting from 100 000 SNPs. Among the 10 loci, 3 SNPs were located in an intron of *KCNQ1*, and the association of this gene with diabetes was confirmatory.[15] To validate the other seven loci for the association with type 2 diabetes, we analyzed them in two independent replication panels of Japanese and Han-Chinese individuals (Table 1, Supplementary Table 2). Only one SNP, rs2250402, which is located in *EIF2AK4*, was found to be significantly associated in the replication-Japanese panel (P=0.039, OR=1.17, 95% CI=1.01–1.36). However, neither this SNP (P=0.41, OR=1.05) nor any of the other six SNPs showed such an association in the replication-Chinese panel. Meta-analyses for these SNPs showed that rs2307027 in *KRT4* and rs3785233 in *A2BP1* yielded P-values of <0.05 and ORs between 1.12 and 1.13 (Table 1). When the original second and third screening